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Stiffness of Hot Mix Asphalt

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Stiffness of Hot-Mix Asphalt

Introduction

This research was initiated from a need to evaluate marginal mixtures that do not meet the Superpave mix design criteria for the air voids content requirements for the construction of hot mix asphalt (HMA) pavements.

The asphalt mixture verification at the asphalt plant is conducted by compacting plant-produced loose mixture with the gyratory compactor. The compacted specimen must meet a target air voids content of $4\% \pm$ tolerances. If the mixture fails to meet this, the contractor must remove the inferior material.

However, over the past two to three years the Indiana Department of Transportation (INDOT) has been applying an appeal process, which allows the contractor to leave the mixture on the road if the mixture stiffness is adequate. The mixture stiffness has been considered adequate if the shear stiffness $|G^*|$, measured with the Simple Shear Tester (SST) at 40°C with 10 Hz frequency, is above 250 MPa. This requirement is an empirical rule of thumb developed in recent years by the industry.

Therefore, this research investigated the possibility of using asphalt mixture stiffness and strength as performance indicators to assess the rutting resistance of marginal mixtures, and the

major objective was to develop a performance criteria or threshold value to be used as a quality control/quality assurance tool in future HMA construction projects. The research concentrated on the asphalt surface mixtures used in Indiana.

Four major mechanical tests used in this research were the dynamic (complex) modulus test, the frequency sweep at constant height (FSCH) shear modulus test, the triaxial shear strength test and the indirect tensile (IDT) strength test. The unconfined dynamic modulus $|E^*|$ testing was performed on all sample sets at two different temperatures (40°C and 54.4°C) using six different frequencies (25 to 0.1 Hz). The triaxial shear strength testing was performed at 54.4°C with the ram loading rates of 50 mm/min and 7.5 mm/min with confinement levels, 0 kPa, 138 kPa, 276 kPa and 414 kPa. The IDT tensile strength testing was conducted at 35°C with the ram loading rate of 0.39 mm/min and 0.06 mm/min. The frequency sweep at constant height (FSCH) shear modulus test was performed by North Central Superpave Center (NCSC) at two different temperatures (40°C and 54.4°C) using ten different frequencies (10 Hz to 0.1 Hz).

Findings

Evaluation of Test Conditions and Parameters

Ranking of mixtures changed significantly when tested at 40 and 54.4°C temperatures. Identified possible reasons are change in relative binder stiffness from low to high temperature; increased damage accumulation in the specimen at higher test temperature; and/or

different mixture behavior due to increased aggregate influence at higher test temperatures.

Confinement in the axial stiffness $|E^*|$ testing reduced the binder influence, which relatively increased the stiffness of the softer mixtures. Furthermore, the use of stiffer binders in the SMA mixtures seems to compensate for

the need of using confinement to verify the mixture performance.

Theoretical relationship between axial and shear stiffness is not valid, which means that $|E^*|$ and $|G^*|$ are not interchangeable, and one cannot be obtained from another by using theoretical formulations. Since $|E^*|$ and $|G^*|$ of mixtures are correlated by stiffness of the asphalt binder, this provides a possibility to predict $|G^*|_{\text{mix}}$ based on $|E^*|_{\text{mix}}$ or vice versa using the Hirsch stiffness prediction model. The average testing variation ranged from 12 to 19%. Testing variation increased with increasing testing temperature and decreasing frequency.

For IDT strength testing there was good correlation between the slower and faster loading rates (R^2 0.84-0.90). In addition, a theoretical relationship exists between the IDT strength and triaxial shear strength. Therefore, for practical purposes, the IDT tensile strength can be used as a surrogate test to replace the triaxial strength test. If no information is available for the friction angle, a ratio of 1.80 of the cohesion to IDT tensile strength is a good approximation. The average testing variation for the IDT strength was less than 10%, which is less than the testing variation for stiffness testing.

Selection of Parameters and Test Conditions

Overall, the dynamic modulus $|E^*|$ and SST shear modulus $|G^*|$ did not rank mixtures in the same way; although the rankings at 40°C temperature were quite similar, at 54.4°C rankings deviated substantially. The plant mixtures were ranked in a similar way by axial and shear stiffness, while field cores gave the most different rankings. Unfortunately, at this point it is not possible to confirm if this reflects the real material behavior or if it is an artifact of the differences between the test methods. However, all test methods and test conditions were generally able to identify the softest and the stiffness mixtures in a similar manner measured from the raw material or plant mixtures.

The stiffness difference between the stiffest and softest mixtures ranged from 2.2 to 4.0. The strength difference between the strongest and weakest mixtures ranged from 1.8 to 6.4. This refers to mixture composition of steel slag, blast furnace slag, and dolomite aggregate combined with three binder grades ranging from PG64-22 to PG76-22.

The average mixture stiffness and strength ratios within a high temperature binder PG grade ranged from 1.4 to 2.4. This suggests that by changing aggregate type and gradation, and binder content it is possible to double the stiffness of mixture without changing the binder grade. For field cores, the strength difference was up to 4.4 reflecting differences in the roller compaction during construction. The $|E^*|$ indicated higher stiffness ratios compared to the $|G^*|$ and IDT testing. The largest difference between mixtures was measured from field cores taken approximately one week after construction followed by the gyratory compacted asphalt plant mixtures.

Based on the research findings, both stiffness and strength are needed to predict mixture performance. Although mixture response obtained at lower and higher testing temperature deviates, at this point the lower testing temperature is recommended mainly to minimize the testing variation. Both temperatures are identifying the softer and stiffer mixtures, which is a requirement for a good performance parameter. The need to use a higher testing temperature may arise from the need for using different low temperature binder grades, which may mask the influence of the binder stiffness at the lower testing temperature, especially for mixture with modified binders.

Performance Criteria Development

The performance criteria for stiffness and strength were developed by using I74 forensic study data as a baseline, and criteria verification was done using findings from the I70 SPS9A study. For stiffness criteria, two different criteria from literature were compared against the measured mixture performance. These criteria were stiffness criteria developed by Pellinen using layered elastic analysis, and rule of thumb criteria from Asphalt Institute. The IDT strength criteria was developed using IDT strength criteria developed by Christensen et al. as the baseline.

Indiana mixtures seem to comply well with the Asphalt Institute rule of thumb stiffness criteria, when it is applied for cores with 7.5% air voids content; while the criteria based on layered elastic analysis was too stringent for the roads with heavier traffic loading. The IDT criteria derived from the Christensen et al. criteria seems to comply well with the Indiana mixtures while the I74 forensic study criteria seems to be too stringent.

It was evident from the I74 failure data that a factor of safety is needed when applying performance criteria to avoid failure. The needed factor of safety may be as high as 3 for the asphalt mixtures in Indiana. However, there is a delicate balance in preventing failure and at the same time rejecting well performing mixtures or accepting fair mixtures. However,

at this point there is not enough data to analyze adequately the risks of acceptance or rejection. It can be speculated that the factor of safety 2.2 may be adequate when tight quality control is exercised during HMA construction. The developed criteria are presented in tabular form in the study report.

Implementation

To assess the “true” mixture performance, it is recommended that QA testing be conducted on “young” field cores, and that the asphalt plant gyratory specimens be used for verification and mainly for production QC testing. The reason for this recommendation is that the roller compacted in-place mixtures have different mechanical properties compared to the gyratory-compacted mixtures. Then, the evaluation of the as-placed properties will eliminate variables that otherwise would confound the performance predictions, thereby improving the accuracy of predictions. In addition, the use of field cores provides an important link between the current volumetric acceptance specification and the possible future performance related specification for Indiana.

The production QC testing can be performed either using standard SGC-compacted specimens after conformance of the air voids requirements is verified or by compacting separate specimens to cut and /or core test specimens at 7.5% air voids content. If test specimens are obtained from the standard QC specimens, the air voids content of the specimens must be measured before testing to obtain the adjustment factor. The use of standard production specimens and the air voids adjustment factor will speed up the testing by simplifying the sample preparation processes. If an engineer wants to predict mixture performance in the mix design stage, the use of mix design trial samples for testing is recommended, similar to the plant SGC specimens discussed above, to speed up the sample preparation and testing.

A novel method of using horizontally-stacked composite specimens to measure the dynamic modulus of thin pavement cores was developed as an alternative for the SST shear testing of pavement cores. However, this method gave significantly higher stiffness values compared to the SST testing, and, therefore, until these deviations can be explained satisfactorily, this method is not recommended to be used in HMA production, which leaves the SST shear testing the only available method to test cores.

For plant SGC specimens and mix design specimens, both the SST shear testing and the dynamic modulus testing are available, although it is not recommended to use confinement in the dynamic modulus testing for the Indiana SMA mixtures. The use of a stiffer binder in these mixtures seems to compensate for the need of using confinement to verify the mixture performance.

The recommended performance parameters are SST shear stiffness $|G^*|$ tested at 40°C with 10 Hz frequency and indirect tensile strength S_t tested at 35°C applying 0.06 mm/min ram rate loading. Both methods need cylindrical test specimens of 150 mm in diameter and 38 to 50 mm in height.

It is recommended that the implementation of the developed criteria will be done by conducting pilot-paving projects. An important task is to verify the response ratios between field cores and SGC compacted plant specimens. It is recommended to use field cores for quality assurance and establish relationship of cores and SGC specimens for quality control purposes.

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16. Abstract <p>This research was initiated from a need to evaluate marginal mixtures that do not meet the Superpave mix design criteria for the air voids content requirements for the construction of hot mix asphalt pavements. The developed criteria is comprised of the base criteria derived from test data of as-placed field cores normalized to 7.5% air voids content, which provides the minimum stiffness and strength requirements for a mixture as a function of the traffic level. The stiffness of pavement cores is measured using Simple Shear Tester to obtain shear stiffness G^* of mix and strength is measured using indirect tensile strength testing. The asphalt mixture will meet the criteria if it meets both the stiffness and strength requirements. Additionally, the criteria include coefficients intended to adjust the base criteria for variable mix density. Given the need to assess the mix performance in the plant mixing stage, an adjustment factor is provided to account for the compaction procedure effects for the gyratory-compacted asphalt plant mixtures relative to pavement cores compacted by rollers. Another adjustment factor to account for the mixture aging effects is provided for the asphalt mixtures tested in the mix design stage. Forensic study of failed interstate pavement near Indianapolis, Indiana suggests that for a heavy traffic of more than 30 million design equivalent single axle load applications, the factor of safety that the developed criteria is providing against rutting is ranging from 2.2 to 2.8.</p>			
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1 INTRODUCTION

1.1 Background and Problem Statement

This report documents research findings of the study SPR-2644 “*Stiffness of Hot Mix Asphalt*” supported by the Purdue Joint Transportation Research Program (JTRP). The research was initiated by a need to evaluate marginal mixtures that do not meet the Superpave mix design criteria for the air voids content requirements.

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Over the past 2-3 years, however, the Indiana Department of Transportation (INDOT) has been applying an appeal process, which allows the contractor to leave the mixture on the road if the mixture stiffness is adequate. The mixture stiffness has been considered adequate if the shear stiffness $|G^*|$, measured with Simple Shear Tester (SST) at 40°C with 10 Hz frequency, is above 250 MPa. This requirement is an empirical rule of thumb developed in recent years by the industry.

A need to verify this empirical rule led to a research request to investigate and determine a threshold mixture stiffness, which could serve as a quality control/quality assurance tool in future construction projects.

In addition, a loss of macro texture and resulting decrease in friction has been identified recently as a concern in some newer pavements, which have been built using Superpave mix design, as well as in some older pavements that were built using the Marshall mix design method. It is believed that the loss of macro texture is caused by the collapse of aggregate structure in the mixture under heavy loads, which is facilitated by low mixture stiffness.

1.2 Objectives

This research investigated the possibility of using asphalt mixture stiffness and strength as performance indicators to assess rutting resistance of marginal mixtures. Therefore, the major objective was to develop a performance criteria or threshold value to be used as a quality control/quality assurance tool in the HMA construction projects. The research concentrated on the asphalt surface mixtures used in Indiana. It was envisioned that the performance criteria must be dependent on the speed of heavy truck traffic and climatic conditions, i.e. pavement temperature.

1.3 Research Approach

Stiffness of hot mix asphalt (HMA) is a fundamental material property, which can be measured using various test equipment and test methods. Traditionally, empirical mix design methods have strongly relied on the belief that the stiffer/stronger the mix, the better the performance against permanent deformation.

One of the candidate tests for a Simple Performance Test (SPT) for the Superpave mix design system, studied by National Cooperative Highway Research Program (NCHRP) 9-19 Project: “*Superpave Support and Performance Models Management*”, was the dynamic modulus $|E^*|$ of the mix measured using servo-hydraulic testing equipment (Witczak et al., 2001; Pellinen, 2001). Research suggested that the $|E^*|$ correlates well with the field measured rutting of hot mix asphalt and can be used as a performance indicator for rutting. Similar findings were obtained for the shear stiffness $|G^*|$ of the mixture measured with the Simple Shear Tester (SST). The correlation of shear stiffness to rutting has been confirmed by several studies in recent years. The outcome of the NCHRP 9-19 study was heavily driven by the large variation of binder stiffness of the mixtures tested. Further research has not been able to confirm findings when more limited binder range of binder stiffness and more variable mixture types and raw materials have been studied. This is not surprising because research suggests that perhaps up to 80% of the mixture stiffness is provided by the binder stiffness (Pellinen, 2004).

Due to the concerns of relating mixture stiffness alone as a simple performance indicator for rutting, Pellinen (2004) suggested a conceptual performance criterion based on the stiffness and shear strength. The most resistance to volume changes is provided by the binder stiffness, while the aggregate gradation, texture and shape play a more important role in the development of the shear resistance or resistance against twist in the mixture. The author argued that for some asphalt mixtures, the stiffness and strength properties are correlated leading to similar performance predictions, but for some mixtures these properties are not correlated, which will lead to a different performance prediction. Therefore, Pellinen suggested that for an optimal pavement performance, both stiffness and shear strength of the mixture must be considered.

A study by Christensen, Bonaquist and Jack (2000) found that cohesion in the asphalt mixture correlated well with the rutting resistance. The shear resistance in the asphalt mixtures is comprised of cohesive forces provided by asphalt binder and aggregate interlock, and frictional resistance between particles is provided by the aggregate texture. They stated that the cohesion parameter could be accurately estimated from the indirect tensile (IDT) strength test, which is a promising simple performance test because it is simple and fast to perform and no instrumentation is necessarily needed.

Therefore, mixture stiffness was measured using the dynamic (complex) modulus $|E^*|$ test and Simple Shear Tester (SST) frequency sweep at constant height (FSCH) tests to obtain shear stiffness $|G^*|$, and mixture strength was measured in two ways, using the triaxial shear strength test and the IDT strength test. In addition, micro-texture retention in the mixture was studied by the repeated load permanent deformation (dynamic creep) test. This test was also one of the candidate SPT tests in the NCHRP 9-19 study (Witczak et al., 2001).

1.4 Scope of Research

The scope of the work was to evaluate stiffness and strength characteristics of different surface mixtures used in Indiana. The stiffness and strength of hot mix

asphalt is dependent on the amount and type of raw materials and additives, as discussed above. In addition, the effectiveness of compaction and type of compaction equipment affect the mixture stiffness and strength characteristics. Therefore, three sets of samples were included in the laboratory testing as follows:

- Laboratory fabricated and compacted mixture using raw materials,
- Asphalt plant loose mixture samples compacted in the laboratory, and
- Pavement cores; 1st set of cores obtained right after pavement construction, and 2nd set of cores obtained approximately one year later.

The research also included taking cores from the failed and survived sections of Interstate I74 before it was overlayed in Spring 2002. It was envisioned that the known performance of the I74 mixture could be used as guidance in the performance criteria development. A section of I74 near Indianapolis was rehabilitated with 76 mm of intermediate and 30 mm of surface hot mix asphalt in Summer 1998. After construction, the eastbound lane suffered rutting failure in Summer 1999 developing 12 to 15 mm of rutting while the westbound lanes survived well developing only 1-3 mm of rutting, although the traffic was heavier in the westbound lanes. Cores were taken by INDOT from the failed and survived pavement sections in Fall 1999 and INDOT conducted an investigation of the cause(s) of pavement failure. Test results suggested that low shear stiffness measured from the surface and intermediate mixtures was responsible for the rutting failure.

The developed performance criteria was verified by utilizing Indiana SPS9-A study by Shah (2004). The advantage of this study was that one of the test sections was instrumented to monitor air and pavement temperatures. Data collection included rut depth measurements at 1.5 and 4 years of traffic, and taking cores between 6 month intervals to measure extracted binder properties.

An additional mini study was also conducted to investigate how the test specimens aged in the laboratory when stored in the cold room or on the shelves at ambient temperature.

2 STUDIED MIXTURES

2.1 Selection of Study Mixtures

The rutting criteria must be applicable to all traffic levels and geographical locations, so two main factors, traffic level and the binder performance grade (PG), were considered. The former is categorized into Low, Medium and High levels of traffic based on the Superpave volumetric mix design system (AASHTO MP2), and the latter uses the binder PG grades used in Indiana, including: PG64-22, PG70-22 and PG76-22. INDOT is also using two different types of surface mixtures: the dense graded mixture and the Stone Matrix Asphalt (SMA) mixture, which were both included in the study.

Table 1 gives the factorial design of the study mixtures showing the combinations of ESALs, binder grades and climate. The three traffic levels, three binder grades, and two mixture types together with the two paving project locations (north and south) would give 36 mixtures.

However, some of the combinations are not realistic and some of the combinations were not available. For instance, all SMA mixtures in Indiana are placed on the roads with relatively heavy traffic, and the binder grade used is PG76-22. In addition, SMA mixtures have steel or blast furnace slag replacing stone in the aggregate skeleton. Because the study mixtures were sampled from the paving contracts let during 2002, the mixture collection had to be adjusted based on what was available at the time. For instance, the actual design traffic for mixture SR135 was 20 million ESALs instead of >30 million ESALs as was targeted. However, it was still considerably more than the design traffic for SR56 and SR66, which had 7.5 and 6.8 million ESALs.

Table 2 shows all realistic combinations of the three factorials combined with the mixture and aggregate types available for the study. Table 3 shows the collected mixtures, and Table 4 lists mixture with location and contractor information.

Table 1. Binder Grades vs. Mix Design ESALs.

Binder PG Grade	10 ⁶ ESALs					
	North			South		
	Low	Med.	High	Low	Med.	High
Low PG 64-22	<3	3-30	n/a	<3	3-30	>30
Medium PG 70-22	<3	3-30	>30	<3	3-30	>30
High PG 76-22	<3	3-30	>30	<3	3-30	>30

Table 2. Mixture Type vs. Aggregate Type.

Mix/ PG Grade		North			South		
		Low ESALs	Med. ESALs	High ESALs	Low ESALs	Med. ESALs	High ESALs
DGM	Low PG	ST ¹	SL ²	n/a	ST	n/a	n/a
	Med. PG	n/a	n/avb	SL	n/a	ST, SL	SL
SMA	High PG	n/a	SL	SL	n/a	SL	SL

n/a = Not applicable, n/avb = Not available, (1) ST = Stone, (2) SL = slag

Table 3. Collected Mixtures.

Mix/ PG Grade		North			South		
		Low ESALs	Med. ESALs	High ESALs	Low ESALs	Med. ESALs	High ESALs
DGM	Low PG	SR15	US24		SR161		
	Med. PG			US30		SR66,SR56	SR135
SMA	High PG		US31	174		SR64	I65

Table 4. Paving Locations and Contractors.

District	County	Road No.	Contract No.	Contractor	Mix Type	PG Grade
Fort Wayne	Wabash	SR15	25904	E&B Paving	DGM	64-22
Fort Wayne	Miami	US24	25943	E&B Paving	DGM	64-22
Vincennes	Spencer	SR161	25840	JH Rudolph	DGM	64-22
Seymour	Scott	SR56	25250	Gohmann	DGM	70-22
Fort Wayne	Kosciusko	US30	25944A	Phend & Brown	DGM	70-22
Vincennes	Posey	SR66	25848	E&B Paving	DGM	70-22
Seymour	Johnson	SR135	26169A	Shelly & Sands	DGM	70-22
La Porte	Fulton	US31	25933	E&B Paving	SMA	76-22
Greenfield	Shelby	I74	25811	Milestone	SMA	76-22
Vincennes	Gibson	SR64	25842	Gohmann	SMA	76-22
Seymour	Bartholomew	I65	25667	Dave O'Mara	SMA	76-22

2.2 Mix Designs

The dense graded mixtures were designed according to the Superpave volumetric mix design method following AASHTO MP1, MP2, and PP28 specifications and standard practices, effective in 2002, and the SMA mixtures were designed using the AASHTO MP1, MP2, MP8, and PP41 specifications and standard practices. All mixtures were designed by the corresponding asphalt contractor. The mix design information obtained from the mix design reports are summarized in Table 5 and presented in more detail in Appendix 1. Table 6 and Table 7 summarize the Job Mix Formula (JMF) properties for the dense-graded and SMA mixtures, respectively. The nominal maximum aggregate size is 9.5 mm for the dense graded mixtures. The SMA mixtures have 12.5 mm nominal aggregate size.

Table 5. Mix Design Information.

Road No.	Mix Type	Aggregate	JMF Design ESALs (10^6)	Specification Design ESALs (10^6)	AASHTO Mix Design Method	N _{des}
SR15	DGM	Dolomite	2.4	0.3 to < 3	MP1, MP2, PP28	75
US24	DGM	B-F Slag	9.6	3 to < 30		100
SR161	DGM	Dolomite	0.5	0.3 to < 3		75
SR56	DGM	Steel slag	7.5	3 to < 30		100
US30	DGM	B-F slag	50.2	>30		125
SR66	DGM	Sand Stone	6.8	3 to < 30		100
SR135	DGM	B-F slag	20.0	3 to < 30		100
US31	SMA	Steel slag	21.4	All	MP1, MP2, MP8, PP41	100
I74	SMA ¹	Steel slag	—	All		100
SR64	SMA ¹	Steel slag	12.1	All		100
I65	SMA ¹	Steel slag	155.0	All		100

1) Mix has fiber

Based on personal communication with Joe Gundersen (2002) the actual binder content is the target binder content the contractor is using in the asphalt plant settings, and it is verified by the ignition oven testing. If the binder is recovered using extraction the effective binder content is used as the target.

Table 6. JMF Mix Design Properties (DGM).

Road No.	P_b^1	P_b^2	Volumetrics @ $N_{des}(\%)$			Specific Gravity			Dust/ P_{beff}	Tensile Strength Ratio (TSR) ³ (%)
			V_a	VMA	VFA	G_{se}	G_{mm}	$G_{mb @ N_{des}}$		
SR15	5.6	5.3	4.0	15.9	74.9	2.718	2.488	2.388	0.8	94.7
US24	5.7	5.4	4.0	16.1	75.0	2.631	2.417	2.319	1.0	97.0
SR161	5.4	5.2	4.0	15.3	73.9	2.668	2.457	2.356	0.8	90.0
SR56	6.2	6.0	4.0	15.4	73.8	2.969	2.659	2.551	1.1	81.2
US30	6.2	6.0	4.0	15.9	74.8	2.702	2.455	2.357	0.8	97.7
SR66	5.7	5.5	4.0	15.1	73.6	2.682	2.457	2.359	1.2	90.5
SR135	6.4	6.0	4.0	15.4	73.9	2.680	2.431	2.334	0.9	89.5

(1) Actual binder content, binder recovery using ignition (by weight-%)

(2) Effective binder content; Binder recovery using extraction (by weight-%)

(3) Tested from specimens with 7.0 ± 1.0 percent air voids.

Table 7. Mixture Design Properties (SMA).

Road No.	P_b^1	P_b^2	Volumetrics @ $N_{des}(\%)$			Specific Gravity			VCA (%)		Drain Down (%)	TSR (%)
			V_a	VMA	VFA	G_{se}	G_{mm}	G_{mb}	DRC ³	Mix		
US31	4.8	4.7	4.0	17.8	77.6	3.294	2.980	2.861	—	33.4	0.08	95.5
I74	5.5	5.4	4.0	17.7	77.4	3.584	3.154	3.028	45.2	36.3	0.00	97.0
SR64	5.5	5.4	4.0	17.9	77.6	3.330	2.966	2.847	41.2	37.5	0.00	83.1
I65	5.9	5.5	4.0	17.8	77.5	3.422	3.017	2.896	43.9	39.9	0.07	88.7

(1) Actual binder content, binder recovery using ignition (by weight-%)

(2) Effective binder content; Binder recovery using extraction (by weight-%)

(3) Dry rodded coarse aggregate

Table 8 shows the annual daily traffic (ADT for both directions) and percent trucks provided by INDOT Materials and Tests (M&T) (personal communication with Kumar Dave 5/31/2005). The table also shows mix design ESALs reported by M&T in Summer 2002 (personal communication with Joe Gundersen, 2002).

Eq. (1) gives a simplified method of calculating ESALs if the truck factor T_f is known. By using $T_f = 1.3$ (provided by INDOT), ADT and percent trucks (T), Table 8 shows the calculated ESALs for each road. The traffic growth was assumed to be 4% per year.

$$ESALs = ADT \times T \times T_f \times L \times D \times G \times 365 \times Y \quad (1)$$

In Eq. (1) L is the lane factor, D is the directional factor, G is traffic growth, and Y is the design life. Values L = 0.8 to 1, D = 0.5, G = 1.5, and Y = 20 years were used in the calculations.

There are some differences in the calculated and reported design ESALs, as the table shows. The largest difference is for I65 mixture, 55.2 versus 155 million ESALs. The reason for the difference is unknown.

Table 8. Traffic Information.

Road No.	Year	ADT	Trucks (%)	Calculated ESALs (10^6)	M&T Design ESALs (10^6)
SR15	1995	5,270	12	4.5	2.4
US24	2002	6,439	10	3.7	9.6
SR161	1996	1,400	7	0.7	0.8
SR56	2002	4,954	7	2.5	7.5
US30	2002	30,690	23	40.2	50.2
SR66	2002	3,000	9	1.5	6.8
SR135	1997	30,000	10	17.1	20.0
US31	2002	11,900	21	14.2	15.3
I74	2002	35,000	15	29.9	33.0
SR64	1996	18,600	6	7.9	12.0
I65	2002	33,450	29	55.2	155.0

2.3 Material Sampling

2.3.1 Sampling Dates and Quantities

Material sampling started in late Spring 2002 and continued to the Winter of 2003. Three different sets of samples were collected: 1) raw materials including aggregate, asphalt binder, and fibers; 2) plant loose mixtures; and 3) pavement cores. The plant loose mixture and raw materials were sampled in the asphalt plant when

each mixture was produced. Table 9 gives the amounts of materials sampled in each contract, and Table 10 gives the sampling dates.

Table 9. Sampling Quantities from Asphalt Plant.

Sampled Materials	5 gal buckets per mix (QTY) ¹	Per mix (kg)	Total (kg)
Loose asphalt mixture	12	420	4620
Aggregate Stockpiles	12	420	4620
Backhouse fines	0.5	20	60
Fiber	—	2	6
Asphalt binder	1	35	385

(1) 35 kg per 5 gallon bucket

The first set of cores was obtained approximately one week after pavement construction, although for some projects this was not the case. The second set of cores was taken during Fall and Winter of 2003, approximately one year from the first coring. For I74 and SR64, contractor quality control (QC) cores were used instead of obtaining separate cores. In Table 10 coring lag for the 1st set of cores refers to the days between mixture sampling from the plant and obtaining the 1st set of cores, and coring lag for the 2nd set of cores refers to the days between the 1st and the 2nd sets of cores.

Table 10. Sampling Dates.

Road No.	Sampling Dates			Coring Lag (Days)	
	Plant Loose Mixture and Raw Materials	1st Set of Cores	2nd Set of Cores	1st Set of Cores	2nd Set of Cores
SR15	6/6/02	6/20/02	9/23/2003	14	460
US24	6/9/02	6/13/02	9/23/2003	4	467
SR161	7/25/02	8/5/02	10/15/2003	11	436
SR56	5/28/02	6/5/02	10/7/2003	8	489
US30	6/25/02	8/1/02	9/25/2003	38	420
SR66	8/12/02	8/20/02	10/14/2003	8	420
SR135	8/27/02	9/5/02	10/8/2003	9	398
US31	8/15/02	10/8/02	10/16/2003	54	373
I74	10/29/02	QC Cores	11/5/2003	—	372
SR64	9/25/02	QC Cores	10/15/2003	—	385
I65	8/29/02	9/10/02	10/7/2003	12	392

2.3.2 Coring Locations

Figure 1 shows a schematic coring plan developed in Spring 2002. The intent was to take 15 cores (150-mm diameter) from the center of the driving lane to prevent any traffic densification in the second set of cores. The contractor or state personnel took the cores in Summer and Fall 2002 and Fall 2003. The core locations were verified in Fall 2004 by Purdue, which revealed that only SR56 was cored exactly by the plan. Due to the inadequate information of the precise location of cores for I74 and I65, core locations could not be verified.

Figure 1. A Schematic Plan for Coring.

Table 11 summarizes the coring locations for each project. The definition of the center of lane coring (CL) includes cores taken from ± 0.3 m of the actual centerline. Wheel path (WP) is defined to locate between 0.5 and 1.2 meters to the right or left of the centerline. All except I65 and US30 cores were taken from the driving lane. US30 cores were taken from the exit lane and I65 cores were taken from the passing lane. Cores obtained for I74 and SR64 were CQ cores, which were taken from variable locations in the driving lane, see Figure 2. A more detailed description of core locations is given in Appendix 5.

Table 11. Coring Locations

Road No.	No. of Lanes per both directions	Core Location Per/Lane	Direction	1 st Coring Location	2 nd Coring Location
SR15	1+1 ¹	Driving	NBL	CL ²	CL-RWP ³
US24	2+2	Driving	WBL	CL-RWP	RWP ⁴
SR161	1+1 ¹	Driving	SBL	CL-RWP	CL-RWP
SR56	1+1 ¹	Driving	EBL	CL	CL
US30	2+3	Exit	WBL	LWP-CL	RWP
SR66	2+2	Driving	WBL	CL	RWP
SR135	2+2 ¹	Driving	SBL	CL	CL-RWP
US31	2+2	Driving	NBL	LWP ³	LWP-CL
I74	2+2	Driving	WBL	QC/Varies	QC/Varies
SR64	1+1 ¹	Driving	WBL	QC/Varies	QC/Varies
I65	2+2	Passing	NBL	CL	CL

(1) Undivided road, (2) Center of Lane $\pm$ 0.30 m, (3) Between Center of Line and Right/Left Wheel Path, (4) Right/Left Wheel Path

Figure 2. 2nd Coring in Fall 2003 for SR64.

3 LABORATORY TESTING

3.1 Test Methods and Test Conditions for Asphalt Mixtures

Five different types of tests were used in this research including the dynamic modulus test, shear modulus test, triaxial strength test, indirect tensile (IDT) strength test, and repeated load permanent deformation test, also called dynamic creep test. Appendix 2 gives a short description of each test method and test parameters. Table 12 summarizes the typical parameters obtained from each test and test protocols used. Table 12 also shows which tests were used for each sample set of laboratory-fabricated samples from raw material, plant loose mixture compacted in the laboratory, and field cores. Due to the sample size limitations, neither confined dynamic modulus nor triaxial strength tests were conducted for field cores.

All sample preparation was done by Purdue University, except the measurements of air voids content for specimens and cores used in the shear modulus testing, which was conducted by North Central Superpave Center (NCSC).

Table 12. Test Methods and Parameters.

Test Method	Parameters	Sample Set			Protocol	Testing Agency
		Laboratory Fabricated Mixture	Plant Loose Mixture	Field Cores		
Dynamic Modulus ¹	$ E^* , \phi$	X	X	X ²	ASU	Purdue
Shear Modulus	$ G^* , \delta$	X	X	X	AASHTO TP7-94	NCSC
Triaxial Strength	c, ϕ^1, S_u	X	X	—	Modified ASU	Purdue
IDT Strength	S_t	X	X	X	Modified AASHTO TP9-96	Purdue
Dynamic Creep	FN, ϵ_p	—	X	—	ASU	Purdue

(1) Confined and Unconfined testing

(2) Only unconfined modulus testing

The ASU protocols in Table 12 refer to the test protocol used by Witczak et al. research team for the development of the simple performance test (SPT) at Arizona State University (ASU) (Witczak, 2001). The shear (complex) modulus tests were conducted using the Simple Shear Tester (SST) at NCSC. All the other tests were conducted at Purdue University bituminous laboratory using UTM25 servo-hydraulic testing machine manufactured by Industrial Process Controls (IPC). IPC control software, UTM38 V2.00 Beta version was used in the data analysis. The IPC software has three analysis methods for obtaining stiffness and phase angle from the measured signals: ASU method, IPC method and SPT method. The SPT method was selected for signal processing because it enables assessment of drift in the transducer signal directly as a part of the regression analysis, which allows more thorough evaluation of test data (Pellinen and Crockford, 2002).

Figure 3 shows an example of the unconfined dynamic modulus testing set up in the UTM 25 testing machine. The confined testing was conducted in a similar manner but membrane was placed around the specimen before attaching instrumentation and the specimen was placed inside the pressure cell, as shown for the triaxial shear strength specimen in Figure 4. Triaxial strength testing was conducted with non-instrumented specimens. The pressure cell was located inside the temperature cabinet as the figure shows. Figure 5 shows the IDT strength testing arrangements in the UTM 25 machine. Testing was conducted without the pressure cell utilizing 150-mm Marshall fixture to load the specimen diametrically. The IDT specimens were not instrumented.

Test conditions for all tests are presented in Table 13, which includes some modifications to the utilized test protocols. For the IDT strength test, both test temperature and loading rate were modified. A temperature of 35°C and two loading rates, 0.06 mm/min and 0.39 mm/min were used, while AASHTO TP9-96 uses a test temperature of 20°C or less and a ram rate of 50 mm/min for tensile strength testing (fatigue cracking analysis). For triaxial shear strength test, besides the ram loading rate of 7.5 mm/min specified by the ASU protocol, a ram loading rate of 50 mm/min was used.

Figure 3. Unconfined Dynamic Modulus Test Set Up.

Figure 4. Triaxial Testing Set up.

Figure 5. IDT Testing Set up.

Table 13. Test Conditions.

Test Method	Temp. (°C)	Frequency (Hz)	Confinement Level (kPa/psi)	Loading Rate (mm/min)	Stress/Strain Level
Dynamic Modulus	40, 54.4	25, 10, 5, 1, 0.5, 0.1	0, 69/10	n/a	LVE ¹
Shear Modulus	40, 54.4	10 to 0.1	n/a	n/a	100 $\mu\epsilon$
Triaxial Strength	54.4	n/a	0 138/20 276/40 414/60	7.5, 50	n/a
IDT Strength	35	n/a	n/a	0.06, 0.39	n/a
Dynamic Creep	54.4	n/a	138 /20	0.1s loading and 0.9 s rest	828 kPa 120psi

(1) Linear visco-elastic region

The stiffness testing was conducted using test temperature based on the effective temperature concept, which is described in Appendix 4. The effective temperature in Indiana is between 37.8°C and 42.5°C, but to simplify laboratory testing, an average temperature of 40°C was used.

Due to the specimen geometry in the IDT test, a lower test temperature gives more pure tensile split of the specimen compared to the higher temperatures, in which the specimen may form permanently. Therefore, based on time-temperature superposition principle, a higher test temperature can be substituted with a lower test temperature when a lower loading rate is used. The lowest loading rate, which the UTM 25 system can apply, is 0.06 mm/min. This loading rate requires a test temperature of 35°C in order to be equivalent to the 54.4°C test temperature with 7.5 mm/min loading rate for the triaxial strength test. Therefore, 35°C test temperature was selected for the IDT strength test. Journal article: “*Relationship between Triaxial Shear Strength and Indirect Tensile Strength of Hot-Mix Asphalt*” (Pellinen & Xiao, 2005) presents the theory and details of the loading rate study.

The dynamic creep test was performed based on ASU test protocol applying 0.1 second haversine cyclic pulse load of 828 kPa with 0.9 second rest period at 54.4°C test temperature. Testing was performed using 138 kPa confinement.

3.2 Mixture Sample Preparation and Instrumentation

3.2.1 Sample Preparation

Table 14 shows the specimen size used for each test. For specimens from plant loose mixtures and laboratory-fabricated mixtures, the specimen size was prescribed by the corresponding test protocol. For composite samples assembled from the field cores, the specimen size was dictated by the size of the cores. Based on the literature, test specimens for the dynamic modulus test must have a minimum height to diameter ratio (H/D) of 1.5 and a minimum diameter of 70 mm to reduce or eliminate the specimen size and geometry effects on testing (Witczak et al, 1999). From a core of 150 mm in diameter, a sawed block that is 75 mm in width and 130 mm in length satisfies both above-mentioned requirements.

The amount of materials needed for fabricating specimens for each testing are listed in Table 15. The total amount of material used was thought to be higher because

of the extra mixture needed for the air voids content trials and for retests of suspicious test results.

Table 14. Specimen Size.

Test Method	Plant Loose Mix Lab Fabricated Mix ¹		Field Cores	
	Diameter (mm)	Height (mm)	Diameter (mm)	Height (mm)
Dynamic Modulus	100	150	~75 ² 2-3 cores combined	~130 2-3 cores combined
Shear Modulus	150	50	150	30-50
Triaxial Strength	100	150	—	—
IDT Strength	150	50	150	30-50
Dynamic Creep Test	150	100		

(1) No triaxial strength and IDT strength specimens

(2) Width of block

Table 15. Number of Specimens Fabricated and Amount of Material Used.

Test Method	No. of Specimens				Amount of material (kg)		
	Plant	Raw	Mix	All	Sample	Mix	All
Dynamic Modulus	3 + 3 ¹	3	9	99	8	72	792
Shear Modulus	3	3	6	66	5	30	330
Triaxial Test (2 loading times)	4 + 4	4 + 4	16	176	8	128	1,408
IDT Strength (0.06 mm/min)	2	3	5	55	5	25	275
IDT Strength (0.39 mm/min)	1	0	1	11	5	5	55
Dynamic Creep Test	3	0	3	33	8	24	264

(1) Unconfined + confined

Laboratory-Fabricated Mixtures

The mixtures were fabricated by combining raw materials obtained from the asphalt plant according to the Superpave mix design JMF for each mixture, see Table 16. The mix design mixing and compaction temperatures were used in the sample fabrication. To double-check the G_{mm} of the mixtures, two samples were batched and tested according to AASHTO T209 using the pycnometer method.

A check for blended aggregate gradation was performed before mixing. Aggregates were first batched using bulk batching and gradation was checked by washed sieve analysis to verify conformance to the JMF gradation. If any sieve size

had a larger difference than 3%, all aggregate stockpiles were dry sieved to separate size fractions. A new blend was batched correcting blending of aggregates based on the results of the washed sieve analysis.

Before compaction, all mixtures made in the laboratory were short-term oven aged in a forced draft oven for 4 hours at 135°C, according to AASHTO PP2, *Standard Practice for Mixture Conditioning of Hot-Mix Asphalt (HMA)*. However, the G_{mm} samples were aged only for two hours (AASHTO PP2).

The target density of the laboratory-compacted specimens was 92.5% of G_{mm} (theoretical maximum specific gravity), i.e., 7.5% air voids. This air void content was considered to be a good approximation of the average in-situ air void content of the paved HMA surface mixtures in Indiana.

Specimens were compacted using Superpave Gyratory Compactor (SGC) with 600 kPa pressure and 1.25° angle settings in accordance with AASHTO T312 specification. The dynamic modulus test specimens and triaxial strength test specimens were compacted to a height of 172 mm, while the shear test specimens and IDT test specimens were compacted to a height of 125 mm.

A core drill was used to take cores from the center of the SGC specimens to obtain the desired specimen diameter of 100 mm for both dynamic modulus test specimens and triaxial strength test specimens. The shear modulus and IDT strength test specimens were obtained by sawing the 150 mm diameter gyratory pill using a masonry saw. For the dynamic modulus test and triaxial strength test, cored specimens were sawed from each end to obtain the height of 150 mm. For the shear modulus and IDT strength test specimens, a 5 mm slice was first cut from each end, and the specimen was then sliced from the middle to obtain two test samples.

Figure 6 to Figure 8 show the cylindrical samples fabricated from the raw material. Figure 6 shows that SR161 had substantial amount of flat particles (34.1%) compared to the other mixtures. It also had the highest as-constructed air voids content.

Table 16. Target Properties for Lab Fabricated Mixtures.

Road No.	Mix Type	Binder PG Grade	JMF P _b (%)	Target V _a (%)	Mineral Filler % of Aggr.	Fiber % of mix	JMF				
							G _{mm}	G _{se}	G _{sb}	°C ¹	°C ²
SR15	DGM	64-22	5.6	7.5	n/a	n/a	2.488	2.718	2.682	149	143
US24	DGM	64-22	5.7	7.5	n/a	n/a	2.417	2.631	2.607	146	140
SR161	DGM	64-22	5.4	7.5	n/a	n/a	2.457	2.668	2.627	145	143
SR56	DGM	70-22	6.2	7.5	n/a	n/a	2.659	2.969	2.830	163	149
US30	DGM	70-22	6.2	7.5	n/a	n/a	2.455	2.702	2.620	160	149
SR66	DGM	70-22	5.7	7.5	n/a	n/a	2.457	2.682	2.457	165	150
SR135	DGM	70-22	6.4	7.5	n/a	n/a	2.431	2.680	2.583	165	145
US31	SMA	76-22	4.8	7.5	8.0	0.00	2.980	3.294	3.294	155	150
I74	SMA	76-22	5.5	7.5	10.0	0.10	3.154	3.584	3.476	170	165
SR64	SMA	76-22	5.5	7.5	5.0	0.20	2.966	3.330	3.275	165	160
I65	SMA	76-22	5.9	7.5	0.0	0.25	3.017	3.432	3.313	165	155

(1) Mixing temperature

(2) Compaction Temperature

Figure 6. Cylindrical Specimens for SR15, US24, and SR161 (DGM).

Figure 7. Cylindrical Specimens for US30, SR56, SR66, and SR135 (DGM).

Figure 8. Cylindrical Specimens for I66, SR64, US31 and I74 (SMA).

Asphalt Plant Loose Mixtures

The target air void content for the plant mixtures was also $7.5\% \pm 0.5\%$. The compaction, coring and sawing equipment, procedures and requirements for specimen dimensions were the same as for the raw material mixtures discussed above. However, mixtures were not laboratory oven aged before compaction.

Field Cores

The first treatment on the field cores was to remove base mixture from the surface layer by sawing. The shear modulus test and the IDT strength test were performed directly on separate surface cores without any further processing.

For the dynamic modulus testing of the thin surface mixtures, a so-called composite specimen method was developed. The round, thin surface layer cores were further cut to obtain rectangular blocks. Then, two or three sawed blocks, depending on the thickness of each block, were simply stacked horizontally without bonding. Then, two hydrostone caps were made to provide flat and smooth loading ends, as well as to restrain the blocks from moving during loading. Figure 9 illustrates the steps to fabricate the composite specimens. This method has three advantages: 1) loading does not span across the interfaces; 2) LVDTs do not have to cross any interfaces; and 3) flat and parallel end conditions can be obtained. A more detailed description of the composite specimen fabrication and quality of specimens is given in the journal article by Pellinen and Xiao (2005) “*Dynamic Modulus Testing of Thin Pavement Cores*”.

3.2.2 Sample Instrumentation

Table 17 shows the number of replicate specimens and required LVDTs to achieve a satisfactory level of accuracy based on the test protocols. Figure 10 shows the instrumented cylindrical gyratory compacted specimen for the unconfined dynamic modulus testing. Figure 11 shows the instrumented composite specimens for the field cores. Gauge length for the cylindrical specimen was 100-mm according to the test

protocol. A 75 mm gauge length was used in the composite specimens due to the limitations of the specimen dimensions. The shear modulus test specimens were instrumented according to the test protocol for the Interlaken SST tester.

Figure 9. A Schematic Plan of Composite Specimen Preparation.

For confined tests, a cylindrical latex membrane was used to wrap the specimen to provide uniform confining pressure. Friction reducing end treatment consisting of vacuum grease placed between two membrane disks, which then were placed between sample and plates was used for all testing. A hole was made in the bottom membrane disks to release air from inside the membrane during confined test.

Table 17. Number of Replicate Specimens and LVDTs .

Test Method	LVDTs per Specimen	Number of Specimens/mix
Dynamic Modulus	3 axial strain, (2 axial strain for cores)	3
Shear Modulus	2 axial strain, 2 shear strain	3
Triaxial Strength	no instrumentation	4 ¹
IDT Strength (0.06 mm/min)	no instrumentation	2
IDT Strength (0.39 mm/min)	no instrumentation	1 ²
Dynamic Creep Test	3 axial strain, 2 radial strains	3

(1) Only one specimen was used for each confinement level

(2) Only one specimen was available

Figure 10. Cylindrical Test Specimen with Instrumentation.

Figure 11. Composite Specimens with Instrumentation.

3.3 Test Methods and Test Conditions for Asphalt Binders

The asphalt binder testing was conducted by NCSC in Spring 2005 to verify binder viscosity of the asphalt plant collected binders. Binder used in the I65 mixtures was not tested due to lack of material. Testing included conventional binder testing to obtain temperature susceptibility parameters, A and VTS, see Table 18.

Table 18. Binder Test Methods and Test Conditions.

Parameter/Test Method	AASHTO No.	Temperature °C	Parameter symbol	Units
Penetration	T49	25	Pen	1/100 mm
Ring and Ball Softening Point	T53	n/a	T _{R&B}	°C
Brookfield viscosity	T316	120,135,175	η	Pa-s

3.4 Laboratory Testing Schedule

Laboratory testing was conducted over a three-year period. Table 19 shows the specimen storage times for each test data set and test method. Overall, the storage times were shortest for the SST testing.

Due to the complexities in developing the composite specimen technique, the $|E^*|$ testing for the 1st set of cores was performed approx. 14 months after obtaining them. Similarly, the IDT testing for plant mixtures was slowed down by the selection of appropriate testing conditions.

The most consistent specimen storage times were for the raw material mixtures. Samples were stored in the cold room as 150 x 180 mm gyratory compacted pills and test specimens were cored and sawed just before testing. The plant mixture samples were processed all the way and were stored in the cold room as 100 x 150 mm specimens. The shear testing was conducted one month after samples were compacted while specimens for the axial stiffness and strength testing were stored longer. Among the test methods, the 1st cores were stored the most variable time before testing, while the 2nd cores were tested in a more concise manner. The effect of sample storage times on stiffness test results is discussed in Appendix 10.

Table 19. Specimen Storage Time in Months.

Parameter	Specimen storage time in months				
	Raw Material	Plant Mixtures	1 st Coring	2 nd Coring	Binder Testing
E*	6.9	3/5 ¹	13.4	9.1 (23) ³	—
G*	5.7	1	4.1	14.1 (28)	—
Triaxial	6.5	6 / 2 ²	—	—	—
IDT	6.5	7	13.8	6.9 (21)	—
All	—	—	—	—	32

1) Confined testing,

2) 50 mm/min/0.06mm/min,

3) from the second coring (from the first coring)

3.5 Test Results

To keep the body of the report concise and brief all test results are given in appendices with the basic statistical information including average, standard deviation, and coefficient of variation. Table 20 shows how the test data for raw material mixtures are arranged in appendices. Table 21 shows the test data for asphalt plant mixtures, and Table 22 shows the test data for field cores. Binder test results are given in Appendix 19 and laboratory aging study results in Appendix 18.

Table 20. Appendices for Raw Material Mixture Test Results.

Appendix	Description	Temperature (°C)	Loading Rate (mm/min)
15.1	Measured G_{mm} Values	n/a	n/a
15.2	Air Voids Content	n/a	n/a
15.3	Unconfined Dynamic Modulus	40, 54.4	variable
15.4	Shear Modulus	40, 54.4	variable
15.5	Triaxial Strength	54.4	7.5
15.6	IDT Strength	35	0.06

In addition, tabular summaries and plots of test data are provided in Appendix 6, 7, and 8, as shown in Table 23. Appendix 6.1 gives the average air voids content of replicate specimens for each test method for all test data sets. For the raw material mixtures, the air voids content was calculated using the measured G_{mm} values given in Appendix 15.1. For plant mixtures, the air voids content was calculated using the

JMF G_{mm} values, and for field cores, the air void content was calculated using measured G_{mm} values shown in Appendix 17.5.

Table 21. Appendices for Asphalt Plant Loose Mixture Test Results.

Appendix	Description	Temperature (°C)	Loading Rate (mm/min)
16.1	Air Voids Content	n/a	n/a
16.2	Unconfined Dynamic Modulus	40, 54.4	variable
16.3	Confined Dynamic Modulus	40, 54.4	variable
16.4	Shear Modulus	40, 54.4	variable
16.5	Triaxial Strength	54.4	7.5
16.6	Triaxial Strength	54.4	50
16.7	IDT Strength	35	0.06 and 0.39
16.8	Dynamic Creep Test	54.4	variable

Table 22. Appendices for Field Core Test Results.

Appendix		Description	Temp. (°C)	Loading Rate (mm/min)
1 st Core	2 nd Core			
17.1		Air Voids Content	n/a	n/a
17.2.1	17.2.2	Geometry of Composite Specimen	n/a	n/a
17.3.1	17.3.2	Combination List of Composite Specimens	n/a	n/a
17.4.1	17.4.2	Air Voids Content of Composite Specimens	n/a	n/a
17.5		Measured G_{mm} Values	n/a	n/a
17.6.1	17.6.2	Unconfined Dynamic Modulus	40, 54.4	variable
17.7.1	17.7.2	Shear Modulus	40, 54.4	variable
17.8.1	17.8.2	IDT Strength	35	0.06 and 0.39

Table 23. Appendices for Summaries of Test Results and Data Plots.

Appendix	Description
6	Analysis of Sample and Test Data Quality
6.1	Test specimen's Air voids Content and Volumetrics
6.2	Maximum Theoretical Specific Gravity Variation
6.3	Testing Variation
7	Tabular Summaries of Test Data
7.1	Dynamic Modulus
7.2	Shear Modulus
7.3	Triaxial Strength
7.4	IDT Strength
7.5	Correlation of $ E^* $ and $ G^* $ at each Test Condition
7.6	Correlation Between Stiffness and Strength
8	Plots of Test Data

Table 24 shows all the symbols and corresponding descriptions used in the subsequent figures and in the figures in the appendices. The definitions and formulas for different parameters are explained in Appendix 2.

Table 24. Symbols for Test Parameters

Symbol	Parameter
$ E^* $	Dynamic Modulus
ϕ	Phase Angle for Dynamic Modulus Test
$ G^* $	Shear Modulus
δ	Phase Angle for Shear Modulus Test
c	Cohesion
ϕ	Friction Angle
S_u	Unconfined Compressive Strength
S_t	Indirect Tensile Strength
ϵ_r	Resilient (recoverable) strain
ϵ_p	Plastic (permanent) strain
ϵ_p/ϵ_r	Plastic strain ratio to resilient strain
$\epsilon_p \text{ ratio}$	Lateral to axial ratio of plastic strain
FN	Flow Number
a, b	Power law coefficients
M_r	Resilient modulus

4 EVALUATION OF TEST CONDITIONS AND PARAMETERS

4.1 Introduction: Analysis Variables

The requirements for a good performance parameter are that it is sensitive to the changes in raw material properties, it is easy to measure, it identifies the marginal mixtures, and that the test results are reliable, i.e., testing variation is small.

The test conditions used were selected based on the literature and empirical knowledge of the behavior of asphalt mixtures. The experimental plan for the laboratory testing included four construction stages: mix design, plant mixing, placement, and in-service stage, as shown in Table 25.

Table 25. Experimental Plan.

Construction Stage	Mixture Fabrication	Compaction Method	Mix Aging	Test Data Set
Planning: Mix design	Laboratory	Gyratory	4h oven at 135°C	Raw Material
QC/QA: Plant Mixing	Plant	Gyratory	Plant aging	Plant Loose
QC/QA: Placement	Plant	Rolling	Lay-down aging	1 st Coring ¹
QA/Forensic: In-service	Plant	Rolling	In-service aging	2 nd Coring ²

(1) appr. one week after construction

(2) appr. one year after construction

There are other variables that must be accounted for in the data analysis including mixture aging and compaction method, besides considering mixture composition, see Table 26. In addition, mixture response for loading is loading direction dependent because of the anisotropy caused by the aggregate orientation in the specimens.

Another phenomenon that takes place during mixing and placement is moisture retention in the asphalt mixtures, which decreases in-place mixtures stiffness and may cause compaction problems in terms of “tender” mixtures. The moisture trapped in the mixture during plant mixing will evaporate eventually and the mixture will stiffen up. Based on research by Heritage Research (personal communication by Gerry Huber, 2005) this takes a few days with warm temperatures. They found that the stiffness decrease due to moisture retention was about 50%.

Table 26. Summary of Variables in the Data Analysis.

Raw Material Variation	Mix Aging	Compaction vs. Loading Direction	Gyratory Compaction	Roller Compaction	Notes
No	No	0°	E* , E* conf.	—	Analysis of temp./ freq. combinations (same specimens)
		90°	G*	E* , G*	
Lab (Reduced)	4h at 135°C	0°	E* Triaxial	—	Should have lowest raw material variation (no density variation)
		90°	G* , IDT	—	
Production (Reduced)	Plant	0°	E* , E* Conf Creep testing	—	Sampling the same truck per mix will reduce variation compared to plant production. (no density variation).
		90°	G* , IDT	—	
Production/ placement	Plant/ 1 week	0°	—	—	Full production raw material and density variation
		90°	—	E* , G* IDT	
Production/ placement	In-situ/ 1 year	0°	—	—	Full production raw material and density variation
		90°	—	E* , G* IDT	

The plant loose mixtures were reheated at Purdue laboratory to obtain required compaction temperature. The reheating apparently dried any moisture trapped in the mixture. The field cores were air-dried a couple of days before they were stored in the cold room waiting to be tested. It is assumed that this was sufficient time for moisture to evaporate from the cores.

4.2 Preliminary Test Data Examination

4.2.1 Test Data Normalization

The target air voids content for the laboratory-fabricated specimens and plant loose mixtures compacted in the laboratory was $7.5 \pm 0.5\%$. 7.5% was selected to reflect INDOT construction specification for the in-place density. Due to the construction variations, the actual in-place air voids content deviated from the target density, and therefore, in order to compare mixtures relatively, the measured

mechanical properties had to be normalized to the same air voids content for equal comparisons. This is because the asphalt mixture is a composite material comprised of aggregate, binder and air and its mechanical properties are dependent of all constituents in the mixture, including air voids content.

It was most important to normalize the core test results to the target air voids of 7.5%, but also the stiffness test data for laboratory compacted specimens were normalized, although the deviations were small and mostly within the allowable tolerance required by each test protocol. In addition, the raw material's strength data was normalized because of variation in the sample preparation that exceeded the set tolerances. The procedures and equations for the data normalization are given in Appendix 3.

4.2.2 Testing Variation

All testing included testing variation, however, not all analyzed test data included material variation, as shown in Table 26. Then, when comparing stiffness test results relatively at different test temperatures and frequencies, material variation is eliminated because testing was conducted using the same specimen. In theory, laboratory fabricated raw material mixtures should have the lowest (or not at all) raw material variation compared to the asphalt plant produced mixtures. The plant mixtures most likely have less material variation than typically is observed in plant production because all mixture samples were taken from the same truck. The field cores should have the highest amount of raw material variation combined with density variation caused by plant mixing and placement.

The total variation in the road construction includes material variation caused by production (mixing and placement of mixture), sampling, and variation caused by testing itself. In the laboratory, the production variation is replaced by the sample fabrication (aggregate blending, mixing and oven aging). The placement of mixture to the gyratory mold causes variation similar to the laid-down operations in the field. In

addition, experimental errors may increase sample preparation variation and cause random and systematic differences.

The testing variation for the dynamic modulus and shear modulus testing, when no sample preparation variation is included, is around 5%. Then, any variation above that is due to the sample preparation, i.e., variation in the raw materials, compaction, and aging, and anisotropy and/or damage accumulation in the specimens.

Table 27 summarizes testing variations for stiffness testing giving the average coefficient of variation (CV%) for two test conditions: 40°C & 10 Hz and 54.4°C & 5 Hz. Table 28 summarizes testing variation for IDT strength over all test conditions. The triaxial strength testing was conducted using only one specimen per confining pressure, which did not allow the assessment of variation. A more detailed summary of testing variation is given in Appendix 6.

Table 27. Summary of Testing Variation for Stiffness.

Sample Set	Parameter	Coefficient of Variation (%)			
		40°C & 10Hz		54.4°C & 5Hz	
		Modulus	ϕ or δ	Modulus	ϕ or δ
Raw Materials	E* Unconfined	13.7	5.1	20.1	11.3
	G*	16.0	6.6	15.2	2.7
Plant Loose	E* Unconfined	15.3	3.3	19.3	5.3
	E* Confined	18.9	4.6	17.8	7.8
	G*	12.1	5.3	21.3	4.0
1 st Coring	E* Unconfined	24.5	8.8	22.1	11.7
	G*	11.0	4.0	12.8	6.0
2 nd Coring	E* Unconfined	25.2	9.2	18.8	8.9
	G*	17.4	6.2	14.7	5.2
Average	E*	19.7	6.6	20.1	9.3
Average	G*	14.1	5.3	16.0	4.5
Average	All	17.1	5.9	18.0	7.0

Table 28. Summary of Testing Variation for IDT Strength.

Sample Set	Parameter	Coefficient of Variation (%)
Raw Materials	IDT S _t	8.9
Plant Loose		9.4
1 st Coring		18.6
2 nd Coring		17.7
Average		13.4

The field cores had the highest testing variation as expected, while the testing variation for the plant and raw material mixtures was very similar. Interestingly, the IDT strength variation was lower than the stiffness testing variation for all test data sets.

Generally, the stiffness testing variation increased with decreasing frequency and increasing testing temperature. Also, the stiffness variation was higher than the phase angle variation. For the same frequencies, the shear testing had slightly lower testing variation compared to the axial testing. However, SST testing variation increased significantly in the lower frequencies (< 0.2 Hz). It can be speculated that the testing variation increase is caused by the difficulty of controlling two actuators simultaneously in addition to the nonlinearity and damage accumulation in the soft specimens. It also can be speculated that the lower SST testing variation at the higher frequencies compared to the axial testing is an artifact of the raw data processing. The raw data is filtered through the Fast Fourier Transformation (FFT), which may remove some of the real testing variation by “smoothing” the measured signals (Pellinen & Crockford, 2003).

Table 29 shows the mixtures with largest testing variation. Mixtures are listed in the table if the stiffness variation exceeds $CV = 30\%$ and strength testing variation exceeds $CV = 25\%$. US24, SR161, and US30 had the most variation throughout all sample test data sets. For I74 and SR64, the higher variation in the field cores is due to using regular QC cores instead of taking separate cores from one specific location as was done for the other mixtures.

Table 29. Mixtures with High Testing Variation.

Param./Condition	Raw Material	Plant Mixtures	1 st Set of Cores	2 nd Set of Cores
$ E^* $ 40°C&10Hz	I65	SR161	US30, R66, SR135 R64, I65	SR15, US24 SR161
$ G^* $ 40°C&10Hz	US24, SR56	—	—	SR15
$ E^* $ 54.4°C&5Hz	US24, US30	US24, SR161 US30	US30, I65	US24, I74
$ G^* $ 54.4°C&5Hz	SR161, R135	SR66, SR64	—	SR161, US30
IDT S_t 0.06 mm/min	—	SR56	SR66, US31, SR64	SR15, SR135

4.3 Evaluation of Test Conditions Used

For the simple performance test (SPT), Pellinen (2001) recommended using unconfined testing for the dense graded mixtures and confined testing with 69-kPa confinement for the SMA mixtures to measure the dynamic modulus of asphalt mixtures. Research concluded that the testing condition, which best correlated to the rutting of asphalt mixtures, was 54.4°C temperature with 5 Hz frequency.

Another consideration, when selecting test conditions, is the rule of thumb criteria used for the SST shear modulus testing to evaluate rutting performance. Many agencies have used shear stiffness $|G^*|$ measured at 40°C with 10 Hz for rutting evaluations. The purpose of the analysis was to determine what test temperature/frequency or loading time combination should be used in the performance testing for stiffness and strength criteria.

4.3.1 Test Temperature/Frequency Combinations

The mixture performance at a given temperature depends mainly on the binder stiffness at that temperature. However, the aggregate properties start to play a role at the elevated temperatures. To compare mixture performance, a linear regression model with zero intercept (non-biased) was used for comparing mixture stiffness at different temperature and frequency combinations, see Table 30. Figure 12 shows the correlation of $|E^*|$ for the best and worst combinations.

Table 30. Temperature/Frequency Combinations.

Test condition	Plant mixtures, R^2 for $ E^* $			
	40°C & 10Hz	40°C & 5 Hz	54.4°C & 10 Hz	54.4°C & 5Hz
40°C & 10Hz	—	0.9961	0.7585	0.7117
40°C & 5Hz	—	—	0.7766	0.7354
54.4°C & 10Hz	—	—	—	0.9949
54.4°C & 5Hz	—	—	—	—

For practical purposes, the relative behavior of asphalt mixtures stays the same when only testing frequency changes, as correlation coefficients (R^2) of 0.9961 and

0.9949 indicate. However, the relative ranking of mixture changes if comparisons are made between the different test temperatures. The largest change in the relative mixture performance occurs when both the temperature and frequency are different, as R^2 of 0.7117 shows.

Figure 12. Relative Ranking of Mixtures based on Temperature and Frequency.

Table 31 shows the correlation (R^2) of the low temperature high frequency and high temperature low frequency testing for the 11 study mixtures (normalized test data). The correlation is fair to good for the raw material and plant loose mixtures but very poor for the field cores. Because testing was conducted using the same specimens, test results suggest that the aggregate skeleton in the roller compacted specimens is weaker than in the gyratory compacted specimens.

Table 31. Correlation between Low and High Test Temperatures.

	R^2 between 40°C&10Hz and 54°C&5Hz			
Parameter	Raw Materials	Plant Loose	1 st Coring (original)	2 nd Coring (original)
E* unconfined	0.79	0.71	0.10	0.44
E* confined	—	0.35	—	—
G*	0.62	0.81	0.78/0.42 ¹	0.0

1))One mixture (I65) derives the correlation and if left out R^2 drops to 0.41

Mixture rankings may also be affected by testing errors because specimens may develop damage when tested at higher temperatures, and therefore test results do not reflect the true mixture response. The damage will lead to non-linear material behavior. For the $|E^*|$ testing, variation was the same at both test temperature while for $|G^*|$ testing variation increased at higher testing temperature. This suggests that for $|G^*|$ it is better to use a lower test temperature to avoid damaging test specimens.

4.3.2 Confinement Effect on Mixture Stiffness

As mentioned above, Pellinen (2001) recommended using 69 kPa confinement when testing SMA mixtures compared to the dense graded mixtures. Table 32 shows the ratios of the unconfined and confined stiffness of the dense graded mixtures and the SMA mixtures. The confinement effect on stiffness is more noticeable at higher temperature and is mixture stiffness (or binder stiffness) dependent, i.e., softer mixtures gain more stiffness when confined compared to the stiffer mixtures. An increasing pore pressure in the test specimen when applying confinement can explain this phenomenon. Then, following soil mechanics theory, the effective stress instead of total stress should be used to evaluate mixture stiffness.

It can be assumed that effective stress is a function of binder viscosity and therefore will lead to similar stiffness values as the unconfined testing. Then, the unconfined testing will give direct access to the binder effect in the mixtures and it seems that the confined testing is not needed to capture mixture stiffness for relative comparisons.

Table 32. Ratio of $|E^*|$ unconfined / $|E^*|$ confined.

Mixture Type	Test Conditions	
	40°C&10Hz	54°C&5Hz
DGM	1.23	1.89
SMA	1.16	1.44
All	1.20	1.69

4.3.3 Loading Time Effect on Strength Parameters

The strength testing was conducted by using time-temperature superposition to calculate equivalent testing conditions for the triaxial and IDT testing. Table 33 shows correlation (R^2) of mixtures tested at different loading times. Because strength testing is destructive, all samples are separate replicates in contrast to the stiffness testing discussed above. Correlations were computed for the 7.5 and 50 mm/min loading times for the cohesion, friction angle ϕ , and S_u , see Figure 13.

Table 33. Loading Time Effect.

Test	R^2 of Strength Parameters between Loading Times				
	Loading time mm/min	Parameter	Plant Loose	1 st Coring	2 nd Coring
Triaxial	7.5 vs. 50	c	0.90	—	—
		ϕ	0.71	—	—
		S_u	0.90	—	—
IDT original	0.06 vs. 0.39	S_t	0.84	0.78	0.63
IDT Normalized	0.06 vs. 0.39	S_t	—	0.43	0.79

Figure 13. Correlation of cohesion between two loading times (Plant Materials).

For the IDT strength, correlations were computed for both the original and normalized test data. Loading time has a large effect on the strength results obtained

from the field cores. Again, similar to the stiffness data discussed above, the roller compaction seems to weaken the sample skeleton, which leads to changes in mixture performance and relative rankings. Cores also have the most raw material and density variation between “replicate” samples, which may affect the relative rankings.

The friction angle has the lowest correlation, which suggests that friction between particles is time dependent. The binder viscosity contributes to the cohesion and to the unconfined strength of the mixture, while friction angle reflects the aggregate texture influence in the mixture. These findings suggest that the mixture response at slower loading times is influenced more by the aggregate and less by the binder compared to the faster loading times, as expected.

4.4 Correlation of Test Parameters

4.4.1 Correlation between Uniaxial and Shear Stiffness

Theoretically $|G^*| = |E^*|/2(1+\mu^*)$ and if Poisson ratio μ^* is taken as 0.5 the $|E^*|$ is 3 times larger than $|G^*|$. Figure 14 shows that the actual relationship between the two stiffness parameters does not agree with the theoretical relationship. This discrepancy is caused by several factors, such as non-linearity, anisotropy, measurement errors, etc. Therefore, $|E^*|$ and $|G^*|$ are not interchangeable and one cannot be obtained from another by using theoretical formulations.

The analysis of the correlation between $|E^*|$ and $|G^*|$ within each frequency/temperature combination separately indicated that the largest variations were between the 40°C/10Hz and 54°C/5Hz combinations, see Table 34. All regressions were performed using power model functional form. The best correlation between $|E^*|$ and $|G^*|$ was within the plant mixtures. This is a surprising result, because raw material mixtures had the least testing variation. The variable laboratory aging of raw material mixtures may be the source of these differences; test specimens for the shear and axial stiffness testing were prepared separately, which may have introduced variation in the prepared specimens. Because asphalt plant mixtures were

taken from the same truck, all stiffness variation caused by varying asphalt plant aging is eliminated.

Figure 14. SST $|G^*|$ and Unconfined $|E^*|$, (Plant Mixtures).

Table 34 Correlation between $|E^*|$ and $|G^*|$.

Parameter	R^2 between $ E^* $ and $ G^* $			
	Raw Materials	Plant Loose	1 st Coring (normalized)	2 nd Coring (normalized)
$ E^* $ vs. $ G^* $	0.19-0.44	0.72-0.91	0.22-0.51	0.10-0.48

As shown in Figure 14, the relationship between $|E^*|$ and $|G^*|$ can be expressed by a simple power law model that has a generalized form as given in Eq. (2):

$$|G^*| = a |E^*|^b \quad (2)$$

Since $|E^*|$ and $|G^*|$ of mixtures are correlated by stiffness of the asphalt binder, this provides a possibility to predict $|G^*|_{\text{mix}}$ based on $|E^*|_{\text{mix}}$ or vice versa. Then by solving $|G^*|$ of binder with the Hirsch model (Christensen et. al, 2004) for the $|E^*|_{\text{mix}}$, the mixture shear stiffness can be estimated by using the solved binder stiffness in the Hirsch model. The whole process can be conveniently accomplished using Solver

function provided by the Microsoft Excel software. Analysis indicated that a very good linear correlation exists between the measured and estimated $|G^*|$ of mixture ($R^2=0.9487$ for plant mixture). Therefore, for practical purposes it is accurate enough to back-calculate $|G^*|$ of binder, and then calculate the $|G^*|$ of mixture from the axial data, or vice versa. Table 35 gives the model coefficients for different test data sets to convert $|E^*|$ to $|G^*|$.

Table 35. Model Coefficients for Stiffness Conversion

Test Data Sets	a	b	R^2
Raw Materials	0.0526	1.1896	0.79
Plant Mixtures	0.0249	1.2817	0.95
1 st Coring	0.0268	1.1675	0.67
2 nd Coring	0.1133	1.0643	0.75

4.4.2 Correlation between Triaxial and IDT Strength

The triaxial shear strength test results were analyzed using Mohr-Coulomb failure theory to obtain c and ϕ . The relationship between the IDT strength S_t and the triaxial shear strength parameters c , ϕ based on the elastic theory is expressed by Eq.(3). This is further explained in the paper “*Relationship between Triaxial Shear Strength and Indirect Tensile Strength*” by Pellinen and Xiao (2005).

$$c = \frac{2 - \sin \phi}{\cos \phi} S_t \quad (3)$$

By using the measured cohesion c and friction angle ϕ as input parameters for Eq. (3) the IDT strength was predicted and then compared to the measured IDT strength. Figure 15 shows that for practical purposes the predicted and measured values agree well.

Table 36 shows the correlation coefficient between cohesion and IDT strength for the raw material and plant mixtures separately. For the raw material mixtures, correlation is fair but for the plant mixtures it is good to excellent. The best correlation

is obtained at the equivalent loading conditions; 7.5 vs. 0.06 mm/min, and 50 vs. 0.39 mm/min.

Figure 15. Correlation of cohesion and IDT Strength.

Table 36. Correlation between cohesion and IDT Strength

Correlation R ²		Raw Material	Plant Mixtures	
Parameter	Loading time mm/min	IDT S _t		
		0.06	0.06	0.39
c	7.5	0.68	0.96	0.85
	50	—	0.78	0.97

For practical purposes, the IDT tensile strength can be used independently replacing the triaxial strength test. If no information is available for the friction angle, a ratio of 1.80 of the cohesion to IDT tensile strength is a good approximation.

4.4.3 Correlation of Triaxial Strength Parameters

Table 37 shows the correlation coefficients (R^2) between different strength parameters obtained from the triaxial testing. Cohesion and unconfined compressive strength have a good to excellent correlation, which is facilitated by the quite narrow

range of friction angle values, i.e., 37 to 47°, measured from the mixtures. The correlation of friction angle to cohesion is poor to fair.

Table 37. Correlation between Triaxial Strength Parameters

Correlation R^2		Raw Material		Plant Mixtures			
Parameter	Loading time mm/min	7.5		7.5		50	
		S_u	ϕ	S_u	ϕ	S_u	ϕ
c	7.5	0.97	0.0	0.95	0.61	0.85	0.62
	50	—	—	—	0.50	0.96	0.64

4.4.4 Correlation between Stiffness and Strength

Many engineering materials possess different strength and stiffness properties. Literature suggests that for asphalt mixtures the correlation of stiffness and strength is mix dependent (Pellinen, 2003).

A nonlinear power model regression was conducted to analyze the correlation between stiffness and strength of Indiana mixtures. The strength data used in the analysis included 7.5 mm/min loading time triaxial testing, and 0.06 and 0.39 mm/min loading time IDT testing. Overall, the correlation between stiffness and strength ranged from very poor to fair when all 11 mixtures were compared together (see Appendix 7), and especially for the field cores the correlation was very poor to non-existent. This confirms that the stiffest mixtures are not necessarily the strongest mixtures.

However, additional analysis was performed to see if the correlation improves when the two different mix types were separated. The $|E^*|$ of dense-graded mixtures had a good to excellent correlation ($R^2 = 0.75$ to 0.96) to cohesion and fair correlation to IDT strength ($R^2 = 0.48$ to 0.74), while the correlation for the SMA mixtures was negative, meaning that the stiffer mixtures were weaker than the softer mixtures. The confined axial stiffness $|E^*|$ did not correlate to strength properties. Again, the field cores did not show any correlation between stiffness and strength.

For $|G^*|$, the plant-produced mixtures had better correlation to strength than the raw material mixtures. In addition, the higher test temperature gave better correlations than the lower temperature, although all correlation values are somewhat lower than that for the axial stiffness

4.5 Mixture Rankings and Marginal Mixtures

Table 38 summarizes the softest/weakest and stiffest/strongest mixtures for the plant mixtures and raw material samples at various test conditions. The table gives mixtures that are within the 5% range; then, for some test conditions several mixtures are listed.

In general, the softest mixtures have the softest binder PG64-22 and the stiffest mixtures are the SMA mixtures with PG76-22 binder. The stiffness ratios are very similar for the axial and shear stiffness ranging from 2.5 to 3.1, although the confined $|E^*|$ testing seems to be less sensitive compared to the unconfined testing. The strength testing seems to capture larger deviations between mixtures because strength ratios are ranging from 2.6 to 5.8.

Table 39 and Table 40 give the stiffness and strength ratios for field cores. The stiffness ratio is ranging from 2.2 to 4 and the strength ratio is ranging from 1.8 to 6.4 (original testing). The softest mixtures are not the same as was identified from the plant and raw material samples. In the second coring, the softest mixture was the SMA mixture US31, which did not have fibers. However, the same mixtures seem to be the weakest at all test data sets. This suggests that the age hardening of binder has a different effect on stiffness and strength.

There seems to be more agreement of the stiffest mixture among different test conditions and test data sets than of the softest mixture. Similarly, there is more agreement of finding the strongest mixture than the weakest mixture among the strength parameters. The IDT test with 0.06 mm/min loading time seems to rank the weak mixtures similarly compared to the $|E^*|$ and $|G^*|$ at 40°C temperature (normalized data).

Table 38. Plant Mixtures and Raw Materials

Test	Para.	Test Condition °C, Hz/ °C, mm	Plant Mixture			Raw Material		
			Soft/ Weak Mix	Stiff/ Strong Mix	Ratio	Soft/ Weak Mix	Stiff/ Strong Mix	Ratio
Unconfined Compressive Stiffness	E*	40,10	SR15	SR64	3.0	SR15	SR64	3.0
		54.4,5	US24	I74 SR64	2.6	SR15	SR64	2.8
Confined	E*	40,10	US31	I74	1.9	-	-	-
		54.4,5	US24 SR161	I74	1.5	-	-	-
Shear Stiffness	G*	40,10	SR15 US24	I74 SR64	2.5	SR15	SR56	3.1
		54.4,5	SR15 US24	SR64 I65	3.8	SR15	SR66	3.0
Shear Strength	c	54.4,7.5	SR15	I65	4.3	SR161	US30	2.6
	ϕ	54.4,7.5	SR64	SR15	1.3	SR64	SR15	1.1
	S _u	54.4,7.5	SR15	I65	3.4	SR161	US30	2.6
	c	54.4,50	US24	I65	4.5	-	-	-
	ϕ	54.4,50	I65	SR135	1.2	-	-	-
	S _u	54.4,50	US24	I65	3.8	-	-	-
IDT Strength	S _t	35,0.06	SR15	I65	5.2	SR15	I65	5.8
	S _t	35,0.39	US24	I65	4.2	-	-	-
Confined Dynamic Creep Test	ε_p	54.4,0.1	SR64	I65	0.3	-	-	-
	$\varepsilon_p/\varepsilon_r$	54.4,0.1	SR64	US30	0.3	-	-	-

Table 39. 1st and 2nd Coring (original data)

Test	Para.	Test Condition °C, Hz	1 st Coring			2 nd Coring		
			Soft/ Weak Mix	Stiff/ Strong Mix	Ratio	Soft/ Weak Mix	Stiff/ Strong Mix	Ratio
Unconfined	E*	40,10	SR15	SR64	4.2	US31	SR64	3.5
		54.45	US30	SR135	2.2	US31	SR64	2.9
Shear Stiffness	G*	40,10	SR15	I65	3.6	SR15	SR64	3.2
		54.4,5	SR15 SR56 US30 SR135	I65	3.5	US31	US30	4.0
IDT Strength	S _t	0.06	US24 SR66 SR56	I74	5.5	SR15	US30	6.4
	S _t	0.39	US24 SR66 SR56	I65	5.6	SR24	US31	1.8

Table 40. 1st and 2nd Coring (normalized data)

Test	Para.	Test Condition °C, Hz	1 st Coring			2 nd Coring		
			Soft/ Weak Mix	Stiff/ Strong Mix	Ratio	Soft/ Weak Mix	Stiff/ Strong Mix	Ratio
Unconfined	E*	40,10	SR15	I65	3.2	US31	SR64	3.4
		54.45	US30	I65	2.3	US31	SR64	2.9
Shear Stiffness	G*	40,10	US24	I65	4.7	US24	SR64	3.4
		54.4,5	SR15 SR56 US30 SR135	I65	5.0	US31	US30	2.5
IDT Strength	S _t	0.06	US24 SR66 SR56	I65	6.0	SR15	I65	5.2
	S _t	0.39	US24 SR66 SR56	I65	6.0	SR24	SR161	3.4

4.6 Stiffness and Strength Ratios Binder Grade

Table 41 to Table 43 give the stiffness and strength ratios within a high temperature binder PG grade. This indicates how much mixture stiffness may vary due to other factors such as aggregate properties, N_{des} , additives, binder stiffness variation, etc.

As an average the |E*| varies from 1.4 to 2.4, while the |G*| varies from 1.7 to 2.4, and the IDT strength varies 1.4 to 4.7. For some reason, extremely high strength variation was measured from the cores for mixtures with soft PG64-22 binder.

Based on the dynamic modulus testing for the plant and raw material mixtures, the SMA mixture had the largest variation in their stiffness properties while the strength properties were similar for both mixture types. However, based on the shear testing, all mixtures had similar stiffness variation within a PG grade.

Table 41. Dynamic modulus $|E^*|$ 40°C&10Hz (normalized data)

Binder Grade	Raw	Plant	1 st Coring	2 nd Coring	Average
PG64-22	1.21	1.69	2.83	1.55	1.82
PG70-22	1.28	1.21	1.76	1.19	1.36
PG76-22	2.25	2.04	1.95	3.41	2.41

Table 42. Shear Modulus $|G^*|$ 40°C&10Hz (normalized data)

Binder Grade	Raw	Plant	1 st Coring	2 nd Coring	Average
PG64-22	1.73	1.80	2.15	2.22	1.98
PG70-22	1.66	1.58	1.66	1.88	1.70
PG76-22	1.75	1.93	2.86	2.88	2.35

Table 43. IDT Strength 0.06 mm/min (normalized data)

Binder Grade	Raw	Plant	1 st Coring	2 nd Coring	Average
PG64-22	1.61	1.42	9.31	4.85	4.67
PG70-22	1.62	1.39	1.64	1.95	1.44
PG76-22	1.58	1.65	1.80	2.98	2.10

5 COMPARISON OF TEST DATA SETS

For performance criteria development, it is important to understand how aging and compaction affect the mechanical response of asphalt mixtures. Mixture aging includes asphalt plant mixing, placement, and in-service aging, which is affected by the mixture densification under traffic.

The amount of laboratory aging depends on the aging procedure used, i.e., aging time and temperature, and if mixture is in a loose or compacted state. In addition, the time and method test specimens are stored before testing may influence the measured mixture response.

5.1 Pavement Densification

Figure 16 summarizes the in-place air voids content measured from the 1st and 2nd set of cores. The figure shows the average air voids content and $\pm 2(s)$ limit for the mean (average), where (s) is the standard deviation of measurements. For I74 and SR64, the high density variation can be explained how cores were obtained, namely regular QC cores were used instead of obtaining a separate set of cores. SR161 had the highest as-constructed density of 12.7%, while SR64 had the lowest density of 4.8%.

Although it was intended that cores would be obtained from the center of lane for both coring sets, for US24, US30, SR66, and SR135 the second set was obtained from the wheel path where some densification had taken place due to traffic loading, as Figure 17 shows. Test results indicated that the higher the as-constructed air voids content the less traffic is needed to densify the mixture, as expected.

For some roads, the traffic densification does not explain the reduction in the measured air voids content for the 2nd set of cores. For instance, for SR56 both cores were taken from the middle of the lane but test results showed 4% air voids content reduction in the 2nd set of cores (see Appendix 5). Most likely this large difference is due to the high variation of in-place density. This was the only road cored by the coring plan, thus, the transverse distance of cores was 0.3 m and longitudinal distance

was 3 meters. However, separating cores this far apart increased density variation, although the intention was exactly the opposite. Then, it is better to take cores closer together to eliminate density variation due to compaction efforts if one wants to study traffic densification.

Figure 16. Average in-place Air Voids Content and $\pm 2s$ Limit.

Figure 17. Average Air Voids Content Change between 1st and 2nd Coring.

By knowing the volume change due to traffic loading, it is possible to calculate the amount of densification caused by traffic. Table 44 shows that SR135 had the most densification after 2 years of traffic loading. The fact that SR135 cores were taken near an intersection where traffic speed is reduced explains this high densification.

Table 44. Amount of Traffic Densification.

Road No.	Traffic Densification mm	Traffic ESALs 2 years	Densification mm/ESAL ^{1/3}
US24	0.6	960,000	6.10E-03
US30	0.9	5,020,000	5.30E-03
SR66	1.3	680,000	15.00E-03
SR135	1.6	200,000	27.00E-03

5.2 Comparison of Test Data Sets

5.2.1 Variation of Mixture Response

Figure 18 and Figure 19 show the mixture rankings of $|E^*|$ and Figure 20 and Figure 21 show the $|G^*|$ shear stiffness measured at 40°C with 10 Hz. Figure 22 and Figure 23 show the ranking of mixtures based on the IDT strength testing.

The figures show a large amount of variation in the mixture response and it is difficult to see if there are any clear systematic trends. Figure 19 shows that SR24 had a large stiffness increase in the 2nd set of cores, which can be partially explained by pavement densification discussed above. Another reason may be a lower binder content of the mixture, which is discussed in Appendix 6. The same clear trend is in the $|G^*|$ measurements for SR24, US30, and SR135, as Figure 21 shows. SR56 also has a large stiffness increase in the 2nd set of cores, which had lower in-place density compared to the 1st coring. It can be concluded that pavement densification, mixture (binder) aging, and in-place raw material and density variation cause the increase in mixture stiffness.

Figure 18. Rankings of Mixtures $|E^*|$ (normalized).

Figure 19. Rankings of Mixtures $|E^*|$ (original).

Figure 20. Rankings of Mixtures $|G^*|$ (normalized).

Figure 21. Rankings of Mixtures $|G^*|$ (original).

Figure 22. Rankings of Mixtures IDT (normalized).

Figure 23. Rankings of Mixtures IDT (original).

5.2.2 Response Ratios

By comparing mixtures between the test data sets, it is possible to investigate the aging, compaction, and anisotropy effects at plant production and laboratory stage, as Table 45 schematically shows.

Table 45. Variables in the Analysis between Test Data Sets.

Ratio Between	Aging Effects	Compaction Effects	Confounded by anisotropy between test parameters
Raw to Plant	Lab vs. asphalt plant aging	No (gyratory)	Yes: $ E^* $ and $ G^* $
Plant to 1 st Coring	Asphalt plant aging	Yes: $ E^* $ compacted and loaded 90° apart	Yes: $ E^* $ and $ G^* $
1 st to 2 nd Coring	1 week to 1 year in-place aging	No (rolling)	No
Raw to 1 st Coring	Lab vs. placement aging	Yes: $ E^* $ compacted and loaded 90° apart	Yes: $ E^* $ and $ G^* $
Raw to 2 nd Coring	Lab vs. 1 year in-place aging	Yes: $ E^* $ compacted and loaded 90° apart	Yes: $ E^* $ and $ G^* $

From the ratios presented in Table 45, the most important ones are the Raw-1st coring, and Plant-1st coring. In the construction process, the mix designer wants to predict how the mix will perform, and the pavement engineer wants to know if the mix will meet the requirements when it has been placed on the road.

The short-term aging procedure STOA (AASHTO PP2) is designed to simulate the aging the mixture will undergo during plant mixing and construction. The ratios of Raw-1st coring and Raw-Plant are the ones to investigate the response adjustment factors that need to be placed on the criteria for mix design stage. The Plant -1st coring is the ratio that covers the difference of cores versus gyratory compacted specimens when variation in mixture aging is minimized.

Figure 24 to Figure 26 show the stiffness and strength ratios at 40°C with 10 Hz frequency . All axial stiffness ratios are between a narrow range of 0.44 to 3.04, while the shear stiffness ratios are ranging from 0.69 to 5.48 and IDT strength ratios from 0.16 to 4.43.

The very high shear $|G^*|$ ratio for the Raw-1st coring for US24, SR56 and SR135 indicates that the gyratory pills were extremely stiff compared to the cores. However, the axial stiffness does not show similar trends. Also, the IDT strength ratios were very high for US24, SR56, and SR66, again suggesting that the raw material samples were much stronger than the cores.

Figure 27 compares $|E^*|$ and $|G^*|$ within each test data set. As discussed before, theoretically the $|E^*|$ should be 3 times stiffer than the $|G^*|$ when Poisson's ratio of 0.5 is used. The raw material mixtures seem to follow this trend quite closely for the dense-graded mixtures. The reason for the good agreement is that the raw material mixtures are stiffer than the other mixtures, which reduces the damage accumulation during testing. This partially verified that some of the differences we see between axial and shear stiffness most likely are artifacts of the testing, not real differences in the material response. The figure verifies the findings above; the largest difference between the $|E^*|$ and $|G^*|$ is in the 1st coring, the largest difference being for SR56 and SR135 mixtures.

Figure 24. Stiffness Ratios for $|E^*|$ at 40°C & 10Hz (normalized).

Figure 25. Stiffness Ratios for $|G^*|$ at 40°C & 10Hz (normalized).

Figure 26. Strength Ratios for IDT at 0.06mm/min (normalized).

Figure 27. Comparison of Stiffness Ratio of $|E^*|/|G^*|$ at 40°C&10Hz.

Table 46 summarizes the average response ratios for all mixtures. Overall, the trends are very clear; the shear stiffness ratios are much higher than the axial stiffness ratios, and the IDT strength ratios are closer to the axial stiffness ratios. The variation of ratios is extremely high for the shear and IDT testing.

Table 46. Summary of Average Response Ratios.

Construction Stage	Average Response Ratios									
	$ E^* $		$ E^* $		$ G^* $		$ G^* $		IDT	
	40°C&10Hz		54.4°C&5Hz		40°C&10Hz		54.4°C&5Hz			
	Avg.	St.D	Avg.	St.D	Avg.	St.D	Avg.	St.D	Avg.	St.D
Raw –Plant	1.16	0.15	1.18	0.16	1.42	0.43	1.49	0.49	1.29	0.47
Plant -1 st Coring	0.92	0.21	0.99	0.21	1.83	0.55	1.88	0.94	1.36	1.19
2 nd – 1 st Coring	1.13	0.67	1.20	0.76	2.00	0.73	2.54	1.31	1.26	1.13
Raw – 2 nd Coring	1.10	0.39	1.15	0.41	1.31	0.37	1.14	0.40	1.57	0.76
Raw -1 st Coring	1.08	0.30	1.18	0.29	2.60	1.20	2.74	1.56	1.71	1.37

To study mixture type effect on response rate variation, the two mixture types were separated to calculate new ratios. At the same time, mixtures with extremely high variation were excluded from the analysis; then for the stiffness analysis, SR56 was excluded and for the strength analysis, US24 and SR66 were excluded. In addition, axial and shear measurement were averaged as well as the two lodging rates for the IDT strength. The calculated new ratios are given in Table 47 and Table 48.

The difference in the plant mixture stiffness ratios for the DGM and SMA is negligible, but there seems to be a difference in the raw material mixture response. The same difference is in the aged core test results, which suggest that the difference in mixture behavior is real. Similarly, the difference in the plant mixture strength ratios for the DGM and SMA do not deviate that much, but for the raw materials and cores there is a larger difference. The aged SMA mixture cores seemed to decrease in strength compared to the cores for the dense-graded mixtures. However, the strength increase for dense-graded mixture cores is less than that of the stiffness increase. It is important to recognize that these differences are not statistically significant due to an extremely large variation in the response ratios.

Table 47. Response Ratios for Different Sample Sets for Stiffness.

Parameter	Raw-Plant	Plant - 1 st Coring	Raw - 1 st Coring	2 nd Coring – 1 st Coring
All	1.26	1.31	1.65	1.52
DGM	1.36	1.25	1.77	1.68
SMA	1.14	1.38	1.51	1.31

Table 48. Response Ratios for Different Sample Sets for IDT S_t .

Parameter	Raw-Plant	Plant - 1 st Coring	Raw - 1 st Coring	2 nd Coring – 1 st Coring
All	1.24	0.94	1.19	0.92
DGM	1.43	0.85	1.32	1.05
SMA	0.99	1.05	1.03	0.75

As mentioned before, the time and method test specimens are stored before testing may play a role in the measured mixture response. A special study was

conducted at Purdue bituminous laboratory in 2004 and 2005 to investigate laboratory aging of asphalt mixtures due to storage of test specimens, see Appendix 10. Specimens prepared from the plant mix and field cores had to be stored for varying time periods before they could be tested. There was a concern of aging of specimens during this storage period, although specimens were sealed in plastic bags and stored in the cold room at 0°C temperature. An investigation was conducted by measuring the dynamic modulus $|E^*|$ of the mixtures before and after storage of eight months.

Based on the analysis it was concluded that the 100 mm diameter and 150 mm high-test specimens aged approximately 12 to 17% when stored in the laboratory shelves for eight months compared to freezer storage where no aging was observed. Then, it can be assumed that if the specimens were stored in the freezer no aging should have occurred during the storage time.

The shear stiffness of the 1st cores was measured after cores were stored for only 4 months, while for axial and IDT testing the cores were stored for 14 months. In addition, cores were exposed to the ambient temperature for one to two weeks during sample preparation. It can be speculated that there was some additional aging of test specimens due to the sample preparation and long storage time.

If we assume that the aging effect is 20 to 30% and anisotropy effect is 10 to 15%, the axial stiffness increase would be 30 to 45%. However, the measures of axial stiffness would still be 50% more than the measured shear stiffness of cores. Then, the reason for the 1st cores having such a low shear stiffness compared to $|E^*|$ cannot be explained with different specimen storage times or anisotropy effects.

5.3 In-Place Aging Rates

In-place service aging rate was studied by taking the ratio of 2nd and 1st coring test results and dividing that with the days that had passed between the two testing dates. Analysis results for individual mixtures are presented in Appendix 8.7. Figure 28 summarizes the results showing that the SMA mixtures aged slightly less than the dense graded mixtures. This can be explained with the stiffer initial binder and higher

binder content in the SMA mixtures compared to the dense-graded mixtures. The aging rates were higher at higher test temperature, as is expected. Shear stiffness and IDT strength indicated similar aging, while the axial stiffness showed much less aging. Again, the reason for axial stiffness for 1st coring being so high compared to the 2nd coring (which gives the result of lesser aging) can only partially be explained by sample preparation, as discussed above.

Figure 28. Summary of Aging Rates.

6 EFFECT OF MIXTURE COMPOSITION ON MECHANICAL RESPONSE

Christensen and Bonaquist (2005) have estimated the effects of mixture composition on the allowable traffic, as shown in Table 49. Then, the binder effect is by far the most important component to increase the mixture performance against rutting. From aggregate properties, the fineness modulus FM_{300} is an important property in designing better asphalt mixtures.

Table 49. Mixture Property Change on Rut Resistance (Christensen et al., 2005).

Mix Property Change	Approximate Effect on Allowable Traffic
1 % increase in design air voids	Increase 1.8 times
1 % decrease in field air voids	Increase 1.8 times
1 % decrease in design VMA	Increase 1.8 to 2.1 times
Increase N_{design} one level	Increase 1.5 to 2.2 times
Increase high temperature binder grade one step	Increase 11 to 18 times
Increase FM_{300} 5 %	Increase 4 to 6 times

6.1.1 Binder Stiffness Effect

In the mix design stage the binder grade is selected based on the design criteria for traffic level, traffic speed, and climatic conditions. Then, a good performance parameter must be sensitive to the binder grade adjustments and grade selection.

A linear regression was employed to study if the increase in binder PG grade correlated to the measured increase in the mixture stiffness and strength. Testing at higher temperature gave slightly better correlations (plant mixture $|E^*|$ $R^2 = 0.66$) compared to 40°C, although overall, correlations were poor to fair. Results are very similar for both the axial and shear stiffness.

The IDT strength for 0.39 mm/min loading time had the best correlation to the binder high-temperature PG grade increase ($R^2 = 0.84$), which suggests that the IDT strength is more driven by the binder stiffness than the axial or shear stiffness. The

correlation for cores was very poor due to the confounding effects of the binder aging and variations in the internal structure of the cores.

Figure 29 shows the ratio of mixture stiffness at 40°C & 10Hz to 54.4°C & 5Hz average over all mixtures. This stiffness ratio is indicative of the damage accumulation in the test specimens at 54.4°C testing, and also includes the binder stiffness ratio between 40 and 54.4°. The relative aggregate contribution is more profound in the softer binders, and the shear modulus seems to be more sensitive for the combined binder and aggregate influence.

Figure 29. Test Specimen Damage Increase at Test Temperature Increases.

Figure 30 shows the stiffness variation within each binder grade. This variation is indicative of the aggregate influence in the mixture. The stiffness variation is expressed as the ratio of maximum and minimum stiffness of mixture with the same binder grade. The stiffness variation ranges from 1.4 to 2.4. Part of this variation is caused by binder stiffness variation within each binder grade, but the rest is caused by variation in aggregate properties, binder content, and packing of aggregate through the compaction. Variation of the Ring and Ball softening point temperature in each binder grade was 5, 8 and 25% for the PG64, PG70, and PG76, respectively (see Appendix 19). Then, it can be estimated that the aggregate influence is between 20 to 114%

depending on the binder type used. Thus, by changing aggregate type and packing or adding fibers, it is possible to double the mixture shear stiffness within the same binder grade used.

Figure 30. Stiffness Variation within Each Binder Grade.

6.1.2 Aggregate Effects

Figure 31 shows the correlation of friction angle ϕ and Bailey method fine aggregate-fine ratio (FA_F), which is used to represent the packing characteristic of the fine portion of the fine aggregate in the gradation. The FA_F seems to explain the magnitudes of the measured friction angles for the studied mixtures. It seems that the SMA mixtures had the lower friction angle due to higher portion of fines compared to the dense-graded mixtures. Based on Mohr-Coulomb theory of shear strength of materials, the higher friction angle should indicate higher aggregate interlock compared to the lower values. Then, the dense-graded mixtures should have better frictional resistance than the SMA mixtures. Figure 32 compares the friction angle of ALF mixtures (Stuart et al., 1999) and WesTrack mixtures (Pellinen, 2001) to the Indiana mixtures. The ALF mixtures have the same gradation but different binder PG grade, and the WesTrack mixtures have the same binder grade but different

gradations. The figure suggests that the use of very stiff binder will lower the friction angle in the mixture. Then, the large difference in the measured friction angle values between the dense-graded and SMA mixtures is not caused by aggregate gradation effects but the use of stiffer binder in the SMA mixture.

Figure 31. Correlation between FA_F Ratio and Friction Angle.

Figure 32. Correlation of binder viscosity and aggregate friction angel.

To investigate more closely the aggregate effect on mixture stiffness ratios Figure 33 shows the correlations of fineness modulus FM_{300} to stiffness ratio of $|E^*|_{40/10}/|E^*|_{54.4/5}$. There does not seem to be any correlation in the $|E^*|$ testing for the

dense-graded mixtures, but a fair correlation for the SMA exists. However, SR66 and US24 seem to be outliers in the trend for the dense-graded mixtures. The lower stiffness ratio indicates that the mixture is able to maintain relatively higher stiffness at the higher test temperature compared to the lower temperature. Then the increase of fines in the mix increases mixture stiffness at higher test temperature, as Table 49 suggests. US24 had a large testing variation due to the raw material variation, which may explain test results.

Figure 33. Correlation of Fineness Modulus and mixture Stiffness Ratios.

Figure 34 shows that for shear stiffness there is a fair to excellent correlation between FM_{300} and stiffness ratio of $|G^*|_{40/10}/|G^*|_{54.4/5}$ for the dense-graded mixtures. However, for the SMA mixtures the ratio is reversed suggesting that less fines is better. However, the fine aggregate influence is confounded by other factors such as the use of fibers and mineral filler. For instance, US31 did not have fibers and I65 did not have mineral filler. Fineness modulus for US31 was 36.1 and for I65 it was 31.6.

Figure 34. Correlation of Fineness Modulus and Mixture Stiffness Ratios.

Figure 35 shows correlation between FM_{300} and friction angle of mixtures. For the SMA mixtures the increase of FM_{300} increase friction angle and mixture resistance to shear. For dense-graded mixtures the trends are less clear, which indicates complicated interactions between the different aggregate properties and binder.

Figure 35. Correlation between FA_F Ratio and Friction Angle.

7 MICRO-TEXTURE COLLAPSE

The objective of the repeated load permanent deformation testing (dynamic creep testing) was to evaluate potential for macro-texture collapse due to the low stiffness of the mixture. In addition, the dynamic creep test was one of the simple performance test candidates for rutting in the NCHRP Study 9-19 (Witczak et al., 2001). Table 50 summarizes the test results while more detailed results are given in Appendix 14. Testing was conducted applying 10,000 cycles of haversine pulse loading of 0.1 second load and 0.9 second rest period at 54.4°C test temperature. Samples were tested using 138 kPa confining stress.

Several permanent deformation parameters were evaluated, including the intercept a , slope b , resilient strain ϵ_r at 200 cycles (%), cumulative permanent strain ϵ_p (%), permanent to elastic strain ratio ϵ_p/ϵ_r , permanent strain ϵ_p ratio ($\epsilon_{\text{lateral}}/\epsilon_{\text{axial}}$), and resilient modulus M_r at 10,000 cycles, and flow number. These parameters are explained in Appendix 2.

Table 50. Summary of Dynamic Creep Test Results.

Road No.	V_a (%)	a	b	ϵ_r 200 (%)	ϵ_p (%)	ϵ_p/ϵ_r	ϵ_p Ratio	M_r (MPa)	Axial FN	Radial FN
SR15	7.8	0.097	0.35	0.055	2.49	43.4	1.30	1,413	9,407	9,876
US24	7.5	0.123	0.37	0.062	3.50	89.8	1.48	2,020	9,018	6,746
SR161	8.0	0.154	0.29	0.060	2.21	36.0	1.48	1,322	9,444	9,306
SR56	7.5	0.315	0.21	0.050	2.02	39.0	1.44	1,628	9,796	3,652
US30	7.5	0.151	0.24	0.062	1.33	20.4	0.77	1,242	9,879	7,575
SR66	7.6	0.147	0.30	0.065	2.27	31.6	0.99	1,139	9,647	2,119
SR135	7.7	0.145	0.31	0.049	2.03	37.7	0.64	1,618	9,738	8,820
US31	7.4	0.328	0.22	0.061	2.28	50.4	1.07	1,759	10,159	7,972
I74	7.5	0.237	0.25	0.045	1.96	50.6	0.61	1,975	9,556	4,778
SR64 ¹	7.2	0.144	0.46	0.045	4.44	118.7	0.71	2,193	5,241	1,273
I65 ¹	7.6	0.077	0.36	0.052	3.43	98.3	0.74	2,287	5,527	5,237
Avg. DGM	7.7	0.162	0.30	0.058	2.27	42.6	1.156	1,483	9,561	6,871
Avg. SMA	7.4	0.197	0.32	0.051	3.03	79.5	1.045	2,053	7,621	4,815
Avg. All	7.6	0.175	0.31	0.055	2.54	56.0	1.116	1,691	8,856	6,123

(1) Some specimens failed in tertiary flow

Only two mixtures SR64 and I65 exhibited tertiary flow during testing, see Figure 36. As an example of the test data that did not exhibit tertiary flow at 10,000

cycles, Figure 37 shows test results for SR161. The Flow Number (FN) given in Table 50 represents a value the IPC control software continuously calculates and reports for each applied cycle.

Then, although the value is designated at flow number, the specimens did not fail at the given number of cycles, except mixtures SR64 and I65 that exhibited tertiary flow and failed. The axial flow number is obtained from the axial strain measurements and the radial flow number is obtained from the radial strain measurements.

The parameters a and b are the general indicator of permanent deformation susceptibility of a mixture. It is assumed that the larger they are, the larger the permanent deformation potential. If this is true, then the SMA mixtures should rut more because, as an average, they have higher intercept and slope compared to the dense-grade mixtures.

Figure 36. Permanent Strain vs. Cycles, I65.

Figure 37. Permanent strain vs. Cycles, SR161.

The new flexible pavement design guide predicts permanent deformation utilizing the plastic (permanent) to resilient strain ratio ϵ_p/ϵ_r assuming that the lower the ratio the better resistance against rutting. Table 50 shows that the SMA mixture had almost double the ratio compared to DGM, indicating a much higher potential for rutting.

The resilient modulus M_r values are consistent with the dynamic and shear modulus test results because the SMA mixtures have higher modulus values compared to the dense-graded mixtures. However, correlation between M_r and dynamic and shear stiffness is poor. This is due to the large dilatation specimens undergo in the repeated testing compared to the dynamic and shear modulus testing, which are conducted in the linear visco-elastic region. Based on the theory of linear visco-elasticity, dilatation is not possible if the specimen is compressed. In the dynamic creep test, specimens exhibit large radial plastic strain and dilatation in compression loading, which is a manifestation of plastic instead of linear or non-linear visco-elastic material behavior.

Table 51 shows the creep strain obtained in the axial dynamic modulus stiffness testing. This creep strain is indicative of the damage accumulation and possible

structural changes during the testing. The largest axial strain was measured from the plant mixtures, which had the least aging. On the other hand, test results for the 1st coring indicate some structural changes in the specimens.

Table 51. Creep Strain in $|E^*|$ Testing.

Road No.	Creep Strain in $ E^* $ testing, Micro-strain									
	Asphalt Plant Loose Mixture				Raw Mixtures		1st Cores		2nd Cores	
	Unconfined		Confined		Unconfined		Unconfined		Unconfined	
	40°C	54.4°C	40°C	54.4°C	40°C	54.4°C	40°C	54.4°C	40°C	54.4°C
SR15	810	443	296	155	1,288	452	4,173	n/a	552	1,103
US24	781	460	673	190	860	404	1,396	2,506	338	377
SR161	1,522	804	473	185	2,155	871	2,036	3,419	672	658
SR56	548	589	822	191	987	695	2,177	1,952	689	343
US30	370	381	553	232	574	262	2,777	543	801	647
SR66	1,164	747	1,344	233	1,347	777	6,771	n/a	457	553
SR135	1,326	661	810	298	1,173	664	1,131	641	818	540
US31	1,357	721	515	160	846	658	2,310	829	1,168	987
I74	1,404	908	865	575	1,433	578	3,149	1,600	1,206	1,039
SR64	1,772	1,249	1,101	384	661	1,349	1,902	1,217	619	946
I65	599	271	703	354	716	550	1,030	474	667	459

Figure 38 compares dynamic creep test, the plastic strain ratio ϵ_p at the end of test to the creep strain obtained from the dynamic modulus $|E^*|$ testing for the confined specimens. There is good correlation between the two readings, which confirms that the behavior of ϵ_p testing is heavily dependent on confinement and perhaps unconfined testing had been better to differentiate the mixtures. Results may not be representative due to the confinement applied in the testing.

Table 52 shows some parameters that are hypothesized to affect the micro-texture collapse. If low axial stiffness $|E^*|$ and large dilatation potential (ϵ_p ratio) are used as criteria, the most vulnerable mixture is US24 followed by SRS161. Both mixtures had softest binder of PG64-22. SR161 had 34% flat particles and small FA_F Bailey Method ratio, which indicates a low amount of fines in the fine portion of aggregate gradation. US24 is the coarsest of all dense graded mixture having the lowest percent passing 4.75 mm sieve and lowest Bailey Method CA ratio.

If high densification (cumulative ε_p) and low stiffness are used as criteria, the most vulnerable mixture is US24.

Figure 38. Dilatation of Test Specimens.

Table 52. Parameters Related to Micro-texture Collapse.

Parameter	Weakest Mix	Strongest Mix	Ratio	Influence
$\varepsilon_p (10^4) (\%)$	SR64, US24	US30	3.3	Suggests high densification
$\varepsilon_p/\varepsilon_r (10^4)$	SR64	US30	5.8	Large relative plastic strain
ε_p Ratio (10^4)	US24, R161	I65	2.4	Suggests large dilatation
$M_r (10^4) (\text{MPa})$	SR66	I65	2.0	Low axial stiffness

The dynamic creep test parameter that was recommended for the simple performance test by Kaloush (2001) was Flow number. However, this parameter does not correlate with the stiffness parameters and it will give erroneous results for the SMA mixtures. Neither does the plastic/elastic strain ratio correlate to the stiffness parameters, which suggests that confined dynamic creep test is not suitable for performance testing and rather unconfined testing is needed.

8 PERFORMANCE CRITERIA DEVELOPMENT

8.1 Background

The objective of the work was to develop a performance criteria or threshold value to be used as a QC/QA tool in HMA construction projects. The study comprised of testing stiffness and strength properties of 11 surface mixtures laid down at various locations in the state of Indiana in 2002.

It was hypothesized that fundamental performance criteria for asphalt mixtures can be developed either for the stiffness or for the strength of the mixture, or for their combination. Currently, there are no criteria for the $|E^*|$ of hot mix asphalt obtained from the dynamic modulus testing. However, Pellinen (2001) developed conceptual stiffness criteria for varying traffic and climate using layered elastic analysis procedure, see Figure 39. However, for the SST shear stiffness $|G^*|$ there is an empirical rule of thumb stiffness that has been used in recent years to assess mixtures in Indiana and elsewhere.

Figure 39. Conceptual Stiffness Criteria (Pellinen, 2001).

The strength or stability of asphalt mixtures was studied heavily in the 1940's and 1950's and several researchers developed mix design methods based on cohesion

and friction angle measured from the triaxial test (McLeod, 1948,1952,1953; Smith, 1949). However, none of the methods were adopted by industry due to complexity of laboratory testing. A more simplified empirical method, Marshall Stability mix design method and stability test, was adopted by industry and published by the Asphalt Institute (1945). There has been more interest in triaxial testing in recent years and in 2002 Christensen et al. proposed to use IDT strength as a surrogate property for shear strength as a simplified performance test for rutting.

Pellinen (2004) suggested a conceptual performance criteria for the stiffness and shear strength of the mixture. The author argued that for some asphalt mixtures the stiffness and strength properties are correlated leading to similar performance predictions, but for some mixtures these properties are not correlated, which will lead to a different performance prediction. Therefore, Pellinen suggested that for an optimal pavement performance, both stiffness and shear strength of the mixture must be considered, see Figure 40.

Figure 40. Conceptual Stiffness and Strength Criteria (Pellinen, 2004).

Today there are numerous empirical models to predict the performance of hot mix asphalt for rutting, fatigue cracking, and low temperature cracking. The latest

ones include the models used in the new pavement design guide software and rutting and fatigue cracking models developed by Christensen et al. (2005) for the refinement of the Superpave volumetric mix design system.

Different approaches were employed to estimate the required mixture stiffness and strength, such as assessment of the failed Interstate I74 material properties (discussed in Appendix 11) and evaluation of the study mixtures against various criteria presented in the literature (discussed in Appendix 13):

- Conceptual stiffness criteria based on Layered Elastic Analysis (Pellinen, 2001).
- Combined stiffness and strength criteria (Pellinen, 2004)
- Rule of Thumb criteria (Anderson et al., 2001)
- Strength criteria based on IDT strength and RSCH test (Christensen et al., 2000; Anderson, Christensen & Bonaquist, 2003)
- Rutting model based on resistivity (Christensen and Bonaquist, 2005)

It was envisioned that the performance criteria would be used as a QC/QA tool; however, it is possible to expand the criteria to the mix design stage because of the three different sample data sets employed in the research. Additional application would be the forensic evaluations of mixture performance.

8.2 Measured Rutting Performance of Study Mixtures

A visual inspection and rut depth measurement were conducted in November 2004 by Purdue for the eleven test sections. Measurements were obtained at the core locations measuring several profiles at each location using a 3 m long straight edge, as shown in Figure 41. For those sites where the core locations could not be found, ruts were measured from random locations from the main lane of the road.

Rutting was visually difficult to detect. Based on measurements, only SR135 exhibited 1.6 to 4.8 mm of rutting in the core location that was near the intersection after two years of traffic loading (see Appendix 4). The measured rutting matched the theoretical calculations of traffic densification of pavement. Densification was

calculated based on air voids content reduction of the pavement cores. Theoretical calculations indicate that some densification had occurred also in US24, US31, and SR66, although the magnitude was too small to be detected by the straight edge measurements. Table 53 gives the estimated rut depth based on theoretical calculations of pavement densification. The table also gives the observed stresses. From all the mixtures, SR56 had the lowest tensile strength ratio and it exhibited potholes. US24 and US30 had longitudinal cracks, which suggest top-down cracking of the pavement, while SR15 had some transverse micro-cracks, which suggest bottom-up cracking of the pavement.

Figure 41. Rutting Measurement in SR64 in Fall 2004.

Table 53. Rut Depths including theoretical densification.

Road No.	Rut depth mm	Visual Distress Survey
SR15	0	Occasional transverse micro-cracks
US24	0.6	Minor longitudinal cracks
SR161	0	
SR56	0	
US30	0.9	Minor longitudinal cracks near shoulder
SR66	1.3	
SR135	1.6-4.8	
US31	0	
I74	0	
SR64	0	Frequent potholes
I65	0	Wearing of pavement surface

8.3 Stiffness Criteria Development

8.3.1 Rule of Thumb (Empirical Criteria)

For the SST shear stiffness $|G^*|$ there is an empirical rule of thumb value that has been used in recent years to assess mixtures in Indiana and elsewhere (NCAT, 1996; Anderson, Bukowski, and Turner, 1999). The rule of thumb states that mixture stiffness is good if it exceeds 250 MPa measured at 40°C with 10 Hz frequency. However, these criteria are not tied to any traffic level or climate, and no field performance data has been provided in the 1999 study to support that adequate mix performance will be obtained. It is also important to recognize that the criteria are based on performance testing of laboratory design mixtures (raw material), and that the air void content specimens were compacted is not mentioned in the 1999 paper.

Anderson, Huber, Walker and Zang (2001) refer to the same criteria in their evaluation of 1992 SPS 9 mixtures. They concluded that the criteria was reasonable because Maryland surface mixture compacted to approximately 7% air voids content had $|G^*|$ of 285 MPa measured at 41°C and it rutted only 6 mm during 6 years of traffic loading. The mixture was placed on Interstate 70 with 11 million design ESALs with 10% trucks.

Table 54 shows the SST $|G^*|$ criteria values and criteria converted to the testing conditions of 54.4°C with 5 Hz by the authors using the Hirsch predictive model. The table also shows the criteria converted to $|E^*|$ using Eq. (7).

Table 54. SST Shear Stiffness Rule of Thumb.

Rutting Performance	Rule of Thumb SST $ G^* $ (MPa)		Rule of Thumb Converted to $ E^* $ (MPa)	
	40°C&10Hz	54.4°C&5 Hz	40°C&10Hz	54.4°C&5 Hz
Good	250 - 345	43- 60	1,325-1,704	336-435
Moderate	150 - 250	26 - 43	889-1,325	227-336
Poor	< 150	< 26	< 889	< 227

8.3.2 Threshold Stiffness from I74

The threshold stiffness properties were evaluated based on the forensic study that investigated the pavement rutting failure in I74 near Indianapolis. This study is described in more detail in Appendix 11. Table 55 to Table 57 summarize the laboratory tests conducted in 1999 and 2002-2004 from cores taken in 1999 and 2002. The tables show the actual in-place properties and properties normalized to the 7.5% air voids content.

Table 55. Measured SST $|G^*|$ at 40°C & 10 Hz

Testing Agency and Time	Failed (I74, EB)		Survived (I74, WB)		Ratio	
	In-place	Norm.	In-place	Norm.	In-place	Norm.
Heritage 1999	170	117	238	209	1.4	1.8
Purdue 2002	139	109	403	399	2.9	3.7
Purdue 2002/2004 ¹	147	116	381	368	2.6	3.2

(1) Sampled at 2002 and tested at 2004. Samples were stored in Purdue's cold room.

Table 56. Measured SST $|G^*|$ at 50 and 54.4°C & 5Hz

Testing Agency and Time	Failed (I74, EB)		Survived (I74, WB)		Ratio	
	In-place	Norm.	In-place	Norm.	In-place	Norm.
1999 (50°C)	44	39	58	56	1.3	1.4
2002 (54.4°C)	30	26	57	56	1.9	2.2
2002/2004 (54.4°C)	47	39	83	80	1.8	2.1

Table 57. Recovered Binder Stiffness.

Parameter	Failed (I74, EB)	Survived (I74, WB)	Ratio
PG Grade	PG64-28	PG70-28	—
G^* (kPa) @64°C	2.12	4.31	2.0
$G^*/\sin\delta$ (kPa) @64°C	2.13	4.34	2.0
Viscosity, η (Pa.s) @64°C	227	465	2.1
Viscosity, η (Pa.s) @40°C	7,930	34,442	4.3

The investigation suggested that the difference of a good (rut depth < 3 mm) and a poor performance (rut depth 12 to 15 mm) was one high-temperature PG grade or 6°C of temperature. The mixture stiffness measured in 1999 was 1.8 times higher in the surviving mixture (normalized) compared to the rutted mixture. Measurements conducted in 2002 and 2004 showed the ratio of 3.2-3.7.

The extracted binder stiffness for the surviving mixture was 2 times higher than for the failing mixture at the original grading temperature of 64°C, see Table 57. RTFOT aged binder criteria of 2.2 kPa was used to grade the recovered binder, which indicated that EB lane had PG64-28 and WB lane had PG70-28.

The Superpave mix design for the I74 was conducted using design traffic of 12 million ESALs for 20 years of design life. However, the traffic verification suggested that the road had close to 30 million ESALs based on the ADT (35,000) and percentage of trucks (15%).

Figure 42 shows the measured stiffness values with testing variation included. The error bars were computed for $\pm 2(s)$ deviations from the mean. Unfortunately, only one replicate was tested in 1999 for the surviving west bound (WB) lane while for the failed east bound (EB) lane 5 samples were tested. As the figure shows, the difference in stiffness is not statistically significant (assuming the same coefficient of variation (36%) for both test results).

Figure 42. Stiffness for Failing and Surviving Lanes at I74.

Because testing variation is masking the stiffness difference for the 1999 test results, it is safer to use average values over all test results to determine the threshold values. Then, the threshold SST stiffness (normalized) for failure and survival are 115 and 325 MPa, respectively, see Table 58. This relates to testing variation of 23 to 27%. These values are in line with the rule of thumb criteria for a poor and a good pavement performance. The table also gives converted criteria for $|E^*|$ of the mix using Hirsch predictive model and Eq. (7).

Table 58. Selected Threshold Stiffness.

Parameter (MPa)	Test Condition	Failed (I74, EB)		Survived (I74, WB)	
		In-place	Norm.	In-place	Norm.
$ G^* $	40°C&10 Hz	152	115	340	325
	54.4°C & 5 Hz	40	32	66	68
$ E^* $	40°C&10 Hz	900	718	1684	1626
	54.4°C & 5 Hz	317	266	469	480

8.3.3 Stiffness Criteria from Layered Elastic Analysis

Pellinen (2001) developed a conceptual $|E^*|$ criteria as a function of effective temperature T_{eff} using Layered Elastic Analysis Program. The criteria states that the mixture will have less than 12.5 mm of rutting during 10 years of traffic loading if the stiffness of the mix is less than the criteria value. This is explained in more detail in Appendix 12. The $|E^*|$ criteria can be converted to the shear $|G^*|$ stiffness using Equation (4), which was obtained from the correlation of axial and shear stiffness for the plant mixtures. By using Equation (5) and coefficients given in Table 59, criteria at any effective temperature can be calculated for the shear stiffness $|G^*|$ of mixture for 10 Hz loading time. Equation (6) shows the effect of traffic on the criteria determination. In a similar manner as for the temperature, the criteria as a function of ESALs can be calculated using the power model coefficients given in Table 59.

$$|G^*| = 0.0249 |E^*|^{1.2817} \quad (4)$$

$$|G^*|_{1,10,100M \text{ ESALs}} = a \times T_{eff}^b \quad (5)$$

$$|G^*|_{38.6,40,42.5^\circ C} = c \times ESALs^d \quad (6)$$

Table 59. Coefficients for Criteria as function of Effective Temperature.

Traffic Level (million ESALs)	a	b	Effective Temperature $T_{eff} (^{\circ}C)$	c	d
1	0.0035	2.6898	37.0	0.0089	0.6349
10	0.0212	2.5930	40.0	0.0115	0.6321
100	0.1208	2.5188	43.0	0.0145	0.6293

8.3.4 Analysis of Study Mixtures

Table 60 and Table 61 summarize the stiffness criteria presented above including: 1) layered elastic analysis criteria (LEA); 2) the rule of thumb criteria (Rule of T); and 3) threshold criteria from I74 forensic study (Threshold I74).

The surviving mixture threshold value was assigned to the roads with design traffic levels higher than 3 million ESALs, and the failing value to the roads with traffic less than 3 million ESALs. Justification for this is that the I74 mix design was used for the design traffic of 12 million ESALs. However, based on the traffic verification, it is possible that design traffic was 30 million ESALs. The WB lane was constructed first and it had all the interstate traffic while the EB lane was under construction. For LEA criteria for I65, only 100 million ESALs traffic was used because the 155 million ESALs would have given unrealistically high criteria value. In addition, the LEA criteria was calculated for both the effective temperature and the testing temperature of 40°C.

These criteria were evaluated against the measured mixture stiffness parameters of $|E^*|$ and $|G^*|$ measured at 40°C with 10 Hz frequency. Analysis results are shown in Figure 43 to Figure 46.

Table 60. Summary of Studied Stiffness Criteria for $|E^*|$.

Road No.	Design ESALs (10^6)	T_{eff} ($^{\circ}C$)	LEA $ E^* /10Hz$ (MPa)		Rule of T $ E^* $ 40 $^{\circ}C/10Hz$ (MPa)	Threshold I74 $ E^* $ 40 $^{\circ}C/10Hz$ (MPa)
			T_{eff}	40 $^{\circ}C$		
SR15	2.4	38.6	710	765	1325	718
US24	9.6	38.9	1432	1515	1325	1626
SR161	0.5	41.5	382	353	1325	718
SR56	7.5	41.6	1454	1342	1325	1626
US30	50.2	38.9	3240	3425	1325	1626
SR66	6.8	42.5	1448	1278	1325	1626
SR135	20	40.8	2263	2176	1325	1626
US31	21.4	38.7	2107	2250	1325	1626
I74	33	40.0	2785	2785	1325	1626
SR64	21.1	41.3	2383	2234	1325	1626
I65	155	40.4	4919 ¹	5970 ¹	1325	1626

1) Criteria for 100 million ESALs

Table 61. Summary of Studied Stiffness Criteria for $|G^*|$.

Road No.	Design ESALs (10^6)	T_{eff} ($^{\circ}C$)	LEA SST $ G^* /10Hz$ (MPa)		Rule of T SST $ G^* $ 40 $^{\circ}C/10Hz$ (MPa)	Threshold I74 SST $ G^* $ 40 $^{\circ}C/10Hz$ (MPa)
			T_{eff}	40 $^{\circ}C$		
SR15	2.4	38.6	112	124	250	115
US24	9.6	38.9	276	298	250	325
SR161	0.5	41.5	51	46	250	115
SR56	7.5	41.6	281	255	250	325
US30	50.2	38.9	788	848	250	325
SR66	6.8	42.5	279	240	250	325
SR135	20	40.8	496	474	250	325
US31	21.4	38.7	452	495	250	325
I74	33	40.0	650	650	250	325
SR64	21.1	41.3	530	490	250	325
I65	155	40.4	1343 ¹	1310 ¹	250	325

1) Criteria for 100 million ESALs

Figure 43. $|E^*|$ for Plant and Raw Material Mixtures.

Figure 44. $|E^*|$ for Field Cores (normalized).

Figure 45. $|G^*|$ Plant and Raw Material Mixtures. Figure 46. $|G^*|$ for Field Cores (normalized).

Table 62 summarizes the number of mixtures that failed the criteria. Almost half of the mixtures failed the LEA criteria, which suggest that they would develop more than 12.5 mm of rutting during 10 years of service life. Almost all of the failing mixtures had design traffic higher than 20 million ESALs. For $|E^*|$ there was no

difference between T_{eff} and 40°C while for the $|G^*|$ one more mixture failed the criteria for T_{eff} compared to 40°C .

Table 62. Number of Failing Mixtures.

Test Data Set	LEA Criteria				Threshold		Rule of Thumb	
	$ E^* T_{eff}$	$ E^* 40^{\circ}\text{C}$	$ G^* T_{eff}$	$ G^* 40^{\circ}\text{C}$	$ E^* $	$ G^* $	$ E^* $	$ G^* $
Raw Mixtures	4	4	4	4	0	0	0	0
Plant Mixtures	5	5	4	4	2	1	1	0
1 st Cores	4	4	9	8	0	8	1	0
2 nd Cores	5	5	4	4	1	0	1	0
Total	41%	41%	48%	45%	7%	20%	7%	0%

None of the mixture failed the rule of thumb for the $|G^*|$ while 20% failed the threshold value of 325 MPa. Most of the failing mixtures were “fresh” cores. Only three mixtures failed the rule of thumb and threshold stiffness for the $|E^*|$. These mixtures were SR15, US24, and US31 (SMA without fiber). Overall, it seems that the rule of thumb criteria works well for the Indiana mixtures when the criteria is applied to samples compacted to 7.5% air voids content.

8.4 Strength Criteria Development

8.4.1 Threshold Strength from I74

Similar to the threshold stiffness, the threshold strength properties were evaluated based on the I74 forensic study described in Appendix 11. Mixture strength was measured in 2005 from the field cores obtained in 2002 and then stored in Purdue’s cold room.

The threshold IDT strength value is between 32 and 90 kPa (normalized), as Table 63 shows. Although testing variation ranged from 5 to 18%, the difference in mixture strength between the failing and revived lane is statistically significant, see Figure 47.

Compared to Christensen et al., (2000) general criteria for the IDT strength (Appendix 13), the WB lane had excellent pavement performance while the EB lane

had poor performance. This verifies that Christensen's general criteria are in the right ballpark. The strength ratio is 2.8 for the normalized data compared to 3.2 to 3.7 for the ratio of shear stiffness values.

Table 63. Threshold for the IDT Strength (2002).

Parameter	Failed (I74, EB)		Survived (I74, WB)		Ratio	
	In-Place	Norm.	In-Place	Norm.	In-Place	Norm.
IDT S_t 35°C, 0.06 m/min	49	32	98	90	2.0	2.8

Figure 47. Strength for Failing and Surviving Lanes at I74.

8.4.2 Christensen et al. Strength Criteria

Christensen et al. (2000) suggested using cohesion, friction angle and IDT strength criteria for rutting and developed guidelines for a good and poor performance (Appendix 13). The authors converted the criteria for the test conditions used in this study and also expanded it for different traffic levels, see Table 64.

Table 64. Strength Criteria Based on 12.5 mm (0.5 in) Rut Depth.

Parameter	Minimum Strength Value (kPa)					
	ESALs, (10^6)					
	<3	3 -10	10 - 30	30 - 50	50 -100	>100
Cohesion 54°C, 7.5 mm/min	56	56 to 86	86 to 27	127 to 153	153 to 196	>196
S _t 35°C, 0.06 mm/min	33	33 to 47	47 to 67	67 to 78	78 to 96	>96

8.4.3 Analysis of Study Mixtures

Table 65 summarizes the strength criteria discussed. Similar to the stiffness criteria, the surviving mixture threshold value was assigned to the roads with design traffic higher than 3 million ESALs and the failing value to the roads with less than 3 million ESALs.

These criteria were evaluated against the measured mixture strength. The evaluated parameters were IDT strength measured at 35°C with 0.06 mm/min ram rate and cohesion c measured at 54.4°C with 7.5 mm/min ram rate. Analysis results are shown in Figure 48 to Figure 50. At this point, the criteria from the friction angle is at best tentative and needs more research.

Table 65. Summary of Strength Criteria.

Road No.	Design ESALs (10^6)	Strength Criteria from Literature c and IDT S _t (kPa), ϕ (°C)				Threshold I74 (kPa)
		Cohesion c Upper	ϕ	IDT S _t Lower	IDT S _t Upper	
SR15	2.4	56	40	33	33	32
US24	9.6	86	40	33	47	90
SR161	0.5	56	40	33	33	32
SR56	7.5	86	40	33	47	90
US30	50.2	153	40	67	78	90
SR66	6.8	86	40	33	47	90
SR135	20	127	40	47	67	90
US31	21.4	127	40	47	67	90
I74	33	153	40	67	78	90
SR64	21.1	127	40	47	67	90
I65	155	>196	40	>96	>96	90

Figure 48. IDT (Upper limit) for Plant and Raw Material Mixtures (normalized).

Figure 49. IDT (Upper limit) for Field Cores (normalized).

Figure 50. Cohesion for Plant and Raw Material Mixtures (normalized).

Table 66 summarizes the number of mixtures that failed the criteria. Overall, more mixtures failed the strength criteria than the stiffness criteria. Both the Christensen et al. upper criteria and threshold criteria seem to be too tight for the study mixtures because over 40% failed. The design traffic varies from 2.4 to 50 million ESALs for these roads. This indicates that the lower IDT limit may be more appropriate for the Indiana mixtures.

Table 66. Number of Failing Mixtures.

Test Data Set	Criteria from Literature			Threshold
	Cohesion Upper	IDT S_t Lower	IDT S_t Upper	IDT S_t
Raw Mixtures	2	2	4	5
Plant Mixtures	5	2	4	5
1 st Cores	—	2	4	5
2 nd Cores	—	3	7	6
Total	16%	20%	43%	48%

8.5 Combined Stiffness and Strength Criteria Development

8.5.1 Hypothesis

It was hypothesized that if a mixture is stiff enough, a lower strength will satisfy the performance requirement. In a similar manner, higher strength will compensate lower stiffness of the mixture. Figure 51 shows a schematic presentation of the combined stiffness and strength criteria; mixture fails when both performance parameters stiffness and strength are below the failing threshold value. A possible failure occurs when either stiffness or strength falls below the surviving threshold value. At this point, it is not known if the likelihood of failure is the same for all sub areas (A, B and C) of the possible failure area.

Figure 51. Combined Stiffness and Strength Criteria.

8.5.2 Development of Base Failure Criteria

The combined criterion tries to identify the mixtures that are marginal in terms of stiffness or strength. The analysis above indicates that the threshold and rule of

thumb criteria gave a better indication of the mixture performance than the LEA criteria, which is intended to predict the performance after 10 years of traffic loading while the other two relate more to the as-constructed properties. Because asphalt mixture is most vulnerable for rutting at its early age, it is more important to develop threshold stiffness against the early-age pavement failures than try to predict actual rutting at the end of the pavement design life.

The combined threshold criteria were developed utilizing the I74 forensic study findings; the threshold failure shear stiffness was 115 MPa and the surviving shear stiffness was 325 MPa for traffic of 30 million ESALs. The threshold failure IDT strength was 32 kPa and the surviving IDT strength was 90 kPa.

The study test data was examined by separating mixtures into three traffic groups; less than 3, from 3 to 30, and more than 30 million ESALs based on the Superpave mix design system. The reason for using only three traffic levels is that the range of the criteria limits has to be larger than the testing variation. Table 67 shows study mixtures assigned for each traffic group. Figure 52 to Figure 54 show the $|G^*|$ and IDT strength relative to the threshold values. The figures also show both Heritage (1999) and Purdue (2002 and 2004) measurements for I74 cores.

Table 67. Mixtures within Each Criteria Traffic Groups

Criteria ESALs (10^6)	Road No.	Design ESALs (10^6)	Mix Type	Binder Type	N _{des}	Aggregate	Notes
<3	SR15	2.4	DGM	PG64-22	75	Dolomite	
	SR161	0.5	DGM	PG64-22	75	Dolomite	
3-30	US24	9.6	DGM	PG64-22	100	B-F Slag	
	SR56	7.5	DGM	PG70-22	100	Steel Slag	
	SR66	6.8	DGM	PG70-22	100	Stand Stone	
	SR135	20	DGM	PG70-22	100	B-F Slag	
	US31	21.4	SMA	PG76-22	100	Steel Slag	No fiber
	SR64	21.1	SMA	PG76-22	100	Steel Slag	
>30	US30	50.2	DGM	PG70-22	125	B-F Slag	
	I74	33	SMA	PG76-22	100	Steel Slag	
	I65	155	SMA	PG76-22	100	Steel Slag	No min. filler

Figure 52. $|G^*|$ for Low Traffic (normalized). Figure 53. $|G^*|$ for Medium Traffic (normalized).

Figure 54. $|G^*|$ for Heavy Traffic (normalized).

The number of mixtures that fell into the failing or possible failing category, based on the stiffness of 1st cores, are listed in Table 68. The number of mixtures that failed the strength criteria are listed in Table 69. Then, based on mixture stiffness, none of the mixtures should fail because none of the mixtures are below the failing threshold for stiffness of 115 MPa. However, the IDT strength predicts failure for US24 and SR66 because their strength is less than failure strength of 32 kPa.

Table 68. Mixtures below Stiffness Threshold Values.

Design Traffic Level 10 ⁶ ESALs	Failure $ G^* < 115$ MPa	Possible Failure $ G^* < 325$ MPa
< 3	0	SR15, US24
3-30	0	all mixtures
> 30	0	US30, I74

Table 69. Mixtures below Strength Threshold Values.

Design Traffic Level 10 ⁶ ESALs	Failure $S_t < 32$ kPa	Possible Failure $S_t < 90$ kPa
< 3	0	SR15
3-30	US24,SR66	SR56,SR135,SR64
> 30	0	US30

Based on the measured field performance, none of these mixtures failed during the two first years of traffic loading, which suggests that the failing threshold criteria are in the right ballpark for stiffness. The examination of data shows that the two failing mixtures have extremely low strength values (10.4 and 7.5 kPa) which may indicate some local weakness in the constructed pavement. In the medium traffic group, all mixtures failed the threshold surviving criteria and two mixtures failed strength failure criteria, which indicates that criteria are too high for the traffic less than 30 million ESALs.

The criteria for the medium traffic roads were adjusted by taking in account the testing variation. The average stiffness testing variation for cores was 14%, which means that the range for the criteria values should be $2(s)\sqrt{3}$ or 49%. This will give a criteria of 200 MPa for traffic between 3 and 30 million ESALs. The average testing variation for the IDT strength was 18% for cores, which will give the range of criteria limits of $2(s)\sqrt{2}$ or 51%. Similarly, this will give strength criteria of 55 kPa. Table 70 summarizes the developed stiffness and strength criteria intended for the field cores less than one month old normalized to 7.5% air voids content.

Table 70. Threshold Criteria for Field Cores < One Month Old.

Design ESALs	Criteria for 1 st Cores	
	$ G^* $ at 40°C&10Hz	IDT At 35°C with 0.06 mm/min
(10 ⁶)	(MPa)	(kPa)
<3	115	32
3-30	200	55
>30	325	90

If the coefficient of variation (CV) is 10%, the probability that mixture stiffness or strength is different in each traffic category is 99%. For the CV of 20% the probability is 90%, and for CV of 30% the probability is 70%.

Table 71 summarizes the mixtures that failed the individual criteria given in Table 70, and the mixtures that failed the combined criteria. For medium traffic, 17% of mixtures failed the combined criteria and for the high traffic 67% of mixtures failed.

Table 71. Base values: Threshold Criteria & Failed Mixtures.

Design Traffic 10 ⁶ ESALs	Criteria G* MPa	Failure for G*	Criteria S _t kPa	Failure for S _t	Failure For G* &S _t
< 3	<115	0	<32	0	0
3-30	<200	SR56,	<55	US24,SR56,SR66	SR56
> 30	<325	US30,I74	<90	US30	US30,SR64

The field performance of the study mixtures, measured in 2004, indicates that these criteria may be too stringent for the Indiana mixtures. Therefore, mixtures were compared against the Asphalt Institute rule of thumb criteria and adjusted to the IDT strength criteria, shown in Table 72. The IDT strength in the table follows the IDT criteria developed from the Christensen et al. recommendations.

Table 72. Rule of Thumb Criteria and Adjusted IDT Criteria for Field Cores.

Design ESALs (10 ⁶)	Criteria for 1 st Cores < 1 mo. old	
	G* at 40°C&10Hz	IDT At 35°C with 0.06 mm/min
	(MPa)	(kPa)
<3	115	32
3-30	150	49
>30	250	67

Table 73 gives the mixtures that failed Asphalt Institute rule of thumb criteria and adjusted IDT criteria. None of the mixtures failed the combined criteria, and only one mixture failed the stiffness criteria and two mixtures failed the strength criteria.

Table 73. Base values: Rule of Thumb Criteria & Failed Mixtures.

Design Traffic 10 ⁶ ESALs	Criteria G* MPa	Failure for G*	Criteria S _t kPa	Failure for S _t	Failure For G* &S _t
< 3	<115	0	<32	0	0
3-30	<150	0	<49	US24,SR66	0
> 30	<250	US30	<67	0	0

8.6 Factor of Safety and Base Criteria

It is very common to use the factor of safety concept in engineering design. In geotechnical engineering, a factor of safety between 1.5 and 5 is used to calculate the allowable bearing capacity.

Based on this study, the mixture stiffness variation within the same high-temperature PG grade ranged from 1.4 to 2.4, while the strength ranged from 1.4 up to 4.7 measured from the cores. The I74 forensic study indicates that the binder stiffness variation within the same high temperature grade can be up to 2 during production, i.e., one PG grade. The mixture stiffness is also affected by the binder absorption and binder aging, which can be up to 2.4 times. The 7-day average pavement temperature can vary $\pm 4^{\circ}\text{C}$ in Indiana, in addition to variation in the traffic loading. The mixture stiffness difference between the failure and survival based on the I74 forensic study was 1.4-1.8 to 3.4. Therefore, it is evident that there is a possibility of failure within the same binder PG grade if the selected grade is too close to the actual failing performance.

Table 74 gives the base threshold criteria and factor of safety based on the I74 forensic study, and Table 75 gives the base rule of thumb criteria. The factor of safety of 2.2 seems to be adequate for Indiana mixtures, although there is some possibility of failure. The factor of safety of 2.8 will most likely provide enough safety against failure on heavily trafficked roads but at the same time, it may reject some adequate mixtures. Then, the decision, which criteria in the long run is more economical for Indiana, can be answered only after using criteria in the pilot projects for some time.

Table 74. Base Threshold Criteria and Factor of Safety.

Design ESALs (10^6)	$ G^* $ 40°C&10Hz	FS	IDT 35°C&0.06 mm/min	FS
<3	115	—	32	—
3-30	200	(1.8)	55	(1.7)
> 30	325	2.8	90	2.8

Table 75. Base Rule of Thumb Criteria and Factor of Safety.

Design ESALs (10^6)	$ G^* $ 40°C&10Hz	FS	IDT 35°C&0.06 mm/min	FS
<3	115	—	32	—
3-30	150	(1.4)	49	(1.5)
>30	250	2.2	67	2.1

An important issue is the right balance between the stiffness and strength. At this point, it is not known if the desirable stiffness and strength are in the right balance and if there is a need to adjust the ratio between them. This must be determined after more experience has been gained by applying the criteria for new and existing paving projects.

Figure 55 shows the original measured mixtures stiffness and IDT strength without air voids content normalization. The SMA mixtures are indicated with (+) in the data labels. Clearly, after one year of service, the studied mixtures are quite stiff relative to their strength and it is obvious that the stiffness is increasing as the binder is age-hardening, but mixture strength is not increasing in a similar manner.

The low mixture strength is due to high in-place density and it can be increased by increasing compactive effort during construction. Due to a large variation of field compaction effort, to construct dense pavements the target density has to be set lower than the current INDOT requirement of 92.5%.

Figure 55. $|G^*|$ and IDT strength for all mixtures (Original).

8.6.1 Adjustments for other Sample Types

The base criteria given in Table 74 and Table 75 are for “young” field cores. These criteria must be adjusted if the performance of the raw material mixtures, plant compacted gyratory pills or cores taken approximately one year after construction is of concern. The criteria adjustment factors, given in Table 76, are obtained from the relative mixture response discussed in Chapter 5. By using the ratios given in Table 76 and base criteria values from Table 74 or Table 75, the adjusted criteria can be calculated.

Data analysis in Chapter 5 shows that the stiffness and strength ratios are extremely variable across the 11 mixture studies. To avoid inflating the needed mixtures performance unnecessarily, the given ratios were obtained by averaging shear and axial stiffness measurements and averaging both loading times for the IDT testing. In addition, the most variable mixtures were excluded from the analysis and the two mixture types, dense-graded and SMA, were separated. Due to large variation

in test data, the ratio between plant mixtures and cores was set for 1.0 for both mixtures types, although the average ratio was 0.94 and individual ratios were 0.85 and 1.05.

Table 76. Adjustment Factors for Different Sample Sets.

Parameter	Mix Type	Plant Mixtures	Raw Materials	2 nd Cores
G* (E*)	DGM	1.3	1.8	1.6
	SMA	1.3	1.5	1.3
IDT S _t	DGM	1.0	1.6	1.1
	SMA	1.0	1.0	0.8

8.6.2 Adjustments for Climate

The effective temperature for the study mixtures (see Appendix 3) varies from 38.6 to 42.5°C. The lab testing was conducted at 40°C to simplify the testing. Table 77 gives the adjustment factors for the effective temperatures for North and South in Indiana.

Table 77. Climate (Geographical Location) Adjustment Factor.

T _{eff} °C	Multiplier
37	0.8
40	1.0
43	1.2

8.6.3 Adjustments for Traffic Speed

The laboratory testing was conducted at 10 Hz loading, which was then tied to the threshold criteria for the interstate traffic with >70 km/h traffic speed. The criterion for the slow moving traffic is estimated from the LTPP binder selection concept as follows.

For slow moving traffic the high-temperature PG grade is pumped up one or two binder grades depending on traffic speed and traffic volume. Based on the I74 forensic

data the difference between failure and survival was one PG grade. This turned out to be a safety factor of 1.8 (normalized to 7.5% air voids content) for the mixture shear stiffness. Then it can be hypothesized that the same relative binder stiffness ratio is needed to overcome the damage introduced by the slower traffic speed. Then, for slow moving traffic the adjustment factor is 1.8.

8.6.4 Air Void Content Adjustments

It was hypothesized that the relative density of the in-situ pavement to the design air voids must be taken in account when assessing stiffness or strength of in-place mixtures. Then, for mixtures with high in-situ air voids content the relative stiffness requirement would be less than the mixture with lower air voids content. Similarly, a mixture with low in-place air voids content must relatively have higher stiffness compared to the mixtures with target density.

The air voids content adjustment factors, given in Table 78, were calculated using the air voids normalization process described in Appendix 3.

Table 78. Air Voids (Density) Adjustment Factor.

V_a (%)	$ G^* $	IDT S_t
0	1.82	3.30
2	1.52	2.40
4	1.29	1.74
6	1.11	1.27
7.5	1.00	1.00
8	0.97	0.92
10	0.85	0.67
12	0.75	0.49

It is important to recognize that although the mixture with low as-constructed density is adequate while compared relatively to a mixture with higher density, this does not mean that the mixture in general is in the acceptable as-placed density because mixture with low density is more vulnerable of moisture damage and age hardening. In addition, the WesTrak failure of coarse mixtures with low in-place

density and high stiffness due to high binder adsorption suggests that there is a possibility of mix instability due to increased dilatation under heavy accelerated traffic loading. Due to the nature of highway traffic with rest periods and age hardening, this type of fast failure is unlikely but possible.

8.6.5 $|G^*|$ Criteria Conversion to $|E^*|$

As Chapter 4 shows, $|E^*|$ and $|G^*|$ are not interchangeable and one cannot be obtained from another by using theoretical formulations. Since $|E^*|$ and $|G^*|$ of mixtures are correlated by stiffness of the asphalt binder, this provides a possibility to predict $|G^*|_{\text{mix}}$ based on $|E^*|_{\text{mix}}$ or vice versa. Then by solving $|G^*|$ of binder with the Hirsch model (Christensen et. al, 2004) for the $|E^*|_{\text{mix}}$, the mixture shear stiffness can be estimated by using the solved binder stiffness in the Hirsch model. The whole process can be conveniently accomplished using Solver function provided by the Microsoft Excel software.

A simplified method is to use Equation (7) with the $|G^*|$ values from Table 74 or Table 75. The coefficients are obtained from correlating the $|E^*|$ and $|G^*|$ measurements for the plant mixtures through the power model functional form. Table 79 gives the converted $|E^*|$ values.

$$|E^*| = \left(\frac{|G^*|}{0.0249} \right)^{\frac{1}{1.2817}} \quad (7)$$

Table 79. $|E^*|$ Base Criteria for “Young” Field Cores (normalized to 7.5% air voids).

Design ESALs (10 ⁶)	Unconfined $ E^* $ 40°C&10Hz	
	Threshold	Rule of Thumb
<3	723	723
3-30	1,113	889
>30	1,626	1,325

9 CRITERIA VERIFICATION

The criteria developed in the previous chapter was verified by comparing criteria values to the known performance of I70 SPS 9A study mixtures (Shah, 2004). This study provides an excellent opportunity for criteria verification because of the similar climatic and traffic conditions compared to the I74 forensic study. Also, the 1992 SPS 9 study by Anderson et al. (2001) provides some mixture performance data for verification.

In addition, pavement rutting was predicted using Christensen et al. (2005) new rutting model based on mixture resistivity. The predicted rutting was then compared to measured field rutting and measured mixture stiffness and strength properties.

9.1 Verification of Mixture Aging

The objective of the Indiana SPS9-A study was to verify the selected Superpave binder PG grades for Indiana, Shah (2004). Six trial pavements were constructed in 1998 on Interstate I70 east of Indianapolis. Material testing included, among others, binder testing and SST shear $|G^*|$ mixture testing. Pavements were monitored for 4 years and rut depths were measured using a dipstick. The study is described in more detail in Appendix 12.

A major part of the study investigated binder aging and its contribution to the mixture properties. Mixture investigation included SST $|G^*|$ testing of gyratory compacted pills made of asphalt plant loose mixture. The completed mixture was long-term oven (LOA) aged before SST testing. Because SST testing did not include short-term oven aged (STOA) or plant loose mixture completed as is, a Hirsch predictive stiffness model was used to estimate the early age mixture stiffness. The binder stiffness needed in the Hirsch model was obtained from the recovered binder after 2 weeks and 48 months of field aging. Table 80 shows LOA aged mixture stiffness was extremely high compared to the predicted mixture stiffness after 2 weeks or 48 months of field aging.

Table 80. Shear Stiffness of I70 Mixtures.

Mix No.	Binder Type	G* 40°C & 10Hz (MPa)				
		Predicted ¹ 2 wks. aged	Predicted ¹ 48 mo. Aged	Measured LOA aged	Ratio LOA/2wks	Ratio LOA/48mo.
S1	AC-20	447	811	1020	2.3	1.3
S2	PG64-28	190	239	1897	10.0	7.9
S3	PG58-28	188	285	379	2.0	1.3
S4	PG64-28 w/ RAP	328	541	2202	6.7	4.1
S5	PG70-28	402	857	1057	2.6	1.2
S6	PG64-16	381	984	1515	4.0	1.5

1) From recovered binder

Figure 56 and Figure 57 compare the I70 mixtures to the study mixtures. It is not possible to make direct comparisons because the I70 mixtures were long-term oven aged before testing, as discussed above. However, it is possible to use predicted mixture stiffness in the comparisons. Figure 56 shows the average of all I70 mixtures and the average of all dense-graded mixtures, which had binder comparable to the binders used in the I70 mixtures. The LOA aged mixtures were excessively stiff compared to the study mixtures or I70 mixtures with 4 years of in-service aging. The predicted I70 stiffness values are in the ballpark of the plant mixtures and 1st cores for the 11 study mixtures. This gives confidence that the measured mixture stiffness values are in the right ballpark.

Figure 57 compares all study plant loose mixtures to the I70 LOA aged mixtures. For some reason, an S3 mixture with PG58-28 binder is very soft relative to the other LOA aged mixtures being in the same ballpark as the plant aged study mixtures. The recovered binder testing does not verify this test result because after 4 years the PG64-28 and PG28-28 had similar binder viscosities indicating similar mixture stiffness values, as Figure 58 shows. The average stiffness increase between 2 weeks and 4 year aged pavement is 1.6 while for PG70-28 the increase was nearly 2.5 times.

Figure 56. Comparison of Average Stiffness of I70 and Study Mixtures.

Figure 57. Comparison of I70 and Study Mixtures.

The odd behavior of mixture S2 and PG64-28 binder is studied more closely in Figure 59, which compares the specific gravity and binder viscosity changes during the 48 months as a function of binder absorption. There seems to be a correlation of specific gravity increase and increase of mixture viscosity as binder absorption

decreases. This suggests that the loss of volatiles stiffens the binder and the binder absorption of the aggregate is reduced due to the increased viscosity. This comparison shows that the binder absorption and aging during production process has high influences for mixture stiffness.

Figure 58. Mixture Aging for In-place aged I70 mixtures.

Figure 59. Binder Absorption vs. Specific Gravity and Viscosity.

9.2 Stiffness Criteria Verification

The developed criteria were verified with the known performance of I70 mixtures. Because the I70 study did not include IDT strength testing at intermediate or high temperatures, only stiffness criteria could be verified. Figure 60 compares the developed criteria to the measured stiffness of LOA aged mixtures and predicted stiffness obtained from the Hirsch predictive model using 2 weeks and 48 months aged binder stiffness values. The predicted mixtures stiffness refers to 7.5% air voids content. The criteria values used were:

- LEA Criteria = 1310 MPa at $T_{eff} = 40^{\circ}\text{C}$ and for 100 million ESALs
- Base Rule of Thumb Criteria = 250 MPa
- Base Threshold Criteria 325 MPa for > 30 million ESALs

Figure 60. I70 Mixtures Compared to Stiffness Performance Criteria at 40°C .

Table 81 summarizes the number of mixtures that failed the criteria. Two mixtures with 2 weeks aged binder failed the threshold and rule of thumb criteria. These mixtures were S2 and S3 with PG64-28 and PG58-28 binders. Mixture S2 with PG64-28 binder failed the rule of thumb criteria even when 48 months aged binder

was used in the mixture stiffness prediction. None of the LOA aged mixtures failed the rule of thumb or threshold criteria. All “young” mixtures failed the LEA criteria, which suggest that the global aging model used in the LEA analysis is underestimating the mixture short-term aging. This analysis suggests that the both the base threshold and the base rule of thumb criteria are too stringent for the Indiana asphalt mixtures when tested at 40°C with 10 Hz.

Table 81. Number of Failing Mixtures.

Mixture Aging	LEA Criteria	Threshold	Rule of Thumb
	$ G^* $	$ G^* $	$ G^* $
2 weeks	6	2	2
48 months	6	2	1
LOA	3	0	0

9.3 Comparison of Rutting Performance

Both I70 and I74 developed rutting during the service-life of the pavement, which allows comparison of the actual in-situ performance relative to the criteria limits. Figure 61 shows the I70 mixtures relative to the criteria and amount of measured rutting. The amount of rutting is not that much, 3 to 6 mm, and therefore the correlation of stiffness to rutting is not that great for 18 months of pavement performance. The direction is correct but because the differences between mixtures are so small, the actual correlation coefficient stays low. The LOA aged mixtures show no correlation, which indicates that LOA aging may not give a good indication of mixture performance.

Figure 62 compares I70 and I74 rutting and mixture stiffness at 40°C&10Hz. Both the rule of thumb and threshold criteria seem to be too stringent for the I70 mixtures, as discussed above. The surviving mixture stiffness at I74 seems to match the I70 mixture stiffness values. This suggests that the predicted mixture stiffness values are in the right ballpark and the base rule of thumb criteria will differentiate good and poor performance if the measured values are far enough from the limit. However, if the mixture stiffness is at the limit or just above or below, there is more

uncertainty of the mixture performance. Then, it can be concluded that if the mixture meets the threshold criteria it will not rut excessively during its early life.

Figure 61. Rutting vs. Mixture Stiffness at 40°C&10Hz.

Figure 63 compares the same mixtures at 54.4°C&5Hz using converted criteria given in Table 54 and Table 58. Now the rule of thumb criteria are matching very well with the I70 predicted mixture stiffness and measured I74 failure. However, the stiffness difference of the failed and survived mixtures is only 1.4 to 2.2, which is within the raw material and binder absorption variation of asphalt mixture production. Then, large testing variation will mask the measured difference and there is higher probability of accepting poorly performing mixture.

Figure 62. Comparison of I74 Forensic Stiffness Data at 40°C&10Hz.

Figure 63. Comparison of I74 Forensic Stiffness Data at 54.4°C.

Table 82 compares mixture properties for S2, S3 of I70 mixtures and EB and WB lanes of I74 mixtures. In addition, the table gives SPS9 study mixture placed on I65 near Lafayette in 1992 (Anderson et al., 2001). The estimated design traffic was 55 million ESALs with 35% trucks. Measured rut depth was 5 mm after 6 years of traffic loading. The measured shear stiffness at 39°C with 10 Hz frequency was 371 MPa obtained from gyratory compacted plant mixture compacted to approximately 7% air voids content. If the plant mixture stiffness is converted to “young” pavement core stiffness by dividing 1.3 and test temperature is adjusted to 40°C by decreasing stiffness approx. 7% more, the “adjusted” stiffness would be 276 MPa. This mixture would be adequate based on the rule of thumb criteria but it would fail based on the threshold criteria. The binder used in the mixture was AC-20, which was graded as PG70-16 based on the recovered binder obtained from the SGC completed field mixture pills.

P_{ba} is binder absorption by weight, and V_{ba} is by volume, V_{beff} is effective binder content, S_a is surface area, and FM_{300} is fineness modulus. All mixtures had aggregate blast furnace slag aggregate. The table shows that mixtures have very similar properties. The rutted mixture I74 EB had the lowest binder absorption by volume being 3.3% and it also had the lowest measured mixture shear $|G^*|$ stiffness of 115 MPa at 40°C&10Hz compared to the other mixtures.

The table indicates that the binder absorption is an important property that may deviate failure from survival at a given binder grade. The table also shows that the failure is within a very narrow range of mixture properties. The estimated design traffic for I74 was 30 million ESALs, and for I70 it was 92 million ESALs. The pavement temperature at 50 mm deep was estimated as 46.0°C for I74 and 46.2°C for I70.

Table 82. Comparison of Mixture Properties.

Property/Road	I-65	1-70 S2	1-70 S3	1-74 EB	1-74 WB
Rut depth, mm	5	5.2	4.9	12-15	0-3
Time, years	6	4	4	1	1
ESALs 10 ⁶	55	92	92	30	30
PG Grade	70-16	64-28	58-28	64-28	70-28 ¹
N	100	126	126	109	109
VMA	18.6	14.4	13.9	15.5	14.5
P _{ba} (%)	—	1.8	2.6	1.5	1.8
V _{ba} (%)	—	4.2	6.0	3.3	4.1
V _{beff} (%)	12.4	11.0	9.7	11.3	10.0
Sa (m ² /kg)	4.52	5.33	5.33	4.69	4.22
Dust/P _{beff}	—	1.04	1.21	1.1	1.07
FM ₃₀₀	—	24.3	24.3	21.3	19.0
Sa/V _{beff}	0.37	0.48	0.55	0.42	0.42
G* (MPa)	276	174	188 ²	115	209

(1) Recovered binder after RTFO criteria, original grade PG64-28

(2) Predicted from 18 months aged binder

9.4 Rutting Model Based on Resistivity

Christensen and Bonaquist (2005) developed a new model for estimating rutting based on compaction level, volumetric composition and binder properties for the National Cooperative Highway Research Program (NCHRP) Project 9-25. The proposed model was calibrated using rutting data from MN/Road, WesTrack and NCAT Test Track test data. A concept of mixture resistivity was introduced to estimate the given aggregate structure resistance to the asphalt binder flow, which is expressed in Eq. (8):

$$P = \frac{|\eta^*| S_a^2 G_b^2}{4.9 VMA^3} \quad (8)$$

where:

P = resistivity, s/nm (seconds per nano-meter)

(capital letter for Greek Rho)

|\eta^*| = binder dynamic viscosity, Pa-s

S_a = aggregate surface area, m^2/kg

G_{sb} = aggregate bulk specific gravity

VMA = Design Voids in the Mineral Aggregate, % by volume

Rut depth was thought to be proportional to the cubic root of traffic loading in ESALs (Christensen, 2005), so the actual rutting rates for all verification sites were calculated based on such a relationship. The best model used resistivity, design gyration number N_{design} , and relative density as predictors to predict rutting depth. The R^2 of the regression model is 89.1%, adjusted for degree of freedom, for which goodness-of-fit is subjectively thought to be good. The regression model is given in Eq. (9), and the rut depth is calculated using Equation (10):

$$RR = 224P^{-1.08}N^{-0.650}(RD)^{-18.6} \quad (9)$$

$$Rut\ Depth = RR \times 0.1 \times ESALs^{1/3} \quad (10)$$

where:

RR = Rutting rate, mm/m thickness/ESALs^{1/3}

P = resistivity, s/nm (seconds per nano-meter)

N = N_{design} or design Marshall hammer blows

RD = relative density, as-constructed density/as-designed density

ESALs = Equivalent Single Axle Load

The viscosity used in the equations is the age-hardened viscosity, and the appropriate aging time is given by the following equation.

$$t_{aging} = \left[\frac{t_{total}^{1/3}}{2} \right]^3 = \frac{t_{total}}{8} \quad (11)$$

9.4.1 Rutting Predictions for I74 (Forensic)

Rutting of I74 mixtures was predicted using Christensen's resistivity model. Input data for the model given in Table 83 and Table 84 shows the predictions. Binder viscosity η was estimated at a temperature of 50 mm deep using recovered binder test data with aged time of 1.5 months. The same binder stiffness was used in the 20-year rutting predictions. The VMA and VTM (voids in total mix or air voids) are obtained from the QC data.

Predictions are quite good and they indicate a problem in the EB lane, which rutted substantially. It is important to note that the prediction is extremely sensitive for the binder stiffness data and if that is incorrect, the predictions will be incorrect.

Table 83. Input data for I74 Mixtures (Forensic).

174 Mixture	VMA %	Sa kg/m ²	G _b	N _{des}	50mm ¹ °C	η^2 Pa-s	P s/nm
SURF EB	15.5	4.69	2.596	109	46.0	1,232	10.0
SURF WB	14.6	4.22	2.596	109	46.0	4,109	32.3
INT EB	14.0	4.74	2.615	109	46.0	1,455	16.6
INT WB	13.4	4.59	2.615	109	46.0	6,575	80.3

1) Pavement temperature at 50 mm deep

1) Recovered binder

Table 84. Predicted and Measured Rutting for I74.

174 Mixture	Design VTM (%)	In-place VTM (%)	Design ESALs (10 ⁶)	Predicted Rut Depth (mm)		Meas'd Rut Depth (mm)
				1Y	20Y	1Y
Surf EB	4.2	4.4	30	10.5	28.5	12
Surf WB	4.2	8.4	30	6.5	17.8	3
INT EB	4	5.5	30	7.8	21.2	3
INT WB	3.9	7.5	30	2.2	5.9	0
Total EB				9.2	24.9	15
Total WB				4.4	11.8	3

9.4.2 Rutting Predictions for I70

Table 85 gives the input data for the rutting predictions for the I70 mixtures. Predictions were done for three cases: rutting after 1.5 and 4 years of traffic and rutting for the 20-year design life. The binder viscosity was estimated at 2.25 months and 6 months and for the 20-year prediction, 2.25 month binder viscosity was used.

Table 86 gives the predicted rutting values, which seem to be in the right ballpark for S2 and S3, but for all other mixtures the model under-predicts rutting.

Table 85. Input data for I70 Mixtures.

170 Mixes	VMA %	Sa kg/m ²	G _b	N _{des}	50mm °C	η^1 Pa-s	P ¹ s/nm	η^2 Pa-s	P ² s/nm
S1	14.8	4.86	2.536	126	46.2	11,006	105.4	18,097	173.2
S2	14.4	5.33	2.573	126	46.2	2,829	36.4	3,181	40.9
S3	13.9	5.33	2.573	126	46.2	2,421	34.5	3,113	44.4
S4	13.5	5.45	2.577	126	46.2	6,337	103.5	9,659	157.8
S5	15.0	4.98	2.573	126	46.2	15,203	151.0	32,732	325.1
S6	14.5	5.45	2.573	126	46.2	10,780	141.8	29,324	385.7

1) 2.25 mo. aged binder, 2) 6 months aged binder

Table 86. Predicted and Measured Rutting for I70.

170 Mixes	Design VTM (%)	In-place VTM (%)	Design ESALs (10 ⁶)	Predicted Rut Depth (mm)			Measured Rut Depth (mm)	
				1.5Y	4Y	20Y	1.5Y	4Y
S1	7.6	7.7	92	1.2	1.0	1.7	3.0	3.2
S2	3	4.3	92	4.9	6.0	6.8	3.2	5.2
S3	4.3	6.5	92	6.2	6.5	8.6	4.2	4.9
S4	4.4	7	92	2.0	1.8	2.8	3.9	4.9
S5	5.1	7.9	92	1.4	0.9	2.0	3.0	4.4
S6	5.5	9	92	1.8	0.8	2.4	2.5	4.2

9.4.3 Rutting Predictions for Study Mixtures

Table 87 gives input data for rutting predictions for the study mixtures. Predictions were done using measured binder data that was aged using Mirza and Witczak (1995) global aging model to obtain binder stiffness at 3 months aging time. In addition, binder stiffness back calculated from the 1st cores was used. Predictions were done for two-year traffic loading and for 20-year design life

Table 87. Input data for Study Mixtures.

Road No.	Design VMA %	Sa kg/m ²	G _b	N _{des}	50mm °C	η ¹ Pa-s	P s/nm	η ² Pa-s	P s/nm
SR15	15.9	4.72	2.682	75	46.4	8,360	68.0	1,988	16.2
US24	16.1	4.76	2.607	100	46.5	9,717	73.2	2,867	21.6
SR161	15.3	4.31	2.627	75	48.3	9,513	69.5	3,647	26.6
SR56	15.4	3.82	2.830	100	48.3	17,985	117.5	6,043	39.5
US30	15.9	4.17	2.620	125	46.5	26,374	159.8	5,270	31.9
SR66	15.1	4.82	2.620	100	49.1	18,052	170.6	5,151	48.7
SR135	15.4	4.75	2.583	100	49.1	15,808	133.0	5,459	45.9
US31	17.8	5.95	3.314	100	47.5	29,832	419.8	3,745	52.7
I74	17.7	6.36	3.476	100	47.0	44,928	808.1	11,160	200.7
SR64	17.9	5.3	3.275	100	49.5	30,938	331.7	8,845	94.8
I65	17.8	6.05	3.313	100	48.9	32,659	474.8	7,027	102.2

1) Estimated 3 mo. aged binder, 2) back-calculated from plant mixtures

Table 88 gives the predicted and measured rut depths. The rutting predicted using 3 months aged binder stiffness is slightly on the high side for soft binders but in the ballpark. The rutting predicted using back-calculated binder viscosity is over-predicted significantly.

Table 88. Predicted and Measured Rutting for Study Mixtures.

Road No.	Design VTM (%)	In-place VTM (%)	Design ESALs (10 ⁶)	Predicted Rut Depth (mm)			Meas'd Rut Depth (mm)
				2Y ¹	2Y ²	20Y ¹	
SR15	4	11.2	2.4	3.8	17.7	8.1	0.0
US24	4	9.5	9.6	3.2	12.0	6.9	0.6
SR161	4	10.8	0.5	2.0	5.6	4.3	0.0
SR56	4	9.6	7.5	1.8	5.9	3.9	0.0
US30	4	6.5	50.2	1.1	6.4	2.4	0.9
SR66	4	12.6	6.8	2.2	8.5	4.7	1.3
SR135	4	8.6	20	0.8	2.6	1.8	1.6
US31	4	8.3	21.4	0.5	4.7	1.1	0.0
I74	4	7.9	33	0.3	1.2	0.6	0.0
SR64	4	4.7	21.1	0.3	1.2	0.7	0.0
I65	4	8.9	155	1.0	5.0	2.1	0.0

(1) 3 months aged binder viscosity

(2) back-calculated binder viscosity

9.5 Minimum Resistivity

By using Eq. (9) and Eq. (10) it is possible to back-calculate the needed resistivity and, thus, establish a resistivity criteria for different traffic levels by assuming maximum rut depth of 12.5 mm (0.5 in) and the cubic root relationship between rut depth and ESALs. A general form of resistivity criteria are expressed by Eq. (11):

$$P_{\min} = \left[\frac{12.5}{0.1x(ESALs)^{\frac{1}{3}}} \times \frac{1}{224} \times N^{0.65} \times (RD)^{18.6} \right]^{-\frac{1}{1.08}} \quad (12)$$

The calculated resistivity criteria using Eq. (11) are given in Table 89, for the design air voids content of 4% and for as-constructed air voids content of 7.5%.

Table 89. Minimum Resistivity Based on 12.5 mm (0.5 in) Rut Depth.

Minimum Resistivity (s/nm)				
ESALs (10^6)				
<3	3 -10	10 - 30	30 - 50	50 -100
24.2	29.5	41.3	42.3	52.4

Table 90 summarizes the calculated resistivity values for different binder viscosity values. Based on Table 89, the resistivity value needed for I70 is 52.4 s/nm and for I74 42.3 s/nm and that the rutting does not exceed 12.5 mm after 20 years of traffic loading. Only I74 WB mix with 6 months aged binder meets the resistivity criteria.

Table 91 gives the resistivity values for the study mixtures at various binder stiffness values. Resistivity values are much higher than that of the I70 and I74 values for the aged binders. This suggests that the Global aging model overestimates the aging of binders.

Relative increase in resistivity was much higher for S3 mix with PG58-28 binder than that of the other binders. This indicates more rapid binder aging and increased rutting resistance. For the study mixtures, the relative binder aging is faster in the softer binders when compared to the stiffer binders.

Table 90. Comparison of Resistivity for I74 and I70.

ESALs (10^6)	Road	PG Grade	P (s/nm) ²			
			Tank	1.5 mo.	2.25 mo.	6 mo.
92	I70 S2	PG64-28	21.9	35.6	36.4	40.9
92	I70 S3	PG58-28	10.9	33.2	34.5	44.4
30	I74 EB	PG64-28	8.1	10.0	11.0	15.9
30	I74 WB	PG70-28 ¹	25.6	32.3	35.7	52.6

1) After RTFO criteria, original Grade PG64-28

2) Recovered binder

Table 91. Comparison of Resistivity of Study Mixtures.

ESALs (10 ⁶)	Road	PG Grade	P (s/nm) ²				
			Tank	1.5 mo.	2.25 mo.	6 mo.	Plant
2.4	SR15	PG64-22	18.0	61.4	64.7	68.0	16.2
9.6	US24	PG64-22	19.4	66.5	69.8	73.2	21.6
0.5	SR161	PG64-22	18.7	63.4	66.5	69.5	26.6
7.5	SR56	PG70-22	32.1	109.6	113.5	117.5	39.5
50.2	US30	PG70-22	43.8	150.4	155.1	159.8	31.9
6.8	SR66	PG70-22	46.9	159.5	165.1	170.6	48.7
20	SR135	PG70-22	38.4	127.1	130.0	133.0	45.9
21.4	US31	PG76-22	122.4	408.5	414.2	419.8	52.7
33	I74	PG76-22	236.6	794.9	801.6	808.1	200.7
21.1	SR64	PG76-22	97.4	324.2	327.9	331.7	94.8
155	I65	PG76-22	139.3	464.4	469.6	474.8	102.2

1) After RTFO criteria, original grade PG64-28

2) Meas'd tank binder aged using Global aging model.

This analysis shows that the resistivity and the mixture rutting resistance is driven by the binder stiffness. It is evident that using tank binder in the rutting predictions may lead to erroneous results, and the age hardened binder viscosity must be used. A simple analysis is to use RTFO aged binder stiffness from the Superpave binder testing at a grade temperature in the resistivity calculations. Table 92 gives the calculated resistivity values for tank and RTFO aged binder stiffness obtained from DSR testing at 64°C temperature. The binder viscosity η was obtained by using Eq. (13) where ω is angular velocity or loading time. For Superpave binder testing, ω is 10 rad/s.

$$\eta = \frac{G^* / \sin \delta}{\omega} \quad (13)$$

By knowing the field performance of the mixtures, it seems that resistivity $P > 2$ s/nm with RTFO aged binder @ 64°C is enough for a good mixture performance, while $P < 2$ s/nm is vulnerable to failure. However, the failure depends on how the binder ages in the field compared to the RTFO aging. The grading temperature of

64°C represents the average pavement temperature at 25 mm deep for adjusted traffic using 98% reliability.

The table also show the resistivity calculated for 1992 SPS 9 study I65 mixture using recovered binder data. It is quite interesting that the binder stiffness is twice the stiffness of I74 survived binder stiffness. The original grade was PG70-16 while the I74 original grade was PG64-22 being almost PG70-22. Then, the binder stiffness variation and especially the variation in the binder aging properties may be the key factor between good and poor performing mixtures when the mixture is designed with a low factor of safety against failure.

Table 92. Comparison of Mixture Properties for I74 and I70.

Mix		Tank		RTROT		Recovered	
	°C	G*/sinδ (kPa)	P (s/nm)	G*/sinδ (kPa)	P (s/nm)	G*/sinδ (kPa)	P (s/nm)
I65	64	—	—	—	—	8.71	8.1
I70 S2	64	1.73	2.2	2.34	3.0	—	—
I70 S3	64	0.53	0.8	1.07	1.5	—	—
I74 EB	64	1.21	1.0	2.24	1.8	2.13	1.7
I74 WB	64	1.61	1.3	2.92	2.3	4.34	3.4

10 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

10.1 Summary of Findings and Conclusions

This research investigated the possibility of using asphalt mixture stiffness and strength as performance indicators to verify rutting resistance of marginal mixtures. The major objective was to develop a performance criteria or threshold value to be used as a quality control/quality assurance tool in the hot mix asphalt construction projects. The research concentrated on investigating asphalt surface mixtures used by Indiana Department of Transportation.

The stiffness of hot mix asphalt is dependent on the amount and type of raw materials and additives. In addition, the compaction effort and type of compaction equipment affect the mixture stiffness and strength characteristics. Therefore, three sets of samples were included in the laboratory testing as follows:

- Laboratory fabricated and compacted mixture using raw materials,
- Asphalt plant loose mixture samples compacted in the laboratory, and
- Pavement cores:
 - 1st set of cores obtained right after pavement construction, and
 - 2nd set of cores obtained approximately one year later.

Laboratory testing comprised of mixture stiffness and strength testing to find the best performance parameters and test conditions for criteria development. Mixture stiffness was measured using SST shear tester to obtain $|G^*|$ and IPC servo-hydraulic testing machine was used to measure dynamic modulus $|E^*|$. Testing was conducted at 40°C and 54.4°C temperatures. The strength of the mixture was studied by measuring triaxial shear strength at 54.4°C using 7.5 and 50 mm/min ram loading rate, and indirect (IDT) tensile strength at 35°C using 0.06 and 0.36 mm/min ram loading rate.

A novel method of using horizontally stacked specimens to measure dynamic modulus of thin pavement cores was developed as an alternative for the SST testing of pavement cores. However, it gave significantly higher stiffness values compared to the

SST shear testing. Therefore, until these deviations can be explained satisfactorily, this method is not recommended to be used in the HMA production.

Evaluation of Test Conditions and Parameters

Stiffness Testing:

Ranking of mixtures changed significantly when tested at 40 and 54.4°C temperatures. Identified possible reasons are change in relative binder stiffness from low to high temperature; increased damage accumulation in the specimen at higher test temperature; and/or different mixture behavior due to increased aggregate influence at higher test temperatures.

Confinement in the axial stiffness $|E^*|$ testing reduced the binder influence, which relatively increased the stiffness of the softer mixtures. Furthermore, the use of stiffer binders in the SMA mixtures seems to compensate the need of using confinement to verify the mixture performance.

The theoretical relationship between axial and shear stiffness is not valid, which means that $|E^*|$ and $|G^*|$ are not interchangeable, and one cannot be obtained from another by using theoretical formulations. Since $|E^*|$ and $|G^*|$ of mixtures are correlated by stiffness of the asphalt binder, this provides a possibility to predict $|G^*|_{\text{mix}}$ based on $|E^*|_{\text{mix}}$ or vice versa using the Hirsch stiffness prediction model.

The average testing variation ranged from 12 to 19%. Testing variation increased with increasing testing temperature and decreasing frequency.

Strength Testing:

For IDT strength testing there was a good correlation between the slower and faster loading rates (R^2 0.84-0.90). In addition, a theoretical relationship exists between the IDT strength and triaxial shear strength. Therefore, for practical purposes, the IDT tensile strength can be used as a surrogate test to replace the triaxial strength test. If no information is available for the friction angle, a ratio of 1.80 of the cohesion to IDT tensile strength is a good approximation.

The average testing variation for the IDT strength was less than 10%, which is less than the testing variation for stiffness testing.

Selection of Parameters and Test Conditions

Overall, the dynamic modulus $|E^*|$ and SST shear modulus $|G^*|$ did not rank mixtures in the same way; although the rankings at 40°C temperature were quite similar, at 54.4°C rankings deviated substantially. The plant mixtures were ranked in a more similar way by axial and shear stiffness, while field cores gave the most different rankings. Unfortunately, at this point it is not possible to confirm if this reflects the real material behavior or if it is an artifact of the differences between the test methods. However, all test methods and test conditions were generally able to identify the softest and the stiffest mixtures in a similar manner measured from the raw material or plant mixtures, which is illustrated in Figure 64. However, this is not the case for the field cores rankings, as Figure 65 shows.

The stiffness difference between the stiffest and softest mixtures ranged from 2.2 to 4.0. The strength difference between the strongest and weakest mixtures ranged from 1.8 to 6.4. This refers to mixture composition of steel slag, blast furnace slag, and dolomite aggregate combined with three binder grades ranging from PG64-22 to PG76-22.

The average mixture stiffness and strength ratios within a high temperature binder PG grade ranged from 1.4 to 2.4. This suggests that by changing aggregate type and gradation, and binder content, it is possible to double the stiffness of mixture without changing the binder grade. For field cores, the strength difference was up to 4.4, reflecting differences in the roller compaction during construction. The $|E^*|$ gave indicated higher stiffness ratios compared to the $|G^*|$ and IDT testing.

The largest difference between mixtures was measured from field cores taken approximately one week after construction followed by the gyratory compacted asphalt plant mixtures.

Figure 64. Plant Mixture Rankings (Normalized).

Figure 65. 1st Coring Mixture Rankings (Normalized).

Many engineering materials possess different strength and stiffness properties. Literature suggests that for asphalt mixtures the correlation of stiffness and strength is mix dependent. The dense-graded mixtures had a good to excellent correlation between stiffness and strength for raw material and plant mixtures, while the correlation for the SMA mixtures was negative, meaning that the stiffer mixtures were weaker than the softer mixtures. The confined axial stiffness $|E^*|$ did not correlate to strength properties.

Field cores had poor correlation between the stiffness and strength properties. This suggests that the construction compaction produces samples which have mechanical properties significantly different compared to the properties obtained from the gyratory compacted specimens. Then, the internal structure of cores is dependent on the types of rollers used and compaction temperature and it differs from the structure produced by the gyratory compactor.

Based on the research findings, both stiffness and strength are needed to predict mixture performance. Although mixture response obtained at lower and higher testing temperature deviates, at this point the lower testing temperature is recommended mainly to minimize the testing variation. Both temperatures are identifying the softer and stiffer mixtures, which is a requirement for a good performance parameter. The need to use a higher testing temperature may arise from the need to use different low temperature binder grades, which may mask the influence of the binder stiffness at the lower testing temperature, especially for mixture with modified binders.

The plant mixtures and field cores obtained one week after construction seemed to follow the binder high-temperature PG grading in identifying the softest/weakest and stiffest/strongest mixtures. The stiffness test results from the one-year old cores indicated that mixtures had aged heavily, and there was a significant change in the relative rankings; mixtures with softer binders had aged more than the mixtures with stiffer binders. The higher amount of binder in the SMA mixtures with stiffer original binder grade may have slowed down their aging while the stiffness of some dense graded mixtures with softer binder doubled.

The IDT strength test results indicated some strength decay in the second cores for the SMA mixtures with stiffer binders. This may indicate a shift of ductile to brittle material behavior. The relatively higher stiffness and loss of strength may contribute to vulnerability to cracking in the SMA mixtures.

The SMA mixtures without fiber had very different properties compared to mixtures with fiber. It had the lowest stiffness of the SMA mixtures and after 2 years of field aging, it had the lowest stiffness among all mixtures. While the strength seemed to decrease for the SMA mixture with fiber, the US31 mixture strength increased 14%. However, because only one mixture was tested, these findings should not be considered significant at this point.

These results verify that asphalt mixtures are at the most vulnerable stage for rutting right after construction, as expected. However, the possibility of failure depends on the time of construction, i.e., Spring or Fall and variation of construction materials, which affects the initial aging of mixtures and the amount of traffic. The fact that the plant mixture behavior deviates from the behavior of cores, and cores are giving the largest difference between studied mixtures, suggests that the performance assessment must be conducted from field cores instead of using gyratory compacted plant mixtures. Because, at this point, the composite specimen technique did not turn out to be a reliable way of obtaining mixture stiffness, the SST shear testing is recommended to be used to measure the stiffness of field cores.

Although dense graded mixtures had a good correlation between stiffness and strength for the plant mixtures, the stiffness and strength correlated for field cores was very poor. These findings suggest that both stiffness and strength must be used for performance assessment of asphalt mixtures.

Micro-texture Collapse

Micro-texture collapse was studied using confined dynamic creep testing. If low axial stiffness $|E^*|$ and large dilatation potential (ϵ_p ratio) are used as the criteria, the most vulnerable mixture is US24 followed by SRS161. Both mixtures had the

softest binder, and SR161 had 34% flat particles and small FA_F Bailey Method ratio, which indicates a low amount of fines in the fine portion of aggregate gradation. US24 is the coarsest of all dense graded mixture having the lowest percent passing 4.75 mm sieve and lowest Bailey Method CA ratio. If high densification (cumulative ϵ_p) and low stiffness are used as criteria, the most vulnerable mixture is US24. These results, however, may be confounded by the confinement used in the testing and it is expected that different results may be obtained if testing is repeated using unconfined testing.

Criteria Development

The performance criteria for stiffness and strength were developed by using I74 forensic study data as a baseline, and criteria verification was done using findings from I70 SPS9A study. For stiffness criteria, two different criteria from the literature were compared against the measured mixture performance. These criteria were stiffness criteria developed by Pellinen using layered elastic analysis and rule of thumb criteria from Asphalt Institute. The IDT strength criteria was developed using IDT strength criteria developed by Christensen et al. as the baseline.

Indiana mixtures seem to comply well with the Asphalt Institute rule of thumb stiffness criteria, when it is applied for cores with 7.5% air voids content; while the criteria based on layered elastic analysis was too stringent for the roads with heavier traffic loading. The IDT criteria derived from the Christensen et al. criteria seems to comply well with the Indiana mixtures; while the I74 forensic study criteria seems to be too stringent.

It was evident from the I74 failure data that a factor of safety is needed when applying performance criteria to avoid failure. The needed factor of safety may be as high as 3 for the asphalt mixtures in Indiana. However, there is a delicate balance in preventing failure and at the same time rejecting good performing mixtures or accepting fair mixtures. However, at this point there is not enough data to analyze adequately the risks of acceptance or rejection. It can be speculated that the factor of

safety 2.2 may be adequate when tight quality control is exercised during HMA construction.

10.2 Recommendations for Performance Testing

To assess the “true” mixture performance, it is recommended that QA testing be conducted on “young” field cores, and that the asphalt plant gyratory pills be used mainly for production QC testing. The reason for this recommendation is that the roller compacted in-place mixtures have different mechanical properties compared to the gyratory-compacted mixtures. Then, the evaluation of the as-placed properties will eliminate variables that otherwise would confound the performance assessment, thereby improving the accuracy of predictions. In addition, the use of field cores provides an important link between the current volumetric acceptance specification and the possible future performance related specification for Indiana.

The production QC testing can be performed either using standard SGC-compacted pills after conformance to the mix design target density is verified or by compacting separate pills to cut and /or core test specimens at VTM of 7.5%. If test specimens are obtained from the standard QC pills, the density of the specimens must be measured before testing to obtain the adjustment factor. The use of standard production specimens and the density adjustment factor will speed up the testing by simplifying the sample preparation process.

If an engineer wants to predict mixture performance in the mix design stage, the mix design trial samples can be used for testing, similar to the plant SGC pills discussed above, to speed up the sample preparation and testing.

A novel method of using horizontally-stacked composite specimens to measure the dynamic modulus of thin pavement cores was developed as an alternative for the SST shear testing of pavement cores. However, this method gave significantly higher stiffness values compared to the SST testing, and, therefore, until these deviations can be explained satisfactorily, this method is not recommended to be used in HMA production, which leaves the SST shear testing the only available method to test cores.

For plant SGC pills and mix design specimens, both the SST shear testing and the dynamic modulus testing are available, although it is not recommended to use confinement in the dynamic modulus testing for the Indiana SMA mixtures. The use of a stiffer binder in these mixtures seems to compensate for the need to use confinement to verify the mixture performance.

The recommended performance parameters are SST shear stiffness $|G^*|$ tested at 40°C with 10 Hz frequency and indirect tensile strength St tested at 35°C applying 0.06 mm/min ram rate loading. Both methods need cylindrical test specimens of 150 mm in diameter and 38 to 50 mm in height.

Error! Reference source not found. gives two alternatives for the base criteria for $|G^*|$ and St ; a base criteria I derived from I-74 forensic study, and base criteria II derived from literature, which provide a factor of safety of 2.8 and 2.2, respectively, against failure for the heavy traffic. The factor of safety is defined as the ratio of criteria stiffness to failure stiffness of mixture obtained from I-74 forensic study. At this point, the factor of safety for strength is not known.

Table 93. Base Criteria for Stiffness and Strength

Design ESALs	Base Threshold		Base Rule of Thumb	
	$ G^* $ (MPa)	IDT (kPa)	$ G^* $ (MPa)	IDT (kPa)
(10 ⁶)	40°C& 10Hz	35°C& 0.06 mm/min	40°C& 10Hz	35°C &0.06 mm/min
<10	114	32	114	32
10-30	200	55	150	49
>30	325	90	250	67

The base criteria I may increase thermal and top-down cracking by facilitating stiffer mixtures, while the base criteria II provide better protection against cracking but introduces a higher possibility for rutting failure. The right balance for the Indiana mixtures must be obtained through the performance monitoring of constructed pavements.

10.3 Recommendations for Performance Criteria

Table 94 and Table 95 give the combined criteria for the base criteria II, joining all the elements discussed in the criteria development. The mixture meets the criteria if it meets the stiffness and the strength criteria; then, the likelihood of failure increases if either the stiffness or strength criteria are not met. The criteria adjustment factors introduced are designated as follows: factor for effective temperature is F_{TE} , factor for density /air voids is F_{DE} , factor for sample types is F_{ST} , and factor for traffic speed adjustment is F_{SP} . When assessing mixture performance, the following items must be considered:

- Stiff and weak mixtures are believed to be prone to low temperature and top-down fatigue cracking.
- In some rare cases, very stiff and weak mixtures with low in-place density may develop rapid rutting failure due to gross instability. This instability is caused by mixture dilatation with very little or no traffic-related pavement densification.
- Weak mixtures with high as-constructed density are prone to moisture damage.
- The rutting rate for soft and strong mixtures is higher than for stiffer and stronger mixtures.

Due to the large variation in the measured mixtures stiffness and strength values obtained for the laboratory-fabricated raw material samples and the field cores approximately one year old, it is recommended that the given adjustment ratios be considered tentative. Therefore, it is recommended that verification of the adjustment coefficients be conducted at the beginning of large construction projects to establish the applicable coefficients relative to the given base criteria applicable for “young” field cores. The density adjustment factor F_{DE} is considered more reliable for the gyratory compacted pills, from which it has been derived, than for the roller compacted cores. However, in a similar manner a verification of the F_{DE} can be performed at the beginning of HMA production.

Table 94. Proposed Minimum Stiffness Criteria.

Standard Speed (>70 km/h) ¹ & T _{eff} = 40°C ² (Central Indiana)				
ESALs (10 ⁶)	SST G* 40°C&10Hz	Sample/Specimen Type	% G _{mm} (VTM%)	F _{DE} ³
Base Criteria (MPa)		Field Cores (< 1 month in service)	100 / 0	1.82
< 3	115		98 / 2	1.52
			96 / 4	1.29
			94 / 6	1.11
3 - 30	150		92.5 / 7.5	1.00
			92 / 8	0.97
			90 / 10	0.85
> 30	250		88 / 12	0.75
		F _{ST} for SGC Pills ^{4,5} (asphalt plant mixture)	DGM F _{ST} = 1.3 SMA F _{ST} = 1.3	
		F _{ST} for MD SGC Pills ^{4,5} (from raw materials)	DGM F _{ST} = 1.8 SMA F _{ST} = 1.5	
		F _{ST} for Field Cores ⁴ (>1 year in service)	DGM F _{ST} = 1.6 SMA F _{ST} = 1.3	

Table 95. Proposed Minimum IDT Strength Criteria.

Standard Speed (>70 km/h) ¹ & T _{eff} = 40°C ² (Central Indiana)				
ESALs (10 ⁶)	IDT St 35°C&0.06 mm/min	Field Cores (< 1 month in service)	% G _{mm} (VTM%)	F _{DE} ³
Base Criteria (kPa)			100 / 0	3.30
< 3	32		98 / 2	2.40
			96 / 4	1.74
			94 / 6	1.27
3 - 30	49		92.5 / 7.5	1.00
			92 / 8	0.92
			90 / 10	0.67
> 30	67		88 / 12	0.49
			F _{ST} for SGC Pills ^{4,5} (asphalt plant mixture)	
		F _{ST} for MD SGC Pills ^{4,5} (from raw materials)	DGM F _{ST} = 1.6 SMA F _{ST} = 1.0	
		F _{ST} for Field Cores ⁴ (>1 year in service)	DGM F _{ST} = 1.1 SMA F _{ST} = 0.8	

- 1) For slow moving traffic, multiply |G*| & S_t with F_{SP}=1.8
- 2) For T_{eff} = 37°C multiply |G*| & S_t with F_{TE} = 0.8, and for T_{eff} = 43°C with F_{TE} = 1.2
- 3) Adjust |G*| & S_t by multiplying with density factor F_{DE}
- 4) Multiply |G*| & S_t with adjustment factor F_{ST} provided for each mix type.
- 5) Measure test specimen's density/air voids content prior to testing to obtain correction factor F_{DE}

10.4 Recommendations for Further Study

To further refine the proposed criteria and verify the response ratios the following studies are recommended:

- Monitor rutting development of the study pavements for several years and take cores to evaluate the mixture aging. Measure SST $|G^*|$ and IDT strength and binder stiffness from extracted binder.
- Take cores from the Indiana I70 SPS 9A study pavements and measure SST $|G^*|$ and IDT strength. Compare test results to I74 forensic study mixtures and these study mixtures to verify the recommended criteria.
- Verify the air void reduction factors for cores by studying core strength at different densities by applying varying roller passes.
- Repeat the macro-texture collapse study by using unconfined dynamic creep testing.

10.5 Recommendations for Implementation

It is recommended that the implementation of the developed criteria will be done by conducting pilot-paving projects. An important task is to verify the response ratios between field cores and SGC compacted plant specimens. It is recommended to use field cores for quality assurance and establish relationship of cores and SGC pills for quality control purposes. The following tasks are recommended to be conducted, at minimum, in the pilot projects:

- Use contractor QC cores or State QA cores to assess the performance of mixture using criteria given in Table 94 and Table 95.
- Use contractor QC SGC completed pills for State QA pills to assess the produced mixture and verify response ratios.

- Take plant loose mix and compact it to 0, 4, 7.5% and 10% air voids content to verify the density adjustment factors.
- It is recommended to use both stiffness and strength testing in the pilot projects to verify adjustment factors for both performance parameters.
- When more data is available as to how Indiana mixtures are behaving relative to the proposed criteria, perhaps only one parameter stiffness or strength can be used for quality control purposes; but if mixture is on the borderline both parameters must be checked in the QA quality assessment.

There are different ways the developed criteria can be used in road construction. Below are some examples of using the criteria in the various construction stages in paving contracts.

EXAMPLE 1

State pavement engineer wants to verify that the in-place mixture stiffness meets the requirements and obtains field cores that have 90% and 95% density. Mixture is placed on the road with design traffic of 1 million ESALs.

The stiffness criteria for 90% density core is $115 \text{ MPa} \times 0.85 = 97 \text{ MPa}$.

The stiffness criteria for the 95% density core is $115 \text{ MPa} \times [(1.29 - 1.11)/(6-4) + 1.11] = 138 \text{ MPa}$.

EXAMPLE 2

The contractor wants to set up a QC operation to control the production of the mixture and wants to use the SST testing. The gyratory compacted pill of dense-graded plant mixture has 2.8% air voids content. The air voids content of the SST specimen (150x50mm) cut from the pill is 2%. Mixture is placed on the road with 15 million design ESALs.

Two adjustment factors are needed to obtain the required stiffness: the field core vs. plant SGC compaction adjustment factor, which is 1.3 for the dense graded mixture, and the air voids adjustment factor, which is 1.52.

The stiffness criteria is $150 \text{ MPa} \times 1.3 \times 1.52 = 342 \text{ MPa}$

EXAMPLE 3

To predict the mix performance, contractor wants to test the stiffness and strength of the designed SMA mixture before construction begins. The SST and IDT strength testing are performed on specimens cut from the SGC trial samples obtained from the mix design. The air voids content of the acceptable SGC pills is 4.0% at N_{des} and the air voids content of the cut specimens is 3%. The design traffic is 50 million ESALs and mixture will be place to South of Indiana where the T_{eff} is 43° C.

Three adjustment factors are needed to obtain the required stiffness and strength: the field core vs. raw material adjustment factor, which is 1.5 for the SMA mixture for stiffness and 1.0 for the IDT strength, and the air voids adjustment factors, which are 1.41 and 2.07 for the stiffness and strength criteria, respectively. In addition, adjustment factor for a hotter climate is 1.2.

The stiffness criteria is $250 \text{ MPa} \times 1.5 \times [(1.52-1.29)/(4-2) + 1.29] \times 1.2 = 634 \text{ MPa}$.

The strength criteria is $67 \text{ kPa} \times 1.0 \times [(2.40-1.74)/(4-2) + 1.74] \times 1.2 = 166 \text{ kPa}$.

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1 MIX DESIGNS

The dense graded mixtures were designed according to the Superpave volumetric mix design method following AASHTO MP1, MP2, and PP28 specifications and standard practices, effective in 2002, and the SMA mixtures were designed using the AASHTO MP1, MP2, MP8, and PP41 specifications and standard practices. All asphalt mixtures were designed by asphalt contractors in each paving project.

The following sections give the Job Mix Formula (JMF) mix design information obtained from the Mix Design Reports provided by the contractors. In addition, some relevant specification requirements are given. For better understanding of the relationship of measured mechanic properties and mixture composition, some additional mixture properties calculated from JMF data have also been included.

1.1.1 Dense Graded Mixtures

1.1.1.1 Raw Material Selection

AASHTO MP1 specifies the requirements of the performance-graded (PG) binders and AASHTO MP2 provides the procedures of asphalt binder grade selection. The main steps included in the binder selection are: (1) Determination of the mean and deviation of the yearly 7-day-average maximum pavement temperature measured at 20 mm below the pavement surface, and the mean and the standard deviation of the yearly 1-day-minimum pavement temperature measured at the pavement surface at the site of the paving project. These temperatures can be obtained using the LTPPBind software; (2) Selection of the design reliability for the high and low pavement temperature; and (3) Determination of the minimum required PG binder grade that satisfies the temperature and reliability requirements. Adjustments to the high temperature grade of the binder may be needed according to Table 1 of MP2 (2004) depending on the traffic speed and/or the design ESALs.

Table 1-1 shows the 7-day maximum and 1-day minimum air temperatures obtained from weather stations near the paving projects using the LTPPBind software. The actual 20 year design traffic in Equivalent Single Axle Loads (ESAL) was obtained from the contractor's Mix Design Reports. Table 1-2 shows the determined PG grade adjusted for traffic level and traffic speed. Adjustment was done assuming traffic speed of >70 km/h for all roads. The unadjusted binder grades were determined using 98% reliability. Pavement temperatures were calculated at 25 mm deep in the pavement for rutting, and at the surface for the low temperature cracking. The actual low temperature binder grade of -22 used in Indiana gives 92 to 98% reliability against low temperature cracking. Table 1-2 gives two approaches to adjust the binder grade; the first one was obtained from the LTPPBind software with the SHRP approach, and the second one was obtained from the current AASHTO MP2, Table 1 procedure.

Table 1-1. Air Temperatures from LTPPBind. (DGM).

Road No.	Weather Station	7-day High Air Temp. (°C)	Std. Dev.	1-day Low Air Temp. (°C)	Std. Dev.
SR15	Goshen College	32.6	1.6	-23.8	3.4
US24	Fort Wayne	32.6	1.7	-23.4	3.4
SR161	Saint Meinrad	33.9	1.5	-22.2	5.0
SR56	Madison Sewage Plant	34.1	2.1	-19.5	4.8
US30	Fort Wayne	32.6	1.7	-23.4	3.4
SR66	Evansville Reg Ap	34.8	1.5	-20.1	4.8
SR135	Salem	33.8	1.7	-22.5	4.9

Table 1-2. Binder PG Grade Selection (DGM).

Road No.	Actual Design ESALs (10 ⁶)	LTPPBind			MP2, Table 1		PG Used
		PG ¹	GE ² SHRP	Adj. PG	GE ² MP2	Adj. PG	
SR15	2.4	58-28	-	58-28	-	58-28	64-22
US24	9.6	58-28	1	64-28	-	58-28	64-22
SR161	0.5	58-28	-	58-28	-	58-28	64-22
SR56	7.5	58-22	1	64-22	-	58-22	70-22
US30	50.2	58-28	1	64-28	1	64-28	70-22
SR66	6.8	58-22	1	64-22	-	58-22	70-22
SR135	20	58-28	1	64-28	1	64-28	70-22

(1) Selected reliability was 98%.

(2) Grade Equivalent for Standard Traffic (Speed > 70 km/h)

The individual aggregate stockpiles and their proportioning are summarized in Table 1-3. Table 1-4 summarizes the source properties for the coarse and fine aggregates obtained from the INDOT aggregate quality control database (Communication with Ron Walker, INDOT). The INDOT database included aggregate specific gravity, water absorption, Los Angeles Abrasion (AASHTO T96), Freeze and Thaw requirements using AASHTO T103 test Method A for fine aggregate, Freeze and Thaw Beam Expansion Test (ITM 210) for coarse aggregate, Brine Freeze and Thaw Method (ITM 209), and Sodium Sulfate Soundness (AASHTO T104). Table 1-5 gives the INDOT criteria for the fine and coarse aggregates. The Blast Furnace slag had a very high LA Abrasion value, while the steel slag had good resistance to abrasion. In addition, the blast-furnace slag had a high water absorption and poor freeze and thaw susceptibility.

Appendix 14 gives detailed descriptions of the raw materials used and their sources. The information includes gradations for each individual aggregate stockpile, proportioning, manufacturer, bulk specific gravity and water absorption of aggregates, and binder PG grade and manufacturer.

Table 1-3. Aggregate Proportioning (DGM).

Aggregate Type and Size ¹		Proportioning (%)						
		SR15	US24	SR161	SR56	US30	SR66	SR135
Coarse	# 11 Dolomite	46	29	38			10	
	# 11 PRA				16			
	# 11 Limestone							27
	# 11 Sand Stone						33	
	# 11 Steel Slag				26			
	# 11 Blast Furnace Slag		29			34		27
	# 12	12		27		34	23	
	# 14 Stone Sand				18			
Fine	# 10			12				
	# 12 F					6.5		
	# 23 Natural Sand	17	20	23			14	10
	# 24 Manufactured Sand	23	20		40	12.5	20	34
	# 24 Natural Sand					11.5		
	Baghouse Fines	2	2			1.5		2

(1) Indiana Department of Transportation Specifications, 1999.

Table 1-4. Aggregate Source Properties (DGM).

Aggregate	Water Absorption (%)	Weight Loss (%)			
		LA Abrasion	Brine ¹	SS ²	FT ³
# 11 Dolomite	1.5	30.4	1.3	—	—
# 11 PRA	1.2	22.8	—	—	1.7
# 11 Limestone	2.2	27.9	29.3	—	—
# 11 Sand Stone	1.9	20.6	—	—	3.1
# 11 Blast Furnace Slag	4.8	40.0	0.7	—	—
# 11 Steel Slag	2.5	19.1	4.5	—	—
# 23 Natural Sand	1.3-1.4	—	3.0-5.0	—	—
# 24 Manufactured Sand	0.8-5.0	—	1.8-7.7	4.5	—

(1) ITM 209, (2) AASHTO T 104, (3) ITM 210

Table 1-5. Aggregate Source Properties (DGM).

Test Method	Property	Criteria	
		Fine ¹	Coarse ¹
AASHTO T96	LA Abrasion	—	40 ²
ITM 209	Brine Freeze and Thaw	12	30
AASHTO T104	Sodium Sulfate Soundness	10	12
AASHTO T103 A	Freeze and Thaw	10	—
ITM 210	Freeze and Thaw Beam Expansion	—	0.06
AASHTO T85	Water Absorption	—	5 ²

(1) Max (%)

(2) Does not apply to Blast Furnace Slag

1.1.1.2 Dense Graded Mixture Designs

The detailed mix design procedures are specified in the AASHTO PP28, including design of aggregate structure, selection of design binder content, and evaluation of moisture susceptibility. The gyratory compaction criteria depend on the design traffic level, as shown in Table 1-6.

The aggregate gradation information of the seven dense graded mixtures included in the study, as well as the corresponding design requirements, are given in Table 1-7 to Table 1-8. Figure 1-1 to Figure 1-2 show the mixture gradations grouped by the binder type used in the mixture. These figures also show the Maximum Density Line (MDL). All gradations are below the “restricted zone” and some gradations seem to have an “S-curved” shape. Figure 1 shows that US24 mixture has

the coarsest gradation of the three low volume traffic mixtures, and Figure 2 shows that SR56 mix has the coarsest fine portion of the mixtures for medium traffic roads.

Table 1-6. Design ESALs and Superpave Gyratory Compaction Efforts. (2005)

Design ESALs (10 ⁶)	Compaction Parameters		
	N _{initial}	N _{design}	N _{max}
< 0.3	6	50	75
0.3 to < 3	7	75	115
3 to < 30	8	100	160
≥ 30	9	125	205

To quantify the gradation deviations, Table 1-9 shows the distance of 2.36 and 4.75 mm sieves from the MDL in terms of percent passing. Based on calculations and visual inspection of gradation curves, SR161, SR56, US30, and SR66 have the S-shape gradation. Table 1-9 also shows the average gradation of each aggregate structure by averaging the percent passing of sieves 0.075, 0.6, 2.36, and 9.5 mm. Based on the average gradation, SR56 has the coarsest aggregate gradation of all dense graded mixtures. Table 1-9 also shows a fineness modulus FM₃₀₀, which was calculated by summing the percent passing the 75, 150, and 300 µm sieves.

Table 1-7. Gradations and Specific Gravity of Combined Aggregate (DGM).

Sieve Size (mm)	% Passing by weight						
	9.5 mm Nominal Maximum Aggregate Size						
	SR15	US24	SR161	SR56	US30	SR66	SR135
12.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0
9.5	93.5	91.1	96.0	90.3	93.2	95.0	91.7
4.75	59.0	52.2	63.0	65.3	61.4	60.3	55.9
2.36	41.0	37.5	36.8	35.9	34.7	35.4	41.3
1.18	30.0	26.8	26.7	21.3	23.6	25.9	28.2
0.6	21.0	19.8	21.1	12.9	15.0	19.6	18.5
0.3	11.0	10.6	8.8	7.5	8.3	9.9	10.0
0.15	6.4	6.2	4.2	4.6	4.8	6.3	5.9
0.075	3.6	4.3	3.8	3.4	4.0	4.6	4.4
Blend G _{sb}	2.682	2.607	2.627	2.830	2.620	2.620	2.583

Table 1-8. Gradation Criteria of Combined Aggregate (DGM).

Sieve Size (mm)	% Passing			
	Aggregate Gradation Control Points		Boundaries of Aggregate Restricted Zone ¹	
	Minimum	Maximum	Minimum	Maximum
12.5	100	—	—	—
9.5	90	100	—	—
4.75	—	90	—	—
2.36	32	67	47.2	47.2
1.18	—	—	31.6	37.6
0.6	—	—	23.5	27.5
0.3	—	—	18.7	18.7
0.15	—	—	—	—
0.075	2	10	—	—

(1) This zone cannot be passed through by the gradation line.

Figure 1-1. Gradation of dense graded mixtures with PG64-22 binder.

Figure 1-2. Gradation of dense graded mixtures with PG70-22 binder.

Table 1-9. Average Gradations, Fineness, and Distance from the MDL ¹ (DGM).

Road No.	Average Gradation (% passing)	Fineness Modulus FM ₃₀₀	Distance from MDL 2.36 mm (% passing)	Distance from MDL 4.75 mm (% passing)	S-shape Gradation
SR15	39.8	21.0	6.2	5.7	No
US24	38.2	21.1	9.7	12.5	No
SR161	39.4	16.8	10.4	1.7	Yes
SR56	35.6	15.5	11.3	-0.6	Yes
US30	36.7	17.1	12.5	3.3	Yes
SR66	38.7	20.8	11.8	4.4	Yes
SR135	39.0	20.3	5.9	8.8	No

(1) Maximum Density Line

Aggregate blend gradations were also compared by calculating ratios of the control sieves following the Bailey method of gradation evaluation (Vavrik et. al., 2001). The three Bailey method ratios are Coarse Aggregate Ratio (CA Ratio), Fine Aggregate-Coarse portion ratio (FA_C), and Fine Aggregate-Fine portion ratio (FA_F), shown in Table 1-10. Definitions of the ratios are given in Appendix 3 and all ratios are based on the volume percent of aggregate gradations. Vavrik et al. also developed

a model to predict the VMA of mixture from the aggregate ratios using Eq. (25) given in Appendix 3.

In addition, Voids in Coarse Aggregate (VCA_{mix}) in the compacted sample were predicted using Eq. (26) given in Appendix 3. This equation was developed for compacting mixtures with 75 SGC gyrations. Based on Vavrik et. al., “the Voids in Coarse aggregate in mixture (VCA_{mix}) are determined from the coarse portion of aggregate blend as a property that identifies the existence of a coarse aggregate skeleton with stone-on-stone contact. A coarse aggregate skeleton is developed when the VCA_{mix} in the mixture is equal or less than the VCA of the loose unit weight configuration.”

Table 1-10. The Bailey Method Gradation Ratios (DGM).

Road No.	CA Ratio	FA_C Ratio	FA_F Ratio	Predicted VMA (%)	Predicted VCA_{mix} (%)
SR15	0.44	0.51	0.30	17.1	46.5
US24	0.30	0.53	0.31	15.2	43.7
SR161	0.69	0.56	0.14	20.6	86.3
SR56	0.95	0.36	0.35	28.1	74.4
US30	0.67	0.43	0.32	21.6	58.1
SR66	0.62	0.55	0.32	19.7	42.8
SR135	0.32	0.45	0.32	16.2	50.1

Combined aggregate requirements are specified by MP2 including size requirements (nominal maximum size, gradation control points and restricted zones), coarse aggregate angularity requirements (fractured faces), fine aggregate angularity requirements (uncompacted void content), sand equivalent requirements, and flat-and elongated particle requirements. Table 1-11 to Table 1-12 give the consensus aggregate properties measured from aggregate blend and reported by the contractor. Specification criteria are dependent on the design traffic level, as Table 1-11 shows.

Flat and elongated particles were not listed in Mix Design reports so measurements were done at Purdue asphalt laboratory, in addition to measuring the uncompacted voids in coarse aggregate according to AASHTO TP56-03 test method. Table 1-12 shows test results obtained from the blended aggregate. The specification

calls for Flat and Elongated particles, but as Table 1-12 shows, aggregate blends did not have any elongated particles but only flat particles. SR161 had the highest percentage of flat particles, 34.1% among the dense-graded mixtures. It also had the lowest uncompacted voids in the fine aggregate. SR56 had the lowest uncompacted voids in coarse aggregate while US30 had the highest.

Table 1-11. Combined Aggregate Consensus Properties (DGM).

Road No.	Actual Design ESALs (10 ⁶)	Uncompacted Voids in Fine Aggregate (%)		Coarse Aggregate Angularity (%)		Sand Equivalency, (%)	
		Actual	Criteria ¹	Actual	Criteria ¹	Actual	Criteria ¹
SR15	2.4	47.0	40	100	75/-	96.9	40
US24	9.6	46.1	45	100	85/80 ²	96.0	45
SR161	0.5	42.0	40	100	75/-	83.0	40
SR56	7.5	46.3	45	100	85/80	79.0	45
US30	50.2	45.2	45	100	100/100	88.1	50
SR66	6.8	45.6	45	100	85/80	89.9	45
SR135	20	45.0	45	100	95/90	87.3	45

(1) Minimum value

(2) 85/80 denotes that 85 percent of the coarse aggregate has one fractured face and 80 percent has two or more fractured faces.

Table 1-12. Aggregate properties Measured at Purdue (DGM).

Road No.	Actual Design ESALs (10 ⁶)	Flat and Elongated Particles				Uncompacted Voids in Coarse Aggregate (%)
		Flat (%)	Elongated (%)	Flat & Elongated (%)	Spec Criteria ¹	
SR15	2.4	9.9	0	0	10	50.5
US24	9.6	9.2	0	0	10	50.9
SR161	0.5	34.1	0	0	10	50.2
SR56	7.5	5.0	0	0	10	47.9
US30	50.2	4.9	0	0	10	53.3
SR66	6.8	7.7	0	0	10	50.1
SR135	20	6.6	0	0	10	52.1

(1) Maximum value

Table 1-13 shows the actual design ESALs of the paving projects, and SGC gyrations required by PP28, as well as the relative density at the initial and maximum gyrations. Table 1-14 presents the JMF Superpave mix design properties, and the corresponding criteria are given in Table 1-15. In addition, Table 1-16 gives the binder absorption in the mixture by weight and volume, and the effective and total binder by volume. SR56 had the highest binder absorption of 1.7% by weight while US24 had the lowest, being 0.36%. This is quite an unexpected result since US24 had Blast-Furnace slag and manufactured sand, both having high water absorption, see Table 1-3 and Table 1-4.

Furthermore, Table 1-16 gives the aggregate surface area (SA) and binder film thickness calculated using the surface area and weight of the effective binder. The surface area and binder film thickness calculations are shown in Appendix 3. SR56 had the lowest surface area and a high film thickness, while SR66 had the highest surface area and lowest film thickness.

Table 1-13. Superpave Gyratory Compaction Effort (DGM).

Road No.	Mix Location	PG	Actual Design ESALs (10^6)	Specification Design ESALs (10^6)	Actual Compaction					
					No. of Gyrations			% G_{mm}		
					N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}
SR15	North	64-22	2.4	0.3 to < 3	7	75	115	87.4	96.0	96.9
US24	North	64-22	9.6	3 to < 30	8	100	160	—	96.0	96.8
SR161	South	64-22	0.5	0.3 to < 3	7	75	115	—	96.0	97.4
SR56	South	70-22	7.5	3 to < 30	8	100	160	84.3	96.0	—
US30	North	70-22	50.2	> 30	9	125	205	—	96.0	97.1
SR66	South	70-22	6.8	3 to < 30	8	100	160	—	96.0	97.2
SR135	South	70-22	20	3 to < 30	8	100	160	85.9	96.0	97.5

Table 1-14. JMF Mixture Design Properties (DGM).

Road No.	NMAS ¹ (mm)	P _b ²	P _b ³	Volumetrics @ N _{des} (%)			Specific Gravity			Dust/ P _{beff}	Tensile Strength Ratio ⁴ (%)
				V _a	VMA	VFA	G _{se}	G _{mm}	G _{mb} @ N _{des}		
SR15	9.5	5.6	5.3	4.0	15.9	74.9	2.718	2.488	2.388	0.8	94.7
US24	9.5	5.7	5.4	4.0	16.1	75.0	2.631	2.417	2.319	1.0	97.0
SR161	9.5	5.4	5.2	4.0	15.3	73.9	2.668	2.457	2.356	0.8	90.0
SR56	9.5	6.2	6.0	4.0	15.4	73.8	2.969	2.659	2.551	1.1	81.2
US30	9.5	6.2	6.0	4.0	15.9	74.8	2.702	2.455	2.357	0.8	97.7
SR66	9.5	5.7	5.5	4.0	15.1	73.6	2.682	2.457	2.359	1.2	90.5
SR135	9.5	6.4	6.0	4.0	15.4	73.9	2.680	2.431	2.334	0.9	89.5

(1) NMAS = Nominal Maximum Aggregate Size

(2) Binder recovery using ignition (by weight-%)

(3) Binder recovery using extraction (by weight-%)

(4) Tested from specimens with 7.0 ± 1.0 percent air voids.

Table 1-15. Superpave HMA Mixture Design Requirements (DGM).

Road No.	Design ESALs (10 ⁶)	Relative Density (% G _{mm})			Volumetrics @ N _{des} (%)			Dust/ P _{beff}	Tensile Strength Ratio (%)
		N _{ini}	N _{des}	N _{max}	V _a	VMA	VFA		
SR15	0.3 to < 3	≤ 90.5	96.0	≤ 98.0	4.0	≥ 15.0	65-78	0.6-1.2	80.0
US24	3 to < 10	≤ 89.0			4.0		65-75		
SR161	0.3 to < 3	≤ 90.5			4.0		65-78		
SR56	3 to < 10	≤ 89.0			4.0		65-75		
US30	≥ 30				4.0		65-75		
SR66	3 to < 10				4.0		65-75		
SR135	10 to < 30				4.0		65-75		

Table 1-16. Binder Absorption¹, Surface Area, and Binder Film Thickness (DGM).

Road No.	P _{ba} (%)	P _{beff} (%)	V _{ba} (%)	V _{beff} (%)	V _{b-total} (%)	Surface area SA (m ² /kg)	Film thickness (μm)
SR15	0.51	5.09	1.2	11.9	13.0	4.72	11.2
US24	0.36	5.34	0.8	12.1	12.8	4.76	11.6
SR161	0.60	4.80	1.3	11.1	12.4	4.31	11.5
SR56	1.71	4.49	4.0	11.4	15.4	3.82	12.5
US30	1.19	5.01	2.6	11.6	14.2	4.17	12.6
SR66	0.90	4.80	1.9	11.1	13.1	4.82	10.4
SR135	1.45	4.95	3.1	11.4	14.5	4.75	11.0

(1) All values calculated from “binder recovery using ignition” values. P by weight, V by volume.

1.1.2 Stone Matrix Asphalt Mixtures

1.1.2.1 Raw Material Selection and Requirements

The asphalt binder is selected based on the AASHTO MP1 and AASHTO MP2 in a similar manner as described for the dense-graded mixtures. Table 1-17 shows the air temperatures obtained from the LTPPBind software similar to the dense-graded mixtures. The actual traffic for US31 and I65 was obtained from the contractor's Mix Design Reports, except I74 design traffic was obtained from Materials and Test's listing of Volumetric and SMA projects in 2002 (communication with Joe Gundersen, INDOT Materials and Test, 2002). For SR64 the Mix Design Report gave design traffic of 12.1 million ESALs, but the project listing gave 21.1 million ESALs. Table 1-18 shows the PG grade selection at 98% reliability level and grade adjustments due to the amount of traffic and speed of loading obtained from the LTPPBind software using SHRP approach and AASHTO MP2 (2004), Table 1.

Table 1-17. Air Temperatures from LTPPBind. (SMA).

Road No.	Weather Station	7-day High Air Temp. (°C)	Std. Dev.	1-day Low Air Temp. (°C)	Std. Dev.
US31	Plymouth Power Subst	33.8	2.1	-24.3	3.6
I74	Indianapolis se side	32.8	1.5	-21.6	3.8
SR64	Albion	35.4	1.6	-20.6	4.1
I65	Scottsburg	34.8	1.9	-21.4	5.2

Table 1-18. Binder PG Grade Selection (SMA).

Road No.	Actual Design ESALs (10 ⁶)	LTPPBind			MP2, Table 1		PG Used
		PG ¹	GE ² SHRP	Adj. PG	GE ² MP2	Adj. PG	
US31	21.4	58-28	1	64-28	1	64-28	76-22
I74	33	58-22	2	70-22	1	64-28	76-22
SR64	21.1	58-22	1	64-22	1	64-28	76-22
I65	155	58-28	2	70-28	1	64-22	76-22

(1) Selected reliability is 98%.

(2) Grade Equivalent for Standard Traffic (Speed > 70 km/h)

The individual aggregate types and proportioning are summarized in Table 1-19. Both coarse and fine aggregates shall be 100 percent crushed and conform to the quality requirements specified in Table 1-20 and Table 1-21, respectively. Table 1-22 gives the measured aggregate properties obtained from the INDOT aggregate database (Communication with Ron Walker) and Table 1-23 gives aggregate shape properties measured by Purdue from the blended aggregates. Table 1-24 gives the amount and type of fiber and mineral filler used in the SMA mixtures. AASHTO MP8 gives the requirements for the mineral filler and stabilizing additives (not shown in the report).

Appendix 14 gives the details of the raw materials used including gradations for each individual aggregate stockpile, proportioning, manufacturer, bulk specific gravity and water absorption of aggregates, and binder grade and manufacturer.

Table 1-19. Aggregate Sources (SMA).

Aggregate Type and Size ¹		Proportion (%)			
		US31	I74	SR64	I65
Coarse	1/2 " Slag (# 11)				62
	3/8 " Slag				26
	# 11 Steel Slag	80	80	87	
Fine	# 24 Manufactured Sand	12		8	
	# 24 Stone Sand		10		12
	# 16 Mineral Filler	8	10	5	

(1) Indiana Department of Transportation Specifications, 1999.

Table 1-20. Coarse Aggregate Quality Requirements (SMA).

Test		Method	Minimum	Maximum
Los Angeles (L.A.) Abrasion (% Loss)		T96	—	30 ¹
Flat and Elongated ² (%)	3 to 1	D4791	—	20
	5 to 1		—	5
Absorption (%)		T85	—	2.0
Soundness (5 Cycles) (%)	Sodium Sulfate	T104	—	15
	Magnesium Sulfate		—	20
Crushed Content (%)	One Face	D5821	100	—
	Two Faces		90	—

(1) Aggregates with higher L.A. Abrasion values have been used successfully to produce SMA. However, when the L.A. Abrasion exceeds 30, excessive breakdown may occur in the laboratory compaction process or during in-place compaction.

(2) Flat and elongated criteria apply to the design aggregate blend.

Table 1-21. Fine Aggregate Quality Requirements (SMA).

Test		Method	Minimum	Maximum
Soundness (5 Cycles) (%)	Sodium Sulfate	T104	—	15
	Magnesium Sulfate		—	20
Liquid Limit (%)		T89	—	25
Plasticity Index (%)		T90	Non-plastic	

Table 1-22. Aggregate Source Properties (SMA).

Aggregate	Water Absorption (%)	Weight Loss (%)			
		LA Abrasion	Brine ¹	SS ²	FT ³
½ " Slag (# 11)	1.3	—	—	—	10.5
3/8 " Slag	5.1	—	—	—	9.0
# 11 Steel Slag	1.2-1.4	11.3-16.3	0.4-2.0	—	—
# 24 Manufactured Sand	1.8-2.1	—	5.1-7.2	—	—
# 24 Stone Sand	1.5-2.0	—	—	—	2.3-7.0
# 16 Mineral Filler	—	—	—	—	—

(1) ITM 209, (2) AASHTO T 104, (3) ITM 210

Table 1-23. Aggregate Blend Properties (SMA).

Road No.	Uncompacted Voids in		Coarse Aggreg. Angularity ¹ (%)	Sand Equiv. ¹ (%)	Flat (%)		Elongated (%)		Flat and Elongated (%)	
	Coarse Aggregate (%)	Fine Aggreg. ¹ (%)			3:1	5:1	3:1	5:1	3:1	5:1
US31	50.2	47.0	100	96.9	8.2	0.8	0	0	0	0
I74	54.7	—	—	—	2.9	5.0	0	0	0	0
SR64	49.4	—	100	—	5.3	2.8	0	0	0	0
I65	50.7	—	—	—	6.4	0.1	0	0	0	0

(1) From JMF Report

Table 1-24. Fiber and Mineral Filler (SMA).

Road No.	Fiber Type	Amount by weight of mix (%)	Filler Type	Amount by Weight of Aggregate (%)
US31	—	0.00		8.0
I74	Cellulose	0.10		10.0
SR64	Cellulose	0.20		5.0
I65	Cellulose	0.25		0.0

1.1.2.2 SMA Mixture Designs

The detailed mix design procedures and specifications are specified in AASHTO PP41 and MP8, including the design of aggregate structure, selection of design binder content, determination of voids in coarse aggregate (VCA), determination of the draindown sensitivity, and evaluation of moisture susceptibility of the mixture. Mixtures are compacted with the Superpave gyratory compactor (SGC) applying 100 gyrations to achieve 4.0 percent design air voids content for all traffic levels. Table 1-25 shows the actual ESALs in each paving project.

The performance of the SMA mixture is evaluated based on the stone-on-stone contact of coarse aggregate skeleton. The stone fraction is the portion of the total aggregate blend retaining in the 2.36 mm sieve for 9.5 mm nominal size aggregate mixture. The stone-on-stone condition in the SMA mixture is obtained when the voids in coarse aggregate (VCA) of the compacted mixture is less than the VCA of the coarse aggregate in the dry rodded test.

Table 1-25. ESALs in Each Paving Project (SMA).

Road No.	Mix Location	PG	Actual Design ESALs (10^6)	Specification ESALs (10^6)	Compaction
					No of Gyrations ¹
					N _{des}
US31	North	76-22	21.4 ²	all	100
I74	North	76-22	33 ³	all	100
SR64	South	76-22	12.1 ² / 21.1 ³	all	100
I65	South	76-22	155 ²	all	100

(1) If aggregate LA Abrasion is > 30% desirable SGC gyrations are 75

(2) Reported in JMF

(3) Reported by INDOT Materials and Test

Table 1-26 gives the gradation requirements of the aggregate blend, which are based on volumetric quantities, while the gradation is specified based on percent passing by weight for the dense graded mixtures. Table 1-27 and Figure 1-3 show the gradations of combined aggregate for the four SMA mixtures. According to Table 1-26 and Table 1-27, all four SMA mixtures in this study were 9.5 mm mixtures.

Table 1-26. Gradation Specification Bands (SMA).

Sieve Size (mm)	% Passing (by Volume)					
	19 mm		12.5 mm		9.5 mm	
	Lower	Upper	Lower	Upper	Lower	Upper
25.0		100				
19.0	90	100		100		
12.5	50	88	90	99	100	100
9.5	25	60	50	85	70	95
4.75	20	28	20	40	30	50
2.36	16	24	16	28	20	30
1.18	—	—	—	—	—	21
0.6	—	—	—	—	—	18
0.3	—	—	—	—	—	15
0.075	8.0	11.0	8.0	11.0	8.0	12.0

Table 1-27. Gradations of Combined Aggregate (SMA).

Sieve Size (mm)	% Passing							
	US31		I74		SR64		I65	
	By Volume	By Weight	By Volume	By Weight	By Volume	By Weight	By Volume	By Weight
12.5	100.0	100.00	100.0	100.0	100.0	100.0	100.0	100.0
9.5	88.1	86.1	84.7	83.6	85.7	85.2	86.9	87.0
4.75	36.8	36.0	39.1	34.7	34.7	32.6	44.5	43.0
2.36	27.4	22.9	26.9	21.9	21.0	18.8	25.3	24.5
1.18	20.0	16.3	21.0	17.1	14.6	13.0	17.3	16.5
0.6	17.3	14.0	17.7	14.5	11.4	10.2	14.2	13.5
0.3	14.7	11.9	15.0	12.4	10.5	9.2	12.4	12.0
0.15	11.7	9.5	13.3	11.1	9.2	8.4	10.3	10.0
0.075	9.7	8.0	10.1	8.5	8.4	7.6	8.9	8.0
Blend G_{sb}	3.314 ²		3.476		3.275		3.313	
NMAS ¹ (mm)	9.5		9.5		9.5		9.5	

(1) Nominal maximum aggregate size is applicable to the Superpave mixtures only. This term is borrowed to indicate the combined aggregate size.

(2) This value seems to be erroneous based on the other reported JMF values for this mix. Therefore, a calculated value of 3.294 was used instead

Similar to dense-graded mixtures, Table 1-28 shows the distance of 2.36 and 4.75 mm sieves from the MDL in terms of percent passing. Table 1-28 also shows the average gradation of each aggregate structure by averaging the percent passing of sieves 0.075, 0.6, 2.36, and 9.5 mm. Based on the average gradation, SR64 has the

coarsest aggregate gradation of all SMA mixtures. Table 1-28 also shows a fineness modulus of FM_{300} , which was calculated by summing the percent passing the 75, 150, and 300 μm sieves.

Figure 1-3. Gradation of SMA mixtures with PG76-22 binder (by Volume).

Table 1-28. Average Gradations, Fineness, and Distance from the MDL ¹ (SMA).

Road No.	Average Gradation (% passing)		Fineness Modulus FM_{300}		Distance from MDL 2.36 mm (% passing)		Distance from MDL 4.75 mm (% passing)	
	By Weight	By Volume	By Weight	By Volume	By Weight	By Volume	By Weight	By Volume
US31	32.8	35.6	36.1	29.4	24.3	19.8	28.7	27.9
I74	32.1	34.9	38.4	32.0	25.3	20.3	30.0	25.6
SR64	30.5	31.6	28.1	25.2	28.4	26.2	32.1	30.0
I65	33.3	33.8	31.6	30.0	22.7	21.9	21.7	20.2

(1) Maximum Density Line

The SMA mixture specifications are presented in Table 1-29. Table 1-30 gives the guidelines to adjust the minimum asphalt binder content based on varying bulk specific gravity of aggregates and Table 1-31 gives the JMF properties.

Table 1-29. Requirements of Mixture Properties (SMA).

Property	Requirement
Air Voids (%)	4.0 ¹
VMA (%)	≥ 17.0
VCA _{MIX} (%)	≤ VCA _{DRC}
Tensile Strength Ratio	≥ 0.70 ²
Draindown at Production Temperature (%)	≤ 0.30
Asphalt Binder Content (%)	≥ 6.0 ³

- (1) For low traffic volume roadways or colder climates, target air void contents less than 4.0 percent can be used, but should not be less than 3.0 percent.
- (2) Tested from specimens with 6.0 ± 1.0 percent air voids.
- (3) When an SMA mixture cannot be designed within the minimum asphalt content requirements using the available aggregates, the guidelines given in Table 1-30 can be used to establish minimum asphalt content requirements based on the combined aggregate bulk specific gravity.

Table 1-30. Guide to Adjust Minimum Asphalt Content Based on Varying Bulk Specific Gravities of Aggregate (SMA).

Combined Aggregate Bulk Specific Gravity	Minimum Asphalt Binder Content (%)
2.40	6.8
2.45	6.7
2.50	6.6
2.55	6.5
2.60	6.3
2.65	6.2
2.70	6.1
2.75	6.0
2.80	5.9
2.85	5.8
2.90	5.7
2.95	5.6
3.00	5.5

Table 1-32 shows the absorbed binder amount and calculated surface area and binder film thickness similar to the dense-graded mixtures. Due to the discrepancy of the calculated G_{se} and reported G_{sb} value for mixture US31, the binder absorption was assumed to be zero (instead of a negative value based on the reported G_{sb} value). SP64 had the lowest surface area and highest binder film thickness among the SMA

mixtures. However, all SMA mixtures had a higher surface area and lower binder film thickness compared to the dense-graded mixtures.

Table 1-31. Mixture Design Properties (SMA).

Road No.	P_b^1	P_b^2	Volumetrics @ N_{des} (%)			Specific Gravity			VCA (%)		Drain Down (%)	Tensile Strength Ratio (%)
			V_a	VMA	VFA ³	G_{se}^3	G_{mm}^3	G_{mb}^3	DRC ⁴	Mix		
US31	4.8	4.7	4.0	17.8	77.6	3.294	2.980	4.8	—	33.4	0.08	95.5
I74	5.5	5.4	4.0	17.7	77.4	3.584	3.154	5.5	45.2	36.3	0.00	97.0
SR64	5.5	5.4	4.0	17.9	77.6	3.330	2.966	5.5	41.2	37.5	0.00	83.1
I65	5.9	5.5	4.0	17.8	77.5	3.422	3.017	5.9	43.9	39.9	0.07	88.7

(1) Binder recovery using ignition (by weight-%)

(2) Binder recovery using extraction (by weight-%)

(3) Not required by specification

(4) Dry rodded coarse aggregate

Table 1-32. Binder Absorption¹, Surface Area, and Binder Film Thickness (SMA).

Road No.	P_{ba} (%)	P_{beff} (%)	V_{ba} (%)	V_{beff} (%)	$V_{b-total}$ (%)	Surface area SA (m ² /kg)	Film thickness (μm)
US31	0.0	4.80	0.0	13.3	13.3	5.95	8.5
I74	0.89	4.61	2.5	13.7	16.2	6.36	7.5
SR64	0.52	4.98	1.4	13.8	15.2	5.30	9.7
I65	1.00	4.90	2.6	13.7	16.4	6.05	8.5

(1) All values calculated from “binder recovery using ignition” values. P by weight, V by volume.

The Bailey method (Vavrik et. al., 2001) aggregate gradation ratios and predicted VMA and VCA_{mix} are presented in Table 1-33 similar to the dense-graded mixtures. The predicted and measured VCA_{mix} values agreed well for US31, but for the other mixtures the model overpredicted the VCA_{mix} values.

Table 1-33. The Bailey Method Gradation Ratios (SMA).

Road No.	CA Ratio	FA _C Ratio	FA _F Ratio	Predicted VMA (%)	Predicted VCA _{mix} (%)
US31	0.15	0.63	0.68	28.6	32.4
I74	0.20	0.66	0.75	33.6	41.8
SR64	0.21	0.54	0.81	44.7	70.1
I65	0.35	0.56	0.73	37.3	47.7

2 DESCRIPTION OF TEST METHODS USED

2.1 Theory of Complex Modulus

Complex mathematics gives a convenient tool to solve the visco-elastic behavior of the asphalt mixtures and binders in cyclic loading. The sinusoidal one-dimensional loading can be represented by a complex form:

$$\sigma^* = \sigma_0 e^{i\omega t} \quad (1)$$

and the resulting strain

$$\varepsilon^* = \varepsilon_0 e^{i(\omega t - \varphi)} \quad (2)$$

The axial complex modulus $E^*(i\omega)$ is defined as the complex quantity

$$\frac{\sigma^*}{\varepsilon^*} = E^*(i\omega) = \left(\frac{\sigma_0}{\varepsilon_0} \right) e^{i\varphi} = E_1 + iE_2 \quad (3)$$

in which σ_0 is the stress amplitude, ε_0 is strain amplitude, and ω is angular velocity, which is related to the frequency by:

$$\omega = 2 \pi f \quad (4)$$

In the complex plane, the real part of the complex modulus $E^*(i\omega)$ is called the storage or elastic modulus E_1 , while the imaginary part is the loss or viscous modulus E_2 , shown in Figure 2-1. For elastic materials $\varphi = 0$, and for viscous materials $\varphi = 90^\circ$. The alternative nomenclature is to call the storage modulus as E' and loss modulus as E'' .

If a linearly visco-elastic material is subjected to a uniaxial compressive, tensile or shear loading $\sigma = \sigma_0 \sin \omega t$, the resulting steady state strain $\varepsilon = \varepsilon_0 \sin(\omega t - \varphi)$ will be out of phase with the stress by the lag angle φ , as shown in Figure 2-2.

Figure 2-1. Complex plane.

The ratios of stress and strain amplitudes σ_0/ε_0 define the dynamic (or cyclic) modulus $|E^*(\omega)|$, shown in Eq. (5):

$$|E^*(\omega)| = \sqrt{E_1^2 + E_2^2} = \frac{\sigma_0}{\varepsilon_0} \quad (5)$$

Figure 2-2. Sinusoidal stress and strain in cyclic loading.

where E_1 and E_2 can be expressed as a function of phase lag or lag angle:

$$E_1 = \frac{\sigma_0 \cos \varphi}{\varepsilon_0} \quad \text{and} \quad E_2 = \frac{\sigma_0 \sin \varphi}{\varepsilon_0} \quad (6)$$

The loss tangent defines the ratio of lost and stored energy in a cyclic deformation:

$$\tan \varphi = \frac{E_2}{E_1} \quad (7)$$

Figure 2-1 shows that the quantity "dynamic modulus" presents a norm i.e., length of the complex modulus vector E^* in a complex plane. It should be noted that since the test can be done using either normal or shear stress, the norm of the complex modulus can be defined either by $|E^*|$ or $|G^*|$. In applied visco-elasticity for the asphaltic materials, the phase angle is usually denoted by φ or ϕ for the mix and δ for the binder.

2.2 Compressive Dynamic Modulus Test (ASU Protocol)

A sinusoidal (haversine) axial compressive stress is applied to a cylindrical specimen of asphalt concrete at a given temperature and loading frequency, Figure 2-3. The applied stress and the resulting recoverable axial strain response of the specimen is measured and used to calculate the dynamic modulus and phase angle, as follows. Over the last 5 loading cycles and for each test condition, the loading stress, σ_o , is calculated as follows:

$$\sigma_o = \frac{\bar{P}}{A} \quad (8)$$

where:

$\bar{P}$ = average load
 A = area of specimen
 σ_o = stress.

Calculate the recoverable axial strain individually for each LVDT, ε_o , as follows:

$$\varepsilon_o = \frac{\bar{\Delta}}{GL} \quad (9)$$

where:

$\bar{\Delta}$ = average deformation
 GL = gage length
 ε_o = strain

Calculate the dynamic modulus, $|E^*|$ individually for each LVDT as follows:

$$\text{Dynamic Modulus, } |E^*| = \frac{\sigma_o}{\varepsilon_o} \quad (10)$$

Calculate the phase angle individually for each LVDT:

$$\phi = \frac{t_i}{t_p} \times (360) \quad (11)$$

where:

t_i = average time lag between a cycle of stress and strain (sec)

t_p = average time for a stress cycle (sec.)

The dynamic modulus testing is performed on 101.6 mm (4.00 in) diameter by 152.4 mm (6.00 in) high test specimens cored from gyratory compacted mixtures. Axial deformations are measured with linear variable differential transformers (LVDT) mounted between gauge points glued to the specimen, Figure 2-4. The deformations are measured at two locations 180° apart or three locations 120° apart. During testing, axial strain is limited to approximately 100 micro-strains to prevent nonlinearity in the testing.

Figure 2-3. Loading pattern for compressive dynamic modulus testing.

Figure 2-4. General schematic of gauge points (not to scale) (After Witczak, Bonaquist, Von Quintus & Kaloush, 2000).

2.3 AASHTO TP7 Simple Shear Tester Shear Modulus

In shear frequency weep test the specimen is sheared from the bottom as Figure 2-5 schematically presents. A horizontal shear strain is applied at a frequency of 10 to 0.01 Hz using a sinusoidal straining pattern. At the same time, the specimen height is kept constant by compressing or pulling the specimen axially based on the closed loop feedback given by the vertical LVDTs attached to the sides of the specimen. The cylindrical test specimen's diameter is 150 mm, height 50 mm and it is glued between two aluminum platens.

Testing is usually conducted at 4, 20 and 40°C, but higher temperatures can also be used. The strain control mode in both actuators makes the test difficult to run and very soft mixtures can cause severe control problems at high temperatures. Also, test temperatures are limited above 4°C because at colder temperatures mix stiffness may exceed the stiffness of the glue and specimens may shear off the platens. Parameters obtained from the testing are the shear modulus $|G^*|$ and phase angle δ .

Figure 2-5. Schematic of Shear Frequency Sweep Test.

The shear (complex) modulus is defined analogues to the dynamic (complex) modulus as the norm of the complex modulus in shear:

$$|G^*| = \frac{\tau_0}{\gamma_0} \quad (12)$$

where:

$|G^*|$ = shear (complex) modulus

τ_0 = peak shear stress amplitude

γ_0 = peak shear strain amplitude

Based upon these results, both the elastic and viscous behavior can be determined through calculations of the storage modulus (G') and the loss modulus (G'') analogues as discussed for the complex (dynamic) modulus test.

2.4 Triaxial Shear Strength Test

The triaxial strength test has traditionally been used in soil property characterization to obtain the shear strength of the soil. The Mohr-Coulomb failure theory, Eq. (13), describes the relationship between shear strength (τ) and applied normal stress (σ) using two material parameters, cohesion (c) and friction angle (ϕ).

$$\tau = c + \sigma \tan \phi \quad (13)$$

Unconfined compressive strength of the mix (q_u) can be determined from Eq (14).

$$q_u = \frac{2c \cos \phi}{1 - \sin \phi} \quad (14)$$

A typical way of conducting the test is to test various specimens under different confinement levels to obtain at least three points in the failure line to estimate cohesion and friction, Figure 2-6. A triaxial test is conducted applying constant ram rate loading to a cylindrical specimen of height to diameter ratio of at least 2. Specimens can be tested with or without instrumentation.

Figure 2-6. Mohr-Coulomb Failure Theory

2.5 IDT Strength Test

The indirect tensile strength test is conducted by applying a diametral compressive load along a vertical plane of a cylindrical specimen. The tensile strength S_t is the maximum horizontal stress that develops at the center of the specimen due to

the loading, Figure 2-7. Specimen size is usually diameter 150-mm and height between 30 to 50mm.

Figure 2-7. Theoretical Stress Distribution on Vertical Diametral Plane for Indirect Tensile Test (Adapted from Yoder and Witczak, 1975)

A Mohr's circle can be constructed according to the principle stresses denoted by Eq. (15) and Eq. (16). The relationship of the unconfined compressive strength and the IDT strength are shown in the Mohr-Coulomb failure envelope in Figure 2-8.

$$\sigma_3 = \sigma_x = -\frac{2P}{\pi t d} \quad (15)$$

$$\sigma_1 = \sigma_y = \frac{6P}{\pi t d} = 3\sigma_x \quad (16)$$

Figure 2-8. Mohr's Circles from IDT Strength and Triaxial Test

2.6 Dynamic Creep Test

The dynamic creep test or repeated load permanent deformation test is conducted by applying repeated dynamic loading for several thousand repetitions and recording the cumulative permanent deformation as a function of the number of cycles (repetitions) over the test period. A haversine pulse load of 0.1 sec and 0.9 second dwell (rest time) is applied for the test duration of approximately 3 hours and results in a total of 10,000 cycles. Test specimen diameter is usually 100 mm and height is 150 mm. Testing can be done unconfined or confined. Figure 2-9 shows an example of a confined test conducted at Arizona State University (ASU). Radial LVDTs are mounted through the pressure cell to measure lateral strain during testing.

A number of parameters describing the accumulated permanent deformation response can be obtained from the test. Figure 2-10 illustrates a typical relationship between the total cumulative plastic strain and number of load cycles. Like the static creep test, the cumulative permanent strain curve is generally defined by three zones: primary, secondary, and tertiary. The starting point, or cycle number, at which tertiary flow occurs is referred to as the “Flow Number” by Witczak et al. (2001). The Flow

Number is calculated by differentiating the axial strain or radial strain measurements to find the minimum strain rate, which presents the inflection point in the strain curve indicating a start point of tertiary flow.

Figure 2-9. Confined Dynamic Creep Test (ASU).

Figure 2-10. Typical Relationship Between Total Cumulative Plastic Strain and Loading Cycles.

Typical permanent deformation parameters obtained and analyzed from the repeated load test include the intercept (a) and slope (b). Note that all of the parameters derived from the linear (secondary) portion of the cumulative plastic strain–repetitions curve ignore the tertiary zone of material deformability. The relationship between the permanent strain and the number of load cycles can be expressed by the classical power model:

$$\epsilon_p = aN^b \quad (17)$$

where "a" and "b" are regression constants depending upon the material-test combination conditions. Figure 2-11 illustrates the relationship when plotted on a log-log scale. The intercept "a" represents the permanent strain at $N=1$, whereas the slope "b" represents the rate of change in permanent strain as a function of the change in loading cycles ($\log(N)$).

Figure 2-11. Regression Constants "a" and "b" When Plotted on a Log-Log Scale

3 DESCRIPTION OF EQUATIONS AND FORMULAS USED

3.1 Bailey Method for Evaluating Aggregate Gradation

In the Bailey method (Varvik et al, 2001) four sieves and three ratios are defined to quantify the aggregate gradation curve. All ratios influence the Voids in Mineral Aggregate (VMA) and Voids in Coarse Aggregate (VCA) of the mixture, which in turn affect the mechanical properties of the dense graded mixture and the stone matrix asphalt mixture, respectively. The four sieves and three ratios quantifying the shape of the gradation curve are discussed below:

Primary Control Sieve (PCS)

Primary control sieve (PCS) concept is used to define the coarse aggregate (CA) and fine aggregate (FA) in an aggregate blend. PCS is defined as follows:

$$PCS = NMPS \times 0.22 \quad (18)$$

where NMPS is the nominal maximum particle size of the aggregate blend, as defined by the Superpave volumetric mix design system, which is one sieve size larger than the first sieve retaining more than 10%.

Half Sieve

The half sieve is used to further break down the coarse aggregate into the coarse portion and fine portion of the coarse aggregate. Eq. (19) is used to determine the half sieve

$$half\ sieve = NMPS \times 0.50 \quad (19)$$

Fine Aggregate Initial Break Sieve (FAIB)

Fine aggregate initial break sieve (FAIB) is defined in the same way as the primary control sieve for the whole aggregate blend and used to further break down the fine aggregate into coarse and fine portions. Eq. (20) gives the definition of FAIB.

$$FAIB = PCS \times 0.22 \quad (20)$$

where FAIB is fine aggregate initial break sieve that separates the fine aggregate into coarse and fine portions.

Fine Aggregate Secondary Break Sieve (FASB)

Likewise, fine aggregate secondary break sieve (FASB) is used to further break down the fine portion of the fine aggregate. Eq. (21) gives the definition of FASB.

$$FASB = FAIB \times 0.22 \quad (21)$$

where FASB is the fine aggregate secondary break sieve that separates the fine portion of the fine aggregate into coarse and fine portions

Coarse Aggregate Ratio

The coarse aggregate (CA) ratio is used to present the packing characteristic of the coarse aggregate of the aggregate blend, and it is defined as follows:

$$CA\ Ratio = \frac{\%half\ sieve - \%PCS}{100 - \%half\ sieve} \quad (22)$$

where:

%half sieve = percentage of passing the half sieve

%PCS = percentage of passing the primary control sieve

Fine Aggregate-Coarse Ratio (FA_C)

The fine aggregate-coarse ratio (FA_C) is used to present the packing characteristic of the coarse portion of the fine aggregate, and it is defined as follows:

$$FA_C = \frac{\%FAIB}{\%PCS} \quad (23)$$

where:

%FAIB = percentage of passing the fine aggregate initial break sieve
 %PCS = percentage of passing the primary control sieve

Fine Aggregate-Fine Ratio (FA_F)

The fine aggregate-fine ratio (FA_F) is used to present the packing characteristic of the fine portion of the fine aggregate, and it is defined as follows:

$$FA_F = \frac{\%FASB}{\%FAIB} \quad (24)$$

where:

%FASB = percentage of passing the fine aggregate secondary break sieve

%FAIB = percentage of passing the fine aggregate initial break sieve

Summary of the Gradation Evaluation Parameters

The aforementioned four sieves are obtained by rounding the calculated values to the closest standard sieves that are used to characterize the aggregate gradation by the Superpave volumetric mix design system. Table 3-1 summarizes the four sieve sizes discussed above.

Table 3-1. Sieve Sizes of the Gradation Evaluation.

Nominal Maximum Particle Size (NMPS)	25 mm	19 mm	12.5 mm	9.5 mm
Primary Control Sieve (PCS)	4.75	4.75	2.36	2.36
Half Sieve	12.5	9.5	4.75	4.75
Fine Aggregate Initial Break Sieve (FAIB)	1.18	1.18	0.60	0.60
Fine Aggregate Secondary Break Sieve (FASB)	0.30	0.30	0.15	0.15

The three ratios, CA ratio, FA_C and FA_F are summarized in Table 3-2. These three ratios can be used to estimate VMA or VCA of the mixture, Eq. (25) and (26).

$$VMA = -24.6 + 20.1(CA Ratio)^2 - 3.8(CA Ratio) - 191.1FA_C^2 + 181.0FA_C + 87.3FA_F^2 - 36.6FA_F \quad (25)$$

$$VCA_{mix} = 169.6 + 59.0(CA Ratio)^2 - 41.5(CA Ratio) - 110.2FA_c^2 + 3.2FA_c + 428.3FA_F^2 - 423.3FA_F \quad (26)$$

Table 3-2. Gradation Evaluation Ratios.

Nominal Maximum Particle Size (NMPS)	25 mm	19 mm	12.5 mm	9.5 mm
Coarse Aggregate (CA) Ratio	$\frac{12.5 - 4.75}{100^1 - 12.5}$	$\frac{9.5 - 4.75}{100^1 - 9.5}$	$\frac{4.75 - 2.36}{100^1 - 4.75}$	$\frac{4.75 - 2.36}{100^1 - 4.75}$
Coarse Aggregate Ratio of Fine Aggregate (FA _C)	$\frac{1.18}{4.75}$	$\frac{1.18}{4.75}$	$\frac{0.60}{2.36}$	$\frac{0.60}{2.36}$
Fine Aggregate Ratio of Fine Aggregate (FA _F)	$\frac{0.30}{1.18}$	$\frac{0.30}{1.18}$	$\frac{0.15}{0.60}$	$\frac{0.15}{0.60}$

(1) Taken as the number 100. All others indicate percentages smaller than the sieves

3.2 Surface Area and Asphalt Film Thickness

Calculation of asphalt film thickness is based on the surface area factor in the Hveem mix design method. In 1959, Hveem found that the asphalt film thickness around the aggregate particles is a function of the diameter of the aggregate and the asphalt content of the mixture. Therefore, surface area of an aggregate blend is estimated based on the gradation and surface area factors. The surface area factor is dependent of the sieve size. Surface area factors and calculations for area surface are presented in Table 3-3.

Table 3-3. Surface Area Calculations.

Sieve Size (mm)	Percent Passing	Surface Area Factor (SAF)	Surface Area (m ² /kg) Percent Passing x SAF/100
Maximum Size	100	0.4	2.00
4.75		0.4	
2.36		0.8	
1.18		1.6	
0.60		2.9	
0.30		6.2	
0.15		12.4	
0.075		33.0	
			$SA = \sum m^2 / kg$

Once the surface area and asphalt content of the mixture are known, the average asphalt film thickness can be determined using Eq. (27):

$$T_F = \frac{V_{beff}}{SA \times W} \times 1000 \quad (27)$$

where:

T_F = average asphalt film thickness, microns

V_{beff} = effective volume of asphalt

SA = surface area of the aggregate (m^2 per kg of aggregate)

W = weight of aggregate (kg)

3.3 Effective Volume of Asphalt

The effective asphalt amount is obtained by subtracting the absorbed asphalt from the total asphalt. The following equations (28) to (31) can also be used to determine the absorbed asphalt and effective asphalt contents.

$$V_b = \frac{G_{mb} \times P_b}{G_b} \quad (28)$$

$$P_{ba} = \frac{G_{se} - G_{sb}}{G_{sb} G_{se}} \times G_b \quad (29)$$

$$V_{ba} = \frac{G_{se} - G_{sb}}{G_{sb} G_{se}} \times G_{mb} \times P_b \quad (30)$$

$$V_{beff} = V_b - V_{ba} \quad (31)$$

where:

V_b = total volume of asphalt

G_{mb} = bulk specific gravity of compacted hot mix asphalt mixture

P_b = asphalt content

G_b = specific gravity of asphalt

- P_{ba} = absorbed asphalt by weight of aggregate
 G_{se} = effective specific gravity of aggregate
 G_{sb} = bulk specific gravity of aggregate
 V_{ba} = volume of absorbed asphalt
 V_{beff} = volume of effective asphalt

3.4 Air Voids Normalization Process for Stiffness

Normalization for the modulus values was done using the Hirsch model to estimate the stiffness change due to the air void change. Hirsch model from Christensen et al. (2005) is the most current of the stiffness predictive models, and it was developed employing composite mechanics theory for a three-phase system of aggregate, binder, and air. Eq. (32) and Eq. (33) are models for the dynamic modulus. The shear modulus models are defined by Eq. (34) and Eq. (35).

$$|E^*| = Pc \left[4,200,000 \left(1 - \frac{VMA}{100} \right) + 3 |G^*|_{binder} \left(\frac{VFA \times VMA}{10,000} \right) \right] + (1 - Pc) \left[\frac{1 - VMA/100}{4,200,000} + \frac{VMA}{3 VFA |G^*|_{binder}} \right]^{-1} \quad (32)$$

where:

- $|E^*|$ = Dynamic (complex) modulus, psi
 Pc = Contact factor, given by Eq. (33)
 VMA = Voids in mineral aggregate, %
 $|G^*|_{binder}$ = Complex shear modulus of the binder, psi
 VFA = Voids filled with asphalt, %

$$Pc = \frac{\left(20 + \frac{VFA \times 3 |G^*|_{binder}}{VMA} \right)^{0.58}}{650 + \left(\frac{VFA \times 3 |G^*|_{binder}}{VMA} \right)^{0.58}} \quad (33)$$

$$|G^*| = P_c \left[601,000 \left(1 - \frac{VMA}{100} \right) + |G^*|_{binder} \left(\frac{VFA \times VMA}{10,000} \right) \right] + (1 - P_c) \left[\frac{1 - VMA/100}{601,000} + \frac{VMA}{VFA |G^*|_{binder}} \right]^{-1} \quad (34)$$

where:

$|G^*|$ = Shear (complex) modulus, psi

P_c = Contact factor, given by (35)

VMA = Voids in mineral aggregate, %

$|G^*|_{binder}$ = Complex shear modulus of the binder, psi

VFA = Voids filled with asphalt, %

$$P_c = \frac{\left(3 + \frac{VFA \times |G^*|_{binder}}{VMA} \right)^{0.678}}{396 + \left(\frac{VFA \times |G^*|_{binder}}{VMA} \right)^{0.678}} \quad (35)$$

The phase angle values were normalized by fitting a second order polynomial through the modulus and phase angle data in the Black space. First a second order polynomial function was obtained by fitting $\log |E^*|$ and ϕ . Second, the normalized phase angle values were obtained using the same function and the normalized modulus values.

First, the average values of moduli and phase angles were obtained from the replicates of each test. Normalization was then applied on the average values using the corresponding average air voids content, instead of normalizing each replicate separately.

3.5 Air Voids Normalization Process for Cohesion and IDT Strength

The air voids normalization process described here is purely empirical and based on limited laboratory testing of triaxial strength of the mixture. An assumption was made that a simple linear relationship exists between the cohesion and the indirect

tensile (IDT) strength. Therefore, further refinement and verification may be needed to improve the accuracy of the normalization processes.

The triaxial strength tests were performed for the seven dense graded mixtures (DGM) and four stone matrix mixtures (SMA) at one temperature of 54.4°C and three loading rates, 1.25 mm/min, 7.5 mm/min and 50 mm/min. In addition, two mixtures were tested with faster loading rates of 100 and 150 mm/min. Test specimens were compacted to varying air voids contents ranging from 0 to 13%. The Mohr Coulomb analyses of data indicated that the cohesion decreased as air voids increased and the effect was loading rate dependent. Therefore, the air voids content effect was analyzed for each loading rate separately. An exponential function was found to be the best model to fit the observed curve of cohesion versus air voids content. The coefficient of determination varied from fair ($R^2 = 0.48$) to good ($R^2 = 0.74$). A general model is expressed in the form:

$$c, S_t = a(\text{air voids})^b \quad (36)$$

where:

c = cohesion, kPa

S_t = IDT tensile strength, kPa

Since this model was not intended to be used to predict the absolute values of measured strength parameters, but the strength parameter ratios between the two different air voids contents, only the power index b was considered. An air voids content of 7.5% was chosen as the reference air voids content. Table 3-4 gives the summary of air void shift factors calculated from the fitting functions.

Table 3-4. Air Voids Shift Factor.

Air Voids	Load Rate (mm/min)					
	1.25		7.5		50	
	DGM	SMA	DGM	SMA	DGM	SMA
1.5	3.4	2.3	2.8	2.0	2.0	1.6
2.5	2.4	2.0	2.4	1.8	1.8	1.5
3.5	2.0	1.7	2.0	1.6	1.6	1.4
4.5	1.7	1.5	1.7	1.4	1.4	1.3
5.5	1.4	1.3	1.4	1.3	1.3	1.2
6.5	1.2	1.1	1.2	1.1	1.1	1.1
7.5	1.0	1.0	1.0	1.0	1.0	1.0
8.5	0.8	0.9	0.8	0.9	0.9	0.9
9.5	0.7	0.8	0.7	0.8	0.8	0.8
10.5	0.6	0.7	0.6	0.7	0.7	0.8
11.5	0.5	0.6	0.5	0.6	0.6	0.7
12.5	0.4	0.5	0.4	0.6	0.6	0.7

3.6 Loading Rate Normalization Process for Cohesion and IDT Strength

The same concept and test data used to develop the air voids normalization process, described above, were analyzed to establish the relationship between loading rate and cohesion, shown in general form in Eq. (37).

$$c, S_t = a(\text{loading rate})^b \quad (37)$$

This analysis also included data points measured at 100 mm/min and 150 mm/min ram rates. The average power index b describing the loading rate effect as function of air voids content is summarized in Table 3-5.

However, because the loading rate dependency on mixture strength is affected by mixture composition, air voids content, and possibly some other factors, caution must be taken when comparing mixture strength values obtained at different loading rates. This procedure was developed because there was a need to shift IDT tensile strength data obtained from literature to the testing conditions used in this study.

Table 3-5. Power Index b Values.

Air Voids Content (%)	0	4.0	7.5
b	0.157	0.236	0.322

4 TEMPEARTURE CONCEPTS

The selection of test temperature for mechanical testing to obtain material properties is one of the most critical considerations for the performance criteria development. There are six different temperature concepts that have been used according to literature: 1) Effective temperature; 2) Maximum temperature; 3) Control temperature; 4) Standard reference temperature; 5) Binder PG-grade temperature; and 6) Critical temperature (Pellinen, 2001).

The effective temperature T_{eff} is defined as the single test temperature at which the amount of permanent deformation or fatigue cracking damage within a given pavement system would be equivalent to that which would be estimated by considering the seasonal fluctuation of temperature and cumulative damage principles throughout the year. It is computed using Mean Annual Air Temperature (MAAT), Witczak et. al. (1992). The maximum temperature is simply a methodology that is based on the highest pavement temperature that the pavement will ever be subjected. Historically, a temperature of 60°C (140°F) has traditionally been used for testing of the Marshall stability. A control temperature T_{ctr} , which is determined using the effective temperature T_{eff} (PD) and design traffic (repetitions), can be estimated using the table from *The Superpave Mix Design Manual for New Constructions and Overlays, SHRP-A-407* by Cominsky et al., (1994). It was used in the Superpave Level 2 and 3 tertiary creep testing. A Standard Reference Temperature T_s , was proposed by Deacon et al. (1994). They recommended temperatures between 15 to 30°C (59 to 86°F) to accommodate about 68 percent of fatigue damage of 10-cm (4") thick pavements and 76 percent of 20-cm (8") thick pavements. An average of about 92 percent of rutting occurs in pavements at deformation testing temperature range of 30 to 45°C (86 to 113°F) temperatures. The average 7-day design temperature is calculated by averaging the seven hottest consecutive days of the year. It is currently used in the Superpave PG binder specifications. There are several definitions for the critical temperature. Deacon et al. (1994) define critical temperature T_c as the temperature in which the largest amount of damage occurs in service. Thus, the critical

temperature is linked to geographical location and pavement structure. Based on their calculations, the critical temperature was approximately 6.9°C (11.4°F) higher than the effective temperature.

Christensen et al. (2005) have defined the critical temperature for rutting using the average 7-day high pavement temperature at a depth of 50-mm at 50% reliability level with no traffic adjustments. The computer program LTPPBIND was used to determine 7-day pavement temperature. Table 4-1 shows the calculated effective temperatures in Indiana for the location of the 11 paving projects. The effective temperature T_{eff} varies about 4°C ranging from 38.6 to 42.5°C.

Table 4-1. Effective and Critical Temperatures.

Road No.	Weather Station	Location	T_{eff} (°C)	$MAAT_{\text{Ave}}$ (°C)	σ_{MAAT}	7-day Pavement Temperature (°C)	
						z=25mm	z=50mm
SR15	Goshen College	North	38.6	10.2	0.6	47.5	45.5
US24	Fort Wayne	North	38.9	10.4	0.7	47.6	45.6
SR161	Saint Meinrad	South	41.5	13.5	0.5	49.2	47.2
SR56	Madison Sewage Plant	South	41.6	13.3	0.6	49.2	47.2
US30	Fort Wayne	North	38.9	10.4	0.7	47.6	45.6
SR66	Evansville Reg Ap	South	42.5	14.4	0.5	49.9	47.9
SR135	Salem	South	40.8	12.7	0.5	49.0	47.0
US31	Plymouth Power Subst	North	38.7	10.4	0.5	48.5	46.5
I74	Indianapolis se side	North	40.0	11.5	0.7	48.0	46.0
SR64	Albion	South	41.3	13.0	0.6	50.3	48.3
I65	Scottsburg	South	40.4	12.2	0.5	49.8	47.8
I70	Greenfield	North	40.5	—	—	48.2	46.2

Table 4-2 shows the average north and south 7-day pavement temperature determined at 25 mm and 50 mm deep in the pavement at 50% reliability with no traffic adjustments.

Table 4-2. Average Geographical Temperatures in Indiana.

Temperature Approach	North Indiana	South Indiana
Effective Temperature	39.0	41.5
7-day Pavement Temperature z=25 mm	47.9	49.6
Critical Temperature for rutting z=50mm	45.9	47.6

5 CORING LOCATIONS

Table 5-1. List of Coring Locations

District	Contractor	Road No.	Lane	Mile Marker / Mile Post
Fort Wayne	E & B Paving Inc.	SR15	NBL	Mile Marker 32+36, Lot 3 Sublot 2
Fort Wayne	E & B Paving Inc.	US24	WBL	Mile Marker 82.6 in Miami County
Vincennes	J. H Rudolph & Co., Inc	SR161	SBL	6+044
Seymour	Gohmann Asphalt	SR56	EBL	Mile Marker 119.10
Fort Wayne	Phend & Brown Inc.	US30	WBL	CR 875W, WBRT, Turn Lane, STA 1090+00~STA 1089+87
Vincennes	E & B Paving Inc.	SR66	WBL	Mile Marker 21
Seymour	Shelly & Sands	SR135	SBL	756+40~754+58
Laporte	E & B Paving Inc.	US31	NBL	Starting from 1337+40
Greenfield	Milestone, L. L. P.	I74	WBL	29+950, 29+400, 30+400, 33+540, 34+863, 37+415, 37+600, 41+540, 36+050 (9 cores) The rest 6 cores were located on London Road on ramp next to Gore Area heading west
Vincennes	Gohmann Asphalt	SR64	WBL	Starting at Mile Marker 0.64
Seymour	Dave O'Mara Contractor, Inc.	I65	NBL	80+633, 81+040, 81+446

2nd Coring (9/23/03) 1st Coring (6/20/02) **SR15: NBL (Driving Lane)**

1st Coring: 0.15 m from the right side of centerline

2nd Coring 0.46 m from the right side of centerline

Transverse distance of cores 0.31 m

Longitudinal distance of cores 0.64 m

Lane width 3.6 m

Rut Depth: none

Visual observations: Occasional transverse micro-cracks

2nd Coring (9/23/03) 1st Coring (6/13/02) **US24: WBL (Driving Lane)**

1st Coring: 0.43 m from the right side of centerline

2nd Coring 1.07 m from the right side of centerline

Transverse distance of cores 0.64 m

Longitudinal distance of cores 3.0 m

Lane width 3.6 m

Rut Depth: none

Visual observations: Minor longitudinal cracks

2nd Coring (10/15/03) 1st Coring (8/5/02) **SR161: SBL (Driving Lane)**

1st Coring: 0.70 m from the right side of centerline
 2nd Coring 0.70 m from the right side of centerline
 Transverse distance of cores 0 m
 Longitudinal distance of cores 1.5 m
 Lane width 3.6 m
 Rut Depth: none

2nd Coring (10/7/03) 1st Coring (6/5/02) **SR56: EBL (Driving Lane)**

1st Coring: 0.15 m from the left side of centerline
 2nd Coring 0.15 m from the right side of centerline
 Transverse distance of cores 0.3 m
 Longitudinal distance of cores 3.0 m
 Lane width 3.6 m
 Rut Depth: none

2nd Coring (9/25/03) 1st Coring (8/1/02) **US30: WBL (Right Turn Lane)**

1st Coring: 0.46 m from the left side of centerline
 2nd Coring: 0.91 m from the right side of centerline
 Transverse distance of cores 1.35 m
 Longitudinal distance of cores 0.50 m
 Lane width 3.6 m
 Rut Depth: none
 Visual observations: Minor longitudinal cracks near shoulder

2nd Coring (10/14/03) 1st Coring (8/20/02) **SR66: WBL (Driving Lane)**1st Coring: centerline2nd Coring 1.20 m from the right side of centerline

Transverse distance of cores 1.20 m

Longitudinal distance of cores 3.0 m

Lane width 3.6 m

Rutting Depth: none

2nd Coring (10/8/03)

1st Coring (9/5/02)

SR135: SBL (Driving Lane)

1st Coring: 0.15 m from the left side of centerline
 2nd Coring 0.53 m from the right side of centerline
 Transverse distance of cores 0.68 m
 Longitudinal distance of cores 3.0 m
 Lane width 3.6 m
 Rut Depth: 1.6 mm

2nd Coring (10/16/03) 1st Coring (10/8/02) **US31: NBL (Driving Lane)**

1st Coring: 1.05 m from the left side of centerline
 2nd Coring: 0.60 m from the left side of centerline
 Transverse distance of cores 0.45 m
 Longitudinal distance of cores 3.0 m
 Lane width 3.6 m
 Rut Depth: none

2nd Coring (11/5/03)1st Coring (QC Cores 11/02) **I74: WBL (Driving Lane)**1st Coring: Location variable2nd Coring: Location variable

Transverse distance of cores varies

Longitudinal distance of cores varies

Lane width 3.6 m

Rut Depth: none

Note: Core locations could not be verified in Fall 2004 because of inaccurate milepost information.

2nd Coring (10/15/03) 1st Coring (QC Cores 10/02) **SR64: WBL (Driving Lane)**1st Coring: location varies2nd Coring: location varies

Transverse distance of cores varies

Longitudinal distance of cores varies

Lane width 3.6 m

Rut Depth: none

Visual observations: Frequent potholes

2nd Coring (10/7/03) 1st Coring (9/10/02) **I65: NBL (Passing Lane)**

1st Coring: no information

2nd Coring :centerline (based on picture on left)

Transverse distance of cores: no information

Longitudinal distance of cores: no information

Lane width 3.6 m

Rut Depth: none

Note: Core locations could not be verified in Fall 2004 because of inaccurate location information

6 ANALYSIS OF SAMPLE AND TEST DATA QUALITY

6.1 Test Specimen's Air Voids Content and Volumetrics

Table 6-1. Average Air Voids Contents (Raw Material).

Road No.	Air Void Content, (%)			
	Unconfined Dynamic Modulus	Shear Modulus	Triaxial Strength	IDT Strength
SR15	7.8	7.5	7.8	8.8
US24	7.6	7.8	7.7	8.6
SR161	7.6	7.6	7.6	8.4
SR56	7.6	7.7	7.5	8.0
US30	6.8	7.8	7.1	7.9
SR66	7.3	7.5	7.5	8.1
SR135	7.4	7.6	7.4	8.4
US31	7.7	8.4	7.8	7.7
I74	8.3	8.2	8.1	7.7
SR64	7.6	7.5	7.5	7.4
I65	6.7	6.9	7.1	7.2
Avg.	7.5	7.7	7.6	8.0

Table 6-2. Average Air Voids Content (Plant Mixture).

Road No.	Air Void Content, (%)				
	Unconfined Dynamic Modulus	Confined Dynamic Modulus	Shear Modulus	Triaxial Strength	IDT Strength
SR15	7.4	7.4	7.7	7.7	7.7
US24	7.8	7.8	7.7	7.9	7.7
SR161	7.6	7.7	7.7	7.9	7.7
SR56	7.4	7.4	7.3	7.5	7.3
US30	7.4	7.3	7.5	7.5	7.5
SR66	7.5	7.5	7.9	7.4	7.6
SR135	7.2	7.2	7.4	7.5	7.5
US31	7.1	7.2	7.3	7.3	7.4
I74	7.3	7.3	7.0	7.3	7.1
SR64	7.4	7.1	7.3	7.4	7.4
I65	7.6	7.8	7.4	7.7	7.4
Avg.	7.4	7.4	7.5	7.6	7.5

Table 6-3. Air Void Contents of 1st Set of Cores

Road No.	Air Void Content, (%)					
	Shear Modulus		Dynamic Modulus		IDT Strength	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
SR15	11.2	0.3	11.1	0.1	11.5	0.1
US24	9.5	0.7	8.7	0.4	9.3	0.4
SR161	10.8	0.4	13.7	0.9	13.4	0.6
SR56	9.6	0.7	8.7	0.3	10.0	0.9
US30	6.5	0.2	7.4	0.2	7.3	0.2
SR66	12.6	0.8	11.5	0.2	11.5	0.7
SR135	8.6	0.2	7.0	0.3	7.0	0.8
US31	8.3	0.8	8.3	0.2	8.3	0.4
I74	7.9 ¹	0.2 ¹	7.9	0.2	7.9	1.4
SR64	4.7 ¹	0.7 ¹	4.7	0.7	4.6	1.1
I65	8.9	0.6	7.4	0.1	7.2	0.2
Average	9.0	0.5	8.8	0.3	8.9	0.6

(1) Not measured, air voids for dynamic modulus specimens were used

Table 6-4. Air Void Contents of 2nd Set of Cores

Road No.	Air Void Content, (%)					
	Shear Modulus		Dynamic Modulus		IDT Strength	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
SR15	9.6	0.3	9.8	0.1	10.0	0.2
US24	4.9	0.3	5.1	0.1	5.1	0.2
SR161	10.7	0.1	13.5	0.6	13.0	1.0
SR56	7.5	1.3	4.5	0.4	6.0	1.0
US30	3.6	0.4	4.5	0.2	4.5	0.1
SR66	8.6	0.6	8.0	1.3	8.1	1.1
SR135	3.5	0.2	4.3	0.4	4.8	0.3
US31	9.2	0.3	6.4	0.5	6.6	0.2
I74	6.0	1.0	4.1	1.6		
SR64	10.6 ¹	0.4	3.0	0.6	4.8	1.2
I65	12.4	0.3	10.5	0.3	11.0	0.4
Average	7.9	0.5	6.7	0.6	7.4	0.7

(1) Erroneous results, not used in the analysis. Instead an average of all cores (4.9%) excluding the erroneous results, was used.

Table 6-5. Volumetric Properties for Raw Material and Loose Mixture Samples.

Road No.	Volumetric Properties @ 7.5% V _a		
	VMA (%)	VFA (%)	V _{beff} (%)
SR15	19.0	60.5	11.5
US24	19.1	60.8	11.6
SR161	18.2	58.7	10.7
SR56	18.5	59.4	11.0
US30	18.7	59.9	11.2
SR66	18.2	58.8	10.7
SR135	18.5	59.5	11.0
US31	20.8	64.0	12.8
I74	20.7	63.7	13.2
SR64	20.8	64.0	13.3
I65	20.7	63.8	13.2
Avg.DGM	18.6	59.7	11.1
Avg.SMA	20.8	63.9	13.1
Avg. All	19.4	61.2	11.8

Table 6-6. Volumetric Properties for 1st Set of Cores

Road No.	@ In-Place V _a				@ Normalized 7.5% V _a		
	VMA (%)	VFA (%)	V _{beff} (%)	V _a (%)	VMA (%)	VFA (%)	V _{beff} (%)
SR15	21.9	48.6	10.6	11.2	18.6	59.6	11.1
US24	18.1	50.1	9.1	9.5	16.7	55.1	9.2
SR161	22.0	42.1	9.2	10.8	17.3	56.6	9.8
SR56	19.2	51.1	9.8	9.6	17.5	57.2	10.0
US30	17.7	59.2	10.5	6.5	17.9	58.1	10.4
SR66	22.3	46.7	10.4	12.6	18.4	59.3	10.9
SR135	17.5	58.0	10.1	8.6	17.6	57.3	10.1
US31	20.6	60.1	12.4	8.3	20.0	62.4	12.5
I74	20.0	64.2	12.8	7.9	20.3	63.0	12.8
SR64	18.4	73.7	13.6	4.7	20.7	63.7	13.2
I65	22.8	66.4	15.2	8.9	22.7	66.9	15.2
Avg. DGM	19.8	50.8	10.0	9.8	17.7	57.6	10.2
Avg. SMA	20.4	66.1	13.5	7.5	20.9	64.0	13.4
Avg. All	20.0	56.4	11.2	9.0	18.9	59.9	11.4

Table 6-7. Volumetric Properties for 2nd Set of Cores

Road No.	@ In-Place Va				@ Normalized 7.5% Va		
	VMA (%)	VFA (%)	V _{beff} (%)	Va (%)	VMA (%)	VFA (%)	V _{beff} (%)
SR15	20.0	52.1	10.4	9.6	18.2	58.7	10.7
US24	15.1	67.6	10.2	4.9	17.5	57.0	10.0
SR161	20.0	46.6	9.3	10.7	17.2	56.3	9.7
SR56	18.0	58.4	10.5	7.5	18.0	58.4	10.5
US30	14.8	75.7	11.2	3.6	18.3	58.9	10.8
SR66	19.1	55.1	10.5	8.6	18.2	58.7	10.7
SR135	15.1	76.8	11.6	3.5	18.7	59.6	11.1
US31	21.6	57.5	12.4	9.2	20.2	62.8	12.7
I74	20.6	70.9	14.6	6	21.9	65.7	14.4
SR64	19.7	75.2	14.8	4.9	21.9	65.8	14.4
I65	24.1	48.6	11.7	12.4	19.9	62.3	12.4
Avg. DGM	17.5	61.7	10.5	6.9	18.0	58.2	10.5
Avg. SMA	21.5	63.0	13.4	8.1	21.0	64.2	13.5
Avg. All	18.9	62.2	11.6	7.4	19.1	60.4	11.6

6.2 Maximum Theoretical Specific Gravity Variation

The material variation caused by construction processes or sample preparation in the laboratory is part of the testing variation. To quantify the material variation caused by construction and/or sample preparation, the Maximum Specific Gravity (G_{mm}) values measured from the cores and laboratory-fabricated samples (raw material samples) were compared to the mix design JMF G_{mm} values (plant loose mixture samples). Field cores were tested by combining two or three cores to obtain enough mixture for testing. The G_{mm} value is not affected by the mixture compaction, and therefore it only reflects the raw material (aggregate, binder content and type, fibers) variation in the mixture. The G_{mm} of plant loose mixtures was not measured.

Table 6-8 summarizes measurements, and replicate test results are given in Appendix 15.1 and 17.5. Figure 6-1 and Figure 6-2 show the G_{mm} ratios for each mixture. For dense-graded mixtures, SR15 and US24 had the largest difference in the measured maximum specific gravity values, the measured values being larger than the JMF. This suggests that the laboratory fabricated samples and field cores had less binder than the target P_b . Figure 6-3 shows theoretical binder content difference for

the raw material samples and field cores calculated from the JMF effective specific gravity G_{se} . The figure shows that SR24 samples may have 1.4 to 2% less binder than JMF was calling for.

Table 6-8. Summary of Measured G_{mm} Values for Each Mixture.

Road No.	JMF G_{mm}	Measured G_{mm}		
		Raw Material	1 st Coring	2 nd Coring
SR15	2.488	2.526	2.501	2.514
US24	2.417	2.479	2.489	2.467
SR161	2.457	2.460	2.483	2.487
SR56	2.659	2.649	2.690	2.674
US30	2.455	2.487	2.479	2.469
SR66	2.457	2.461	2.450	2.458
SR135	2.431	2.443	2.458	2.428
US31	2.980	2.973	3.013	3.004
I74	3.154	3.127	3.171	3.107
SR64	2.966	2.949	2.972	2.925
I65	3.017	2.968	2.943	3.050

The SMA mixtures had lower specific gravity than the target P_b indicating that prepared samples and/or cores had more binder than was intended. The US31 was the exception, having higher G_{mm} measured from the cores compared to the JMF, which indicates less binder in the mixture. This was the only SMA mixture without fibers and some binder drain-down may have occurred during the placement of the mixture. I65 mixture had a large variation in mixture maximum specific gravity values between the first and second coring, which suggest some non-homogeneity in the mixture. Table 6-9 gives the target JMF binder contents and calculated binder contents for each mixture.

Figure 6-1. Difference of Measured G_{mm} and JMF (DGM). Figure 6-2. Difference of Measured G_{mm} and JMF (SMA).

Figure 6-3. Theoretical Difference in Binder Content (P_b %). Table 6-9. Theoretical Binder Contents based on Measured G_{mm} .

Road No.	Estimated Binder Content P_b (%)			
	JMF	Raw Material	1 st Coring	2 nd Coring
SR15	5.6	4.6	5.3	4.9
US24	5.7	4.0	3.7	4.3
SR161	5.4	5.3	4.7	4.6
SR56	6.2	6.4	5.5	5.9
US30	6.2	5.4	5.6	5.8
SR66	5.7	5.6	5.9	5.7
SR135	6.4	6.1	5.7	6.5
US31	4.8	4.9	4.3	4.4
I74	5.5	5.9	5.3	6.2
SR64	5.5	5.8	5.4	6.2
I65	5.9	6.7	7.1	5.4

6.3 Testing Variation and Test Data Quality

Test data quality was evaluated by calculating testing variation and plotting the test data. The testing variation for the dynamic modulus and shear modulus testing, when no sample preparation variation is included, is around 5% to 10%. Then, any variation above that is due to the sample preparation (variation in the raw materials, compaction, and aging), anisotropy, and/or damage accumulation in the specimens.

Testing variation was evaluated two ways, first averaging all test data over all frequencies, and then evaluating testing variation for the 10 Hz and 5 Hz frequency data.

Stiffness data can be plotted to the Black space and Complex plane to study the test data quality. A good test data should form a smooth curve combining both test temperatures and frequencies to a single curve. Discontinuities or shift in the test data indicates damage accumulation in terms of aggregate skeleton movements in the specimen.

Table 6-10. Summary of Testing Variation for Stiffness (all frequencies).

Sample Set	Parameter	Coefficient of Variation (%)			
		40°C		54.4°C	
		Modulus	ϕ or δ	Modulus	ϕ or δ
Raw Materials	E* Unconfined	14.4	5.1	20.0	7.1
	G*	18.4	6.3	19.5	5.6
Plant Loose	E* Unconfined	16.1	4.0	19.5	5.9
	E* Confined	18.0	5.0	17.5	8.7
	G*	18.9	9.2	30.0	16.1
1 st Coring	E* Unconfined	24.2	10.4	21.9	14.5
	G*	17.5	9.1	19.0	14.1
2 nd Coring	E* Unconfined	20.5	7.0	20.4	11.5
	G*	21.8	7.2	22.9	9.4

Table 6-11. Raw Material Mixtures (all frequencies).

Road No.	Coefficient of Variation (%)							
	Unconfined Dynamic Modulus Test				Shear Modulus Test			
	40°C		54.4°C		40°C		54.4°C	
	E*	φ	E*	φ	G*	δ	G*	δ
SR15	6.9	4.5	19.1	10.1	18.6	4.8	10.5	5.5
US24	18.2	3.7	29.6	5.3	27.2	7.1	27.0	8.2
SR161	9.5	5.4	10.9	15.5	23.1	8.3	29.7	5.5
SR56	8.0	0.5	4.0	5.2	39.8	7.3	24.8	9.7
US30	18.5	11.1	31.7	6.9	23.2	8.3	14.0	5.3
SR66	5.7	6.3	5.2	5.0	10.1	4.6	27.3	7.4
SR135	19.1	3.8	22.2	1.8	18.9	11.6	47.2	8.1
US31	10.4	3.4	15.5	6.0	13.4	6.7	7.0	3.2
I74	24.1	9.6	30.7	7.0	2.7	1.9	9.3	2.7
SR64	5.0	3.9	26.0	8.5	9.2	2.5	9.2	2.0
I65	33.0	3.7	25.1	6.3	15.8	6.5	8.7	3.6
Avg.	14.4	5.1	20.0	7.1	18.4	6.3	19.5	5.6

Table 6-12. Plant Loose Mixtures (all frequencies).

Road No.	Coefficient of Variation (%)											
	Unconfined Dynamic Modulus Test				Confined Dynamic Modulus Test				Shear Modulus Test			
	40°C		54.4°C		40°C		54.4°C		40°C		54.4°C	
	E*	φ	E*	φ	E*	φ	E*	φ	G*	δ	G*	δ
SR15	6.7	2.3	10.7	7.6	19.0	3.6	48.5	21.3	31.2	17.3	31.0	23.9
US24	23.7	4.9	33.1	11.9	26.4	5.8	18.8	1.3	18.6	13.1	30.9	24.1
SR161	33.7	6.0	39.7	7.4	22.0	6.5	1.0	4.4	18.1	10.3	29.8	31.5
SR56	9.3	3.4	4.9	4.2	19.1	5.0	13.7	12.9	8.3	5.9	23.4	10.0
US30	14.1	9.0	29.9	3.1	12.6	4.4	23.5	13.1	9.8	5.0	33.6	17.2
SR66	13.7	0.8	19.1	3.7	12.0	8.9	8.1	9.1	34.3	7.2	45.5	13.9
SR135	20.8	4.0	43.0	8.1	28.2	1.9	23.8	9.8	15.6	7.9	26.4	15.5
US31	9.5	2.1	5.7	2.5	20.1	6.0	18.8	9.1	12.9	4.6	22.0	9.0
I74	12.6	2.1	10.5	8.1	11.6	6.8	16.2	2.2	10.0	3.4	11.5	9.7
SR64	24.9	5.6	14.9	3.4	12.0	1.8	12.8	3.0	38.2	22.3	50.0	15.3
I65	7.7	3.6	2.5	5.1	15.4	4.6	7.7	9.3	11.0	4.6	26.3	6.7
Avg.	16.1	4.0	19.5	5.9	18.0	5.0	17.5	8.7	18.9	9.2	30.0	16.1

Table 6-13. 1st Set of Cores (all frequencies).

Road No.	Coefficient of Variation (%)							
	Unconfined Dynamic Modulus Test				Shear Modulus Test			
	40°C		54.4°C		40°C		54.4°C	
	E*	φ	E*	φ	G*	δ	G*	δ
SR15	9.1	10.1			11.9	9.9	36.8	16.7
US24	20.0	15.4	16.3	23.4	23.0	7.7	31.5	21.2
SR161	6.6	8.4	10.0	8.1	13.0	9.6	8.3	9.8
SR56	29.5	23.1	9.4	7.6	11.0	10.3	7.3	9.7
US30	28.0	3.2	40.2	9.2	38.9	6.0	21.0	16.0
SR66	27.4	14.3			13.0	12.0	9.8	10.5
SR135	36.5	14.4	16.6	33.4	25.8	17.4	18.6	25.0
US31	10.5	5.3	21.6	9.9	19.8	9.2	17.9	12.5
I74	11.9	2.3	5.0	17.5	22.0	5.1	29.6	10.1
SR64	35.6	6.1	25.9	12.5	10.8	7.5	21.9	19.0
I65	51.4	12.0	51.7	8.8	3.0	5.3	5.8	4.6
Avg.	24.2	10.4	21.9	14.5	17.5	9.1	19.0	14.1

Table 6-14. 2nd Set of Cores (all frequencies).

Road No.	Coefficient of Variation (%)							
	Unconfined Dynamic Modulus Test				Shear Modulus Test			
	40°C		54.4°C		40°C		54.4°C	
	E*	φ	E*	φ	G*	δ	G*	δ
SR15	34.7	17.3	32.1	22.5	41.9	9.8	38.8	12.3
US24	29.4	5.7	45.4	19.1	11.7	8.7	32.9	9.4
SR161	18.1	6.2	6.6	7.2	11.2	5.6	30.8	8.1
SR56	8.8	6.9	11.1	18.3	26.2	2.1	11.9	9.0
US30	23.0	3.9	14.7	6.0	47.2	23.3	35.2	11.1
SR66	13.8	11.6	11.7	8.3	16.9	4.8	8.3	5.1
SR135	22.2	2.1	19.7	13.7	26.2	5.0	16.0	10.9
US31	8.9	8.4	19.1	4.7	11.1	6.2	31.1	11.3
I74	29.5	3.8	30.1	6.1	6.9	3.6	17.2	12.3
SR64	21.7	6.6	22.6	13.5	14.7	5.8	10.5	7.8
I65	15.4	4.9	11.6	6.6	25.9	4.5	19.3	6.6
Avg.	20.5	7.0	20.4	11.5	21.8	7.2	22.9	9.4

Table-6-15. Raw Material Mixtures (10 and 5Hz frequency).

Road No.	Coefficient of Variation (%)							
	Unconfined Dynamic Modulus Test				Shear Modulus Test			
	40°C/10Hz		54.4°C/5Hz		40°C/10Hz		54.4°C/5Hz	
	E*	φ	E*	φ	G*	δ	G*	δ
SR15	9.0	13.1	21.6	10.6	15.5	5.4	12.6	1.7
US24	17.2	8.3	30.7	3.8	33.9	10.5	9.8	1.4
SR161	11.4	5.6	14.9	69.4	20.2	9.0	29.7	2.9
SR56	7.5	0.7	1.7	3.7	34.8	6.1	12.0	5.6
US30	19.2	9.0	30.6	5.8	17.1	12.5	16.5	1.7
SR66	4.0	5.4	4.3	5.2	9.1	5.6	16.6	3.0
SR135	20.3	1.6	23.0	1.2	15.0	7.1	34.6	6.0
US31	10.9	3.2	16.3	5.1	9.8	6.0	4.8	0.1
I74	11.9	0.7	29.6	6.3	2.9	1.4	10.1	0.7
SR64	4.2	4.7	23.9	6.7	8.3	1.6	10.9	2.2
I65	35.4	3.8	25.0	6.7	9.8	7.3	9.4	4.6
Avg.	13.7	5.1	20.2	11.3	16.0	6.6	15.2	2.7

Table-6-16. Plant Mixtures (10 and 5Hz frequency).

Road No.	Coefficient of Variation (%)							
	Unconfined Dynamic Modulus Test				Shear Modulus Test			
	40°C/10Hz		54.4°C/5Hz		40°C/10Hz		54.4°C/5Hz	
	E*	φ	E*	φ	G*	δ	G*	δ
SR15	6.2	0.8	9.9	5.5	17.2	1.8	22.7	9.1
US24	23.1	3.8	34.2	13.6	13.8	3.8	21.4	2.3
SR161	33.0	7.6	38.9	7.9	10.6	6.1	17.2	1.5
SR56	9.3	3.4	5.5	2.6	2.3	2.5	14.9	3.0
US30	15.4	5.2	29.8	3.0	2.2	3.4	24.9	3.9
SR66	4.1	0.6	16.3	2.9	26.7	5.7	40.5	4.1
SR135	20.9	2.5	42.4	6.5	11.0	7.0	21.1	2.8
US31	8.3	2.0	7.3	2.5	8.5	3.7	13.4	3.1
I74	14.8	1.5	10.6	6.9	11.1	1.6	7.2	4.4
SR64	25.1	4.5	14.6	2.9	24.4	20.3	30.6	4.9
I65	8.6	3.9	2.8	4.0	4.7	2.2	21.0	5.2
Avg.	15.35	3.25	19.30	5.30	12.05	5.28	21.35	4.03

Table-6-17.1st Coring (10 and 5Hz frequency).

Road No.	Coefficient of Variation (%)							
	Unconfined Dynamic Modulus Test				Shear Modulus Test			
	40°C/10Hz		54.4°C/5Hz		40°C/10Hz		54.4°C/5Hz	
	E*	φ	E*	φ	G*	δ	G*	δ
SR15	7.8	9.4	--	--	5.1	3.5	24.3	10.3
US24	16.6	11.8	16.1	18.1	21.6	5.5	13.5	7.3
SR161	7.3	7.8	9.3	0.1	7.4	2.6	11.2	1.2
SR56	17.1	29.8	10.8	7.0	10.7	2.5	10.6	7.1
US30	30.1	1.5	39.3	11.0	21.9	2.8	18.6	10.5
SR66	31.1	6.5	--	--	2.0	2.4	7.9	2.8
SR135	36.3	6.6	18.7	29.5	10.8	4.6	6.4	8.0
US31	8.7	5.9	23.2	10.2	14.1	5.0	8.8	3.4
I74	20.8	1.1	4.1	13.1	14.4	4.9	17.6	6.1
SR64	37.8	4.7	24.9	7.6	7.2	2.7	14.9	8.2
I65	55.3	12.2	52.4	8.3	5.3	6.8	6.5	1.1
Avg.	24.45	8.85	22.09	11.66	10.95	3.94	12.75	6.00

Table-6-18. 2nd Coring (10 and 5Hz frequency).

Road No.	Coefficient of Variation (%)							
	Unconfined Dynamic Modulus Test				Shear Modulus Test			
	40°C/10Hz		54.4°C/5Hz		40°C/10Hz		54.4°C/5Hz	
	E*	φ	E*	φ	G*	δ	G*	δ
SR15	45.2	17.6	21.9	14.5	43.6	20.3	13.4	12.7
US24	31.2	3	46.9	17.7	7.4	3.4	16.2	4.6
SR161	47.2	15.8	6.2	2.8	11	4.4	31.5	3.4
SR56	10.4	8.4	13	14.7	28.4	3.4	8.1	2.3
US30	23.1	3.5	14	4.8	15.1	15.9	27.1	13.3
SR66	17.4	13.3	6.7	4.4	9.7	3.8	7.3	2.7
SR135	23.3	0.6	18.2	10.5	19.2	7.8	9.8	2.9
US31	8.9	7.9	18.1	2.1	9.5	3.3	9.1	4.1
I74	29.1	3	30.1	7.1	10.5	2.5	17.2	2
SR64	23.5	21.4	23	12.4	21.3	3	7.1	3.7
I65	17.9	6.2	8.5	7	16.3	0.6	14.5	5
Avg.	25.2	9.15	18.78	8.91	17.45	6.22	14.66	5.15

Table 6-19. Summary of IDT Strength Testing Variability

Road No.	Coefficient of Variation (%) ¹			
	Raw Material Mixtures	Plant Loose Mixture	1 st Set of Cores	2 nd Set of Cores
SR15	5.0	18.6	19.3	44.5
US24	13.8	0.2	18.9	1.5
SR161	2.6	17.5	14.4	20.9
SR56	6.8	20.1	1.3	12.9
US30	15.4	2.4	4.9	15.2
SR66	2.8	16.3	42.6	3.1
SR135	8.8	4.5	11.5	26.4
US31	8.4	9.2	28.1	6.1
I74	15.0	1.6	5.6	
SR64	4.7	3.8	37.3	23.0
I65	14.7	9.1	20.6	23.0
Avg.	8.9	9.4	18.6	17.7

(1) Only for 0.06 mm/min loading rate

7 TABULAR SUMMARIES OF TEST DATA

7.1 Dynamic Modulus

Table 7-1. Normalized Dynamic Modulus and Phase Angle (Raw Material).

Road No.	Unconfined $ E^* $ (MPa)				ϕ (degree)			
	40°		54.4°		40°		54.4°	
	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
SR15	1743	1327	618	522	33.1	32.5	28.9	26.9
US24	2308	1807	794	646	31.5	31.9	31.0	29.0
SR161	1735	1305	600	468	36.2	36.3	32.8	30.6
SR56	2884	2312	997	816	28.2	29.3	29.0	27.8
US30	3167	2547	1410	1193	29.9	30.1	24.0	22.4
SR66	2764	2167	891	724	30.0	30.8	28.2	26.4
SR135	2537	2046	894	748	28.5	29.2	25.6	23.7
US31	1829	1510	763	655	31.9	31.4	25.8	24.1
I74	2517	1885	1065	911	29.1	29.2	25.4	23.8
SR64	3969	3249	1393	1131	27.6	28.4	27.4	26.6
I65	2938	2374	1132	957	28.8	29.1	26.1	25.0
Avg. DGM	2448	1930	886	731	31.1	31.4	28.5	26.7
Avg. SMA	2813	2255	1088	914	29.4	29.5	26.2	24.9
Avg. All	2581	2048	960	797	30.4	30.7	27.6	26.0

Table 7-2. Normalized Dynamic Modulus (Plant Loose).

Road No.	Unconfined $ E^* $ (MPa)				Confined $ E^* $ (MPa)			
	40°		54.4°		40°		54.4°	
	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
SR15	1,053	799	463	398	2,065	1,669	1,164	1,069
US24	1,506	1,185	411	337	2,069	1,703	961	871
SR161	1,775	1,344	529	428	2,712	2,197	1,001	858
SR56	2,554	2,041	766	645	2,842	2,334	1,397	1,219
US30	2171	1741	714	620	1,842	1,492	1,235	1,103
SR66	2,621	2,070	748	614	2,836	2,329	1,158	1,000
SR135	2,212	1,794	943	807	2,757	2,282	1,318	1,151
US31	1,540	1,237	638	561	1,834	1,515	1,023	919
I74	2,733	2,202	1,056	883	3,538	2,864	1,466	1,255
SR64	3,135	2,541	1,067	892	3,267	2,697	1,417	1,233
I65	2,511	2,006	900	751	2,859	2,310	1,247	1,052
Avg.DGM	1,985	1,568	653	550	2,446	2,001	1,176	1,039
Avg.SMA	2,480	1,997	915	772	2,875	2,347	1,288	1,115
Avg. All	2,164	1,723	748	630	2,602	2,127	1,217	1,066
Ratio	—	—	—	—	1.20	1.23	1.63	1.69

Table 7-3. Normalized Phase Angle (Plant Loose).

Road No.	Unconfined ϕ (degree)				Confined ϕ (degree)			
	40°		54.4°		40°		54.4°	
	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
SR15	37.6	36.5	28.8	26.1	31.9	30.8	22.6	20.5
US24	32.0	31.3	29.1	26.3	28.5	28.0	21.5	19.6
SR161	35.0	35.2	33.0	30.3	29.1	28.9	28.7	26.2
SR56	30.4	30.7	28.9	27.1	28.5	28.8	27.2	25.4
US30	29.5	29.0	26.8	25.1	29.0	28.2	23.1	21.3
SR66	31.3	31.8	30.8	28.9	30.8	31.5	26.4	24.7
SR135	30.3	30.4	26.2	24.4	28.9	28.9	26.1	24.8
US31	30.9	29.8	24.7	23.1	29.1	28.2	23.5	22.0
I74	28.8	29.3	28.4	27.2	28.3	28.5	26.5	25.2
SR64	29.2	29.9	28.5	27.3	28.2	28.9	25.4	24.7
I65	31.1	31.1	29.9	28.7	29.1	29.3	27.0	26.2
Avg. DGM	32.3	32.1	29.1	26.9	29.5	29.3	25.1	23.2
Avg. SMA	30.0	30.0	27.9	26.6	28.7	28.7	25.6	24.5
Average all	31.5	31.4	28.6	26.8	29.2	29.1	25.3	23.7
Ratio	—	—	—	—	0.93	0.93	0.88	0.88

Table 7-4. Original Dynamic Modulus (1st Set of Cores).

Road No.	$ E^* $ (MPa)				ϕ (degree)			
	40°		54.4°		40°		54.4°	
	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
SR15	843	694	1	1	32.39	29.77	1	1
US24	1,989	1,438	955	897	35.52	33.44	18.11	16.26
SR161	2,048	1,607	783	695	32.85	32.16	24.24	24.06
SR56	2,868	2,134	766	672	32.82	32.33	27.52	25.01
US30	1,799	1,477	557	496	33.00	31.11	24.19	21.26
SR66	1,725	1,545	1	1	32.27	33.12	1	1
SR135	3,157	2,335	1,163	1,082	33.12	31.62	20.43	17.71
US31	1,812	1,356	680	598	40.45	36.74	23.5	21.8
I74	2,396	1,846	1116	941	31.73	31.86	24.74	23.29
SR64	3,505	2,752	982	839	31.44	30.61	25.89	23.61
I65	2,634	2,042	923	793	31.88	32.19	26.04	25.03
Avg. DGM	2061	1604	845	768	33.1	31.9	22.9	20.9
Avg. SMA	2587	1999	925	793	33.9	32.9	25.0	23.4
Avg. All	2252	1748	881	779	33.4	32.3	23.9	22.0

(1) LVDT brackets broke off from the specimen surface during testing

Table 7-5. Normalized Dynamic Modulus (1st Set of Cores)

Road No.	E* (MPa)				φ (degree)			
	40°		54.4°		40°		54.4°	
	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
SR15	1055	865	1	1	32.39	29.77	1	1
US24	2166	1567	1039	977	35.52	33.44	18.11	16.26
SR161	3025	2387	1162	1026	32.85	32.16	24.24	24.06
SR56	3105	2315	830	727	32.82	32.33	27.52	25.01
US30	1787	1467	553	493	33.00	31.11	24.19	21.26
SR66	2216	1986	1	1	32.27	33.12	1	1
SR135	3044	2249	1119	1042	33.12	31.62	20.43	17.71
US31	1903	1425	713	626	40.45	36.74	23.5	21.8
I74	2454	1891	1143	964	31.73	31.86	24.74	23.29
SR64	2964	2318	826	708	31.44	30.61	25.89	23.61
I65	2620	2031	918	788	31.88	32.19	26.04	25.03
Avg. DGM	2343	1834	941	853	33.1	31.9	22.9	20.9
Avg. SMA	2485	1916	900	772	33.9	32.9	25.0	23.4
Avg. All	2394	1864	923	817	33.4	32.3	23.9	22.0

(1) LVDT brackets broke off from the specimen surface during testing

Table 7-6. Original and Normalized Dynamic Modulus (2nd Set of Cores).

Road No.	Original E* (MPa)				Normalized E* (MPa)			
	40°		54.4°		40°		54.4°	
	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
SR15	2774	2029	753	628	3207	2354	872	724
US24	3361	2585	1178	991	2842	2177	990	835
SR161	1957	1653	793	657	2869	2433	1165	959
SR56	2786	2091	897	733	2252	1684	727	598
US30	2615	2086	880	730	2112	1681	714	596
SR66	2052	1686	883	751	2117	1740	911	774
SR135	2716	2115	884	736	2167	1682	708	593
US31	1252	985	596	517	1169	920	559	487
I74	2533	2025	1193	1033	2078	1657	976	846
SR64	4338	3558	1892	1514	3370	2746	1443	1155
I65	2004	1610	919	741	2393	1927	1099	884
Avg. DGM	2609	2035	895	747	2509	1964	870	726
Avg. SMA	2532	2045	1150	951	2253	1813	1019	843
Avg. All	2581	2038	988	821	2416	1909	924	768

7.2 Shear Modulus

Table 7-7. Normalized Shear Modulus and Phase Angle (Raw Material).

Road No.	G* (MPa)				δ (degree)			
	40°		54.4°		40°		54.4°	
	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
SR15	433	316	117	78	51.9	53.0	62.3	59.3
US24	873	661	178	130	42.2	43.7	62.0	60.5
SR161	572	432	139	97	44.7	46.0	60.2	58.9
SR56	1011	744	225	165	32.7	33.2	53.4	51.4
US30	760	582	194	137	40.3	40.5	55.7	52.3
SR66	748	592	257	196	36.8	38.0	54.7	52.5
SR135	858	668	261	194	36.5	37.8	54.5	52.1
US31	417	305	117	85	47.5	46.8	57.8	54.7
I74	419	313	113	81	47.0	45.6	58.5	56.4
SR64	706	549	166	121	38.9	38.8	56.0	54.0
I65	572	443	172	132	39.9	38.6	51.2	47.8
DGM	750	570	196	142	40.7	41.7	57.5	55.3
SMA	528	402	142	105	43.3	42.5	55.9	53.2
Average	670	509	176	129	41.7	42.0	56.9	54.5

Table 7-8. Normalized Shear Modulus and Phase Angle (Plant Loose).

Road No.	G* (MPa)				δ (degree)			
	40°		54.4°		40°		54.4°	
	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
SR15	260	179	61	37	57.9	58.8	69.4	66.6
US24	269	186	63	40	56.0	56.9	67.4	63.5
SR161	467	330	87	56	51.8	52.9	68.2	65.0
SR56	555	409	147	99	45.4	47.0	60.2	60.8
US30	352	246	91	66	50.9	51.6	64.3	61.6
SR66	523	394	147	104	43.7	44.4	62.6	63.0
SR135	526	383	175	125	47.3	48.6	64.8	62.3
US31	345	257	88	65	47.2	46.2	54.1	50.7
I74	667	497	185	138	41.5	41.8	51.6	50.4
SR64	663	509	197	152	37.7	38.6	54.6	51.3
I65	599	457	190	145	39.2	38.8	48.4	45.2
Avg. DGM	422	304	110	75	50.4	51.5	65.3	63.3
Avg. SMA	569	430	165	125	41.4	41.4	52.2	49.4
Avg. All	475	350	130	93	47.1	47.8	60.5	58.2

Table 7-9. Original Shear Modulus (1st Set of Cores).

Road No.	G* (MPa)				δ (degree)			
	40°		54.4°		40°		54.4°	
	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
SR15	133	93	40	29	62.96	62.75	69.01	67.73
US24	178	125	56	40	65.87	65.83	66.34	64.29
SR161	260	187	53	39	50.14	51.86	65.45	64.39
SR56	165	115	41	30	59.10	59.95	68.79	67.02
US30	226	157	47	35	58.64	58.93	66.27	62.30
SR66	183	127	50	34	56.10	56.70	64.86	62.59
SR135	211	145	45	33	57.60	56.99	64.17	61.67
US31	245	192	84	66	51.28	49.19	50.75	47.44
I74	299	223	99	75	46.82	45.59	52.29	50.79
SR64	335	250	85	64	46.94	46.45	56.46	54.41
I65	475	376	152	116	42.27	41.25	49.10	45.56
Avg. DGM	194	136	47	34	58.6	59.0	66.4	64.3
Avg. SMA	339	260	105	80	46.8	45.6	52.2	49.6
Avg. All	246	181	68	51	54.3	54.1	61.2	58.9

Table 7-10. Normalized Shear Modulus (1st Set of Cores).

Road No.	G* (MPa)				δ (degree)			
	40°		54.4°		40°		54.4°	
	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
SR15	174	121	50	35	62.96	62.75	69.01	67.73
US24	209	147	65	45	65.87	65.83	66.34	64.29
SR161	335	241	67	47	50.14	51.86	65.45	64.39
SR56	194	135	47	33	59.10	59.95	68.79	67.02
US30	209	145	44	33	58.64	58.93	66.27	62.30
SR66	264	183	69	46	56.10	56.70	64.86	62.59
SR135	229	157	48	35	57.60	56.99	64.17	61.67
US31	259	203	88	69	51.28	49.19	50.75	47.44
I74	307	230	101	77	46.82	45.59	52.29	50.79
SR64	274	205	70	53	46.94	46.45	56.46	54.41
I65	515	409	165	127	42.27	41.25	49.10	45.56
Avg. DGM	231	161	56	39	58.6	59.0	66.4	64.3
Avg. SMA	339	262	106	82	46.8	45.6	52.2	49.6
Avg. All	270	198	74	55	54.3	54.1	61.2	58.9

Table 7-11. Original Shear Modulus (2nd Set of Cores).

Road No.	G* (MPa)				δ (degree)			
	40°		54.4°		40°		54.4°	
	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
SR15	313	231	147	117	54.97	53.40	71.42	67.99
US24	502	352	164	121	51.43	52.87	68.71	67.02
SR161	547	414	125	89	42.47	42.64	60.46	59.48
SR56	669	498	162	113	45.42	45.90	62.03	60.06
US30	532	396	252	220	48.03	47.05	63.08	54.06
SR66	336	254	126	93	46.89	46.00	58.27	56.09
SR135	704	526	240	194	44.72	45.25	65.79	61.66
US31	315	236	72	55	51.58	48.19	53.98	50.10
I74	453	337	131	97	47.97	46.18	57.14	53.13
SR64	992	772	162	119	37.86	37.89	55.28	52.25
I65	438	342	139	104	47.27	46.58	54.06	51.31
Avg. DGM	515	382	174	135	47.7	47.6	64.3	60.9
Avg. SMA	550	422	126	94	46.2	44.7	55.1	51.7
Avg. All	527	396	156	120	47.1	46.5	60.9	57.6

Table 7-12. Normalized Shear Modulus (2nd Set of Cores).

Road No.	G* (MPa)				δ (degree)			
	40°		54.4°		40°		54.4°	
	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
SR15	365	270	173	137	54.97	53.40	71.42	67.99
US24	406	283	131	97	51.43	52.87	68.71	67.02
SR161	686	524	160	114	42.47	42.64	60.46	59.48
SR56	668	498	162	113	45.42	45.90	62.03	60.06
US30	390	288	182	159	48.03	47.05	63.08	54.06
SR66	365	276	137	101	46.89	46.00	58.27	56.09
SR135	520	383	172	139	44.72	45.25	65.79	61.66
US31	354	265	81	61	51.58	48.19	53.98	50.10
I74	412	306	119	88	47.97	46.18	57.14	53.13
SR64	859	662	136	100	37.86	37.89	55.28	52.25
I65	594	469	194	145	47.27	46.58	54.06	51.31
Avg. DGM	486	360	159	123	47.70	47.59	64.25	60.91
Avg. SMA	555	425	132	98	46.17	44.71	55.12	51.70
Avg. All	511	384	150	114	47.15	46.54	60.93	57.56

7.3 Triaxial Shear Strength Test

Table 7-13. Triaxial Shear Strength (Raw Material).

Road No.	Shear Strength (7.5 mm/min @ 54.4°C)		
	c (kPa)	ϕ (°)	S _u (kPa)
SR15	100.37	46.59	504.25
US24	113.76	45.77	559.95
SR161	89.22	44.89	429.58
SR56	170.23	45.68	835.84
US30	234.27	44.18	1108.61
SR66	158.57	42.11	714.21
SR135	144.48	44.37	686.93
US31	176.78	42.02	794.49
I74	133.89	41.54	595.07
SR64	145.59	40.92	637.74
I65	163.44	42.04	734.81
Avg. DGM	144.4	44.8	691.3
Avg. SMA	154.9	41.6	690.5
Avg. All	148.2	43.6	691.0

Table 7-14. Triaxial Shear Strength (Plant Loose).

Road No.	Shear Strength Parameter					
	7.5 mm/min			50 mm/min		
	c (kPa)	ϕ (°)	S _u (kPa)	c (kPa)	ϕ (°)	S _u (kPa)
SR15	62.39	47.61	321.79	102.55	43.50	477.36
US24	64.06	44.45	305.17	74.10	43.21	342.58
SR161	98.13	45.00	473.79	144.25	40.78	629.81
SR56	135.69	44.80	651.90	202.16	41.74	902.69
US30	139.35	44.47	664.08	193.74	42.88	888.64
SR66	135.26	44.14	639.48	194.39	41.61	865.18
SR135	139.35	44.47	664.08	197.47	43.38	916.54
US31	183.38	39.63	779.90	266.22	38.56	1105.28
I74	114.74	42.26	518.58	209.66	38.97	878.52
SR64	120.23	38.99	504.03	207.50	38.64	863.05
I65	192.97	41.89	864.58	369.30	35.35	1429.32
Avg. DGM	110.6	45.0	531.5	158.4	42.4	717.5
Avg. SMA	152.8	40.7	666.8	263.2	37.9	1069.0
Avg. All	125.96	43.43	580.67	196.49	40.78	845.36

7.4 IDT Strength Test

Table 7-15. IDT Strength (Raw Material).

Road No.	IDT Tensile Strength (0.06 mm/min @ 35°C)	
	S _t (Original) (kPa)	S _t (Normalized) (kPa)
SR15	29.23	36.6
US24	48.65	58.9
SR161	26.72	31.2
SR56	110.21	120.2
US30	106.88	114.6
SR66	66.83	74.2
SR135	76.21	89.1
US31	119.41	122.1
I74	82.26	84.1
SR64	80.77	79.9
I65	129.13	124.9
Avg. DGM	66.4	75.0
Avg. SMA	102.9	102.8
Avg. All	79.7	85.1

Table 7-16. IDT Tensile Strength (Plant Loose).

Road No.	IDT Tensile Strength S _t (kPa)	
	0.06 mm/min	0.39 mm/min
SR15	27.90	86.14
US24	37.58	50.13
SR161	39.66	77.23
SR56	53.39	141.88
US30	60.81	111.23
SR66	74.23	118.66
SR135	64.57	110.38
US31	93.94	159.56
I74	87.76	150.04
SR64	94.49	166.77
I65	144.61	209.15
Avg. DGM	51.16	99.38
Avg. SMA	105.20	171.38
Avg. All	70.81	125.56

Table 7-17. Original IDT Tensile Strength (1st and 2nd Set of Cores).

Road No.	IDT Tensile Strength S _t (kPa)			
	1 st Set of Cores		2 nd Set of Cores	
	0.06 mm/min	0.39 mm/min	0.06 mm/min	0.39 mm/min
SR15	38.09	48.52	18.45	
US24	10.39	35.65	44.8	106.2
SR161	47.83	43.33	68.65	133.94
SR56	35.06	49.97	50.6	132.93
US30	74.25	100.69	118.71	175.70
SR66	7.86	22.33	59.52	119.00
SR135	66.78	116.03	78.64	134.58
US31	89.31	136.54	102.07	188.14
I74	119.01	110.18	33.13	111.65
SR64	91.18	119.21	62.91	107.11
I65	116.25	204.11	87.38	115.71
Avg. DGM	40.0	59.5	62.8	133.7
Avg. SMA	103.9	142.5	71.4	130.7
Avg. All	63.3	89.7	65.9	132.5

Table 7-18. Normalized IDT Tensile Strength (1st and 2nd Set of Cores).

Road No.	IDT Tensile Strength S _t (kPa)			
	1 st Set of Cores		2 nd Set of Cores	
	0.06 mm/min	0.39 mm/min	0.06 mm/min	0.39 mm/min
SR15	76.4	78.2	29.2	
US24	14.6	42.1	29.5	79.8
SR161	140.6	82.5	198.5	223.7
SR56	52.3	69.8	42.3	98.6
US30	71.7	97.2	69.6	124.3
SR66	16.7	32.7	72.7	113.5
SR135	57.1	121.7	47.2	102.3
US31	103.5	144.7	88.8	171.7
I74	117.0	123.8	32.6	125.4
SR64	61.1	85.5	43.9	76.2
I65	112.3	197.4	166.2	148.5
Avg. DGM	61.3	74.9	69.9	123.7
Avg. SMA	98.5	137.9	82.9	130.5
Avg. All	74.8	97.8	74.6	126.4

7.5 Correlation of $|E^*|$ and $|G^*|$ at Each Test ConditionTable 7-19. Correlation (R^2) of $|E^*|$ and $|G^*|$ at each test condition.

	Unconfined E* Raw Material				
G*	40/10	40/5	54.5/10	54.4/5	All
40/10	0.39	0.40	0.22	0.19	0.7747
40/5	0.41	0.42	0.24	0.20	
54.4/10	0.41	0.42	0.24	0.21	
54.4/5	0.42	0.44	0.26	0.23	
	Unconfined E* Plant Mixture				
G*	40/10	40/5	54.5/10	54.4/5	All
40/10	0.82	0.80	0.78	0.72	0.9487
40/5	0.82	0.81	0.79	0.74	
54.4/10	0.82	0.82	0.91	0.87	
54.4/5	0.82	0.83	0.93	0.90	

Table 7-20. Correlation (R^2) of $|E^*|$ and $|G^*|$ at each test condition (cores).

Plant Mix	Unconfined E* (original data)	Unconfined E* (normalized data) 1 st Cores				
G*	All	40/10	40/5	54.5/10	54.4/5	All
40/10	0.6652	0.46	0.51	0.45	0.33	0.7593
40/5		0.43	0.47	0.42	0.34	
54.4/10		0.22	0.24	0.34	0.28	
54.4/5		0.22	0.22	0.33	0.26	
Plant Mix	Unconfined E* (original data)	Unconfined E* (normalized data) 2 nd Cores				
G*	All	40/10	40/5	54.5/10	54.4/5	All
40/10	0.7626	0.32	0.36	0.48	0.43	0.6436
40/5		0.32	0.36	0.48	0.44	
54.4/10		0.43	0.41	0.19	0.15	
54.4/5		0.32	0.30	0.10	0.08	

7.6 Correlation between Stiffness and Strength

Table 7-21. Summary of R^2 between $|E^*|$ and Strength (all mixtures).

Correlation Confident R^2		Strength ¹			
		c	ϕ	S_u	$S_{t\ 0.06}$
Stiffness $ E^* $ @ 40°C & 10Hz	Raw	0.36	-0.22	0.30	0.46
	Plant: Unconfined	0.47	-0.32	0.45	0.48
	Plant: Confined	0.12	-0.20	0.09	0.20
	1 st Coring (original)	—	—	—	0.10
	1 st Coring (normalized)	—	—	—	0.10
	2 nd Coring (original)	—	—	—	-0.14
	2 nd Coring (normalized)	—	—	—	-0.04
Stiffness $ E^* $ @ 54.4°C & 5Hz	Raw	0.59	-0.30	0.50	0.54
	Plant: Unconfined	0.59	-0.40	0.57	0.61
	Plant: Confined	0.09	-0.07	0.09	0.10
	1 st Coring (original)	—	—	—	0.0
	1 st Coring (normalized)	—	—	—	0.09
	2 nd Coring (original)	—	—	—	-0.02
	2 nd Coring (normalized)	—	—	—	0.0

(1) 7.5 mm/min for triaxial strength and 0.06 mm/min for IDT tensile strength.

Table 7-22. Summary of R^2 between $|G^*|$ and Strength (all mixtures).

Correlation Confident R^2		Strength ¹			
		c	ϕ	S_u	$S_{t\ 0.06}$
Stiffness $ G^* $ @ 40°C & 10Hz	Raw	0.07	0.09	0.11	0.05
	Plant	0.45	0.33	0.43	0.46
	1 st Coring (original)	—	—	—	0.42
	1 st Coring (normalized)	—	—	—	0.32
	2 nd Coring (original)	—	—	—	0.05
	2 nd Coring (normalized)	—	—	—	0.12
Stiffness $ G^* $ @ 54.4°C & 5Hz	Raw	0.17	0.00	0.19	0.14
	Plant	0.64	0.44	0.61	0.67
	1 st Coring (original)	—	—	—	0.35
	1 st Coring (normalized)	—	—	—	0.29
	2 nd Coring (original)	—	—	—	0.0
	2 nd Coring (normalized)	—	—	—	0.01

(1) 7.5 mm/min for triaxial strength and 0.06 mm/min for IDT tensile strength.

Table 7-23. Summary of R^2 between $|E^*|$ and Strength (DGM).

Correlation Confident R^2		Strength ¹			
		c	ϕ	S_u	$S_{t\ 0.06}$
Stiffness $ E^* $ @ 40°C & 10Hz	Raw	0.91	-0.34	0.93	—
	Plant: Unconfined	0.92	-0.38	0.87	0.48
	Plant: Confined	0.19	-0.04	0.18	0.19
Stiffness $ E^* $ @ 54.4°C & 5Hz	Raw	0.96	-0.12	0.83	—
	Plant: Unconfined	0.75	-0.03	0.7	0.74
	Plant: Confined	0.2	-0.07	0.15	0.68

(1) 7.5 mm/min for triaxial strength and 0.06 mm/min for IDT tensile strength.

Table 7-24. Summary of R^2 between $|E^*|$ and Strength (SMA).

Correlation Confident R^2		Strength ¹			
		c	ϕ	S_u	$S_{t\ 0.06}$
Stiffness $ E^* $ @ 40°C & 10Hz	Raw	-0.26	-0.45	-0.18	—
	Plant: Unconfined	-0.03	-0.84	0	0
	Plant: Confined	-0.06	-0.58	0	0
Stiffness $ E^* $ @ 54.4°C & 5Hz	Raw	-0.38	-0.35	-0.18	—
	Plant: Unconfined	-0.1	-0.69	0	0
	Plant: Confined	-0.25	-0.57	-0.09	-0.07

(1) 7.5 mm/min for triaxial strength and 0.06 mm/min for IDT tensile strength.

Table 7-25. Summary of R^2 between $|G^*|$ and Strength (DGM).

Correlation Confident R^2		Strength ¹			
		c	ϕ	S_u	$S_{t\ 0.06}$
Stiffness $ G^* $ @ 40°C & 10Hz	Raw	0.32	-0.14	0.72	—
	Plant	0.62	-0.14	0.54	0.49
Stiffness $ G^* $ @ 54.4°C & 5Hz	Raw	0.34	-0.47	0.67	—
	Plant	0.8	-0.16	0.79	0.6

(1) 7.5 mm/min for triaxial strength and 0.06 mm/min for IDT tensile strength.

Table 7-26. Summary of R^2 between $|G^*|$ and Strength (SMA).

Correlation Confident R^2		Strength ¹			
		c	ϕ	S_u	$S_{t\ 0.06}$
Stiffness $ G^* $ @ 40°C & 10Hz	Raw	-0.02	-0.26	0	—
	Plant	-0.01	-0.68	0	0
Stiffness $ G^* $ @ 54.4°C & 5Hz	Raw	0	0	0.13	—
	Plant	0	-0.74	0.08	0.1

(1) 7.5 mm/min for triaxial strength and 0.06 mm/min for IDT tensile strength.

8 PLOTS OF TEST DATA

Figure 8-1. Black Space, Mix SR15.

Figure 8-2. Complex Plane, Mix SR15.

Figure 8-3. Black Space, Mix US24.

Figure 8-4. Black Space, Mix US24.

Figure 8-5. Black Space, Mix SR161.

Figure 8-6. Black Space, Mix SR161.

Figure 8-7. Black Space, Mix SR56.

Figure 8-8. Black Space, Mix SR56.

Figure 8-9. Black Space, Mix US30.

Figure 8-10. Black Space, Mix US30.

Figure 8-11. Black Space, Mix SR66.

Figure 8-12. Black Space, Mix SR66.

Figure 8-13. Black Space, Mix SR135.

Figure 8-14. Black Space, Mix SR135.

Figure 8-15. Black Space, Mix US31.

Figure 8-16. Black Space, Mix US31.

Figure 8-17. Black Space, Mix I74.

Figure 8-18. Black Space, Mix I74.

Figure 8-19. Black Space, Mix SR64.

Figure 8-20. Black Space, Mix SR64.

Figure 8-21. Black Space, Mix I65.

Figure 8-22. Black Space, Mix I65.

9 ASPHALT BINDER STIFFNESS AND AGING

9.1 Introduction

The aging of asphalt binders and mixtures is due to oxidation and volatilization of specific components of binder. Oxidation is the chemical reaction between oxygen in the air and asphalt. Oxygen combines with hydrogen in the asphalt and forms water. The removal of hydrogen will increase the carbon/hydrogen ratio, which leads to hardening (higher viscosity and stiffness) and loss of ductility and adhesion.

Volatilization is the evaporation of the lighter hydrocarbon molecules. Volatilization results in loss of ductility and increase in specific gravity. Volatilization rate increases with the increase in temperature. Aging takes place during plant mixing, hauling, placement operations, and during in-place service of the pavement.

Two laboratory-aging procedures try to simulate mixture aging. The short-term aging procedure STOA (AASHTO PP2) is designed to simulate the aging the mixture will undergo during plant mixing and construction. The long-term aging procedure LOA (AASHTO PP2) is designed to simulate the total aging the compacted mixture will undergo during 7 to 10 years of service. In the STOA procedure, a loose mixture is aged in the forced draft oven 2 or 4 hours at 135°C temperature. The Superpave mix design uses 2-hour aging, and 4-hour aging is intended for the mixture to be used to prepare specimens for performance testing. In the LOA procedure, a compacted mixture of aggregate and asphalt binder is aged in a forced draft oven for 5 days at 85°C.

For asphalt binders there are also two aging methods developed to simulate the binder aging. Based on AASHTO T240, the Rolling Thin Film Oven Test (RTFOT) method “indicates approximate change in properties of asphalt during conventional hot-mixing at about 150°C (302°F), as indicated by viscosity and other rheological measurements. It yields a residue, which approximates the asphalt condition as incorporated in the pavement. If the mixing temperature differs appreciably from the

150°C (302°F) level, more or less effect on properties will occur. This method can also be used to determine mass change, which is a measure of asphalt volatility”.

Based on AASHTO PP1, the Pressure Aging Vessel method (PAV) “covers the accelerated aging (oxidation) of asphalt binders by means of pressurized air and elevated temperature. The test method is intended to simulate in-service oxidative aging of asphalt binders and is intended for use with residue from T240 (RTFOT)”.

9.1.1 Binder Viscosity and Temperature Susceptibility

All asphalts (bitumen) are thermoplastics; they become harder, i.e., stiffer (more viscous) with decrease in temperature and softer (less viscous) with increase in temperature. Temperature susceptibility varies from one source of crude oil to another. Even when two asphalts have the same stiffness or viscosity at a specific temperature, they may still respond differently to the change in temperature, as Figure 9-1 illustrates.

Figure 9-1. Temperature Susceptibility of Binders.

The binder temperature susceptibility can be expressed using Eq. (3), where A is the intercept and VTS is the slope of the regression line. Research shows that the VTS is related to the aging of binders. Mirza and Witczak (1995) developed a global aging model for asphalt mixtures where they expressed A and VTS for tank and mix lay-down conditions, and then for long term aging.

$$\log(\log(\eta)) = A + VTS \log(T_R) \quad (38)$$

where:

η = viscosity, cP

T_R = Temperature in Ranking, °R

A and VTS regression coefficients

There also exists a relation between the measured penetration for 100g, 5 sec loading and viscosity in poise. The penetration data is valid only for temperatures 10 and 25°C. The viscosity-penetration relation is considered valid between a penetration range of 3 to 300 and is more accurate between values of 3 and 15 (Mirza & Witczak, 1995). The statistical model relating penetration to viscosity is given by Eq. (39) The viscosity corresponding to the softening point and penetration 800 is equal to 13,000 poise for most unmodified binders.

$$\log \eta = 10.5012 - 2.2601 \log(Pen) + 0.00389(\log(Pen))^2 \quad (39)$$

Bonaquist, Pellinen and Witczak (1998) developed an equation for converting binder stiffness modulus $|G^*|$ (Pa) to binder viscosity η (cP), given by Eq. (40). The relation between phase angle, binder stiffness and VTS slope is given by Eq. (41).

$$\eta = \left(\frac{|G^*|}{\omega} \right) \cdot \left(\frac{1}{\sin \delta} \right)^{a_0 + a_1 \omega + a_2 \omega^2} \quad (40)$$

where:

ω = angular frequency, rad/sec

a_0, a_1, a_2 = model coefficients

$$\delta = 90 - (24.878 + 7.2734VTS) \log |G^*| + (1.8118 + 0.77054VTS) (\log |G^*|)^2 \quad (41)$$

The model parameters, a_0 , a_1 and a_2 can be changed according to unmodified or modified binders, RTFOT and PAV conditions. Typical values of the η - $|G^*|$

conversion equation model parameters were reported by Bonaquist et al., (1998) and are presented in Table 9-1.

Table 9-1. Model Parameters for η - $|G^*|$ Empirical Conversion Equation

SUBSET	No	a0	a1	a2	Se	Se/Sy	R ²
Unmodified Tank	321	3.254765	0.109889	-0.000696	561654	0.190	0.964
Modified Tank	108	7.312996	0.062311	-0.000468	847646	0.268	0.930
Modified RTFOT	99	7.215250	0.195295	-0.001683	208017	0.156	0.976
Modified PAV	94	4.089242	0.182680	-0.001468	750367	0.218	0.953
All modified	301	4.480776	0.174142	-0.001408	1114823	0.396	0.844
All Tank	429	3.453603	0.118474	-0.000781	1106875	0.367	0.866
All	676	3.639216	0.131373	-0.000901	1055338	0.377	0.858

9.1.2 Short Term Aging Study

A study by Pellinen (1996) compared 2- and 4-hour short-term oven aged laboratory-fabricated asphalt mixtures to the plant produced mixtures. The SST shear stiffness $|G^*|$ of the 4-hour aged mixtures was 23% higher than the stiffness of the 2-hour aged mixtures, see Table 9-2.

However, the study could not confirm whether 2- or 4-hour aged samples matched to the asphalt plant aging because data did not show any systematic trends. Then, some plant-aged mixtures were softer and some were stiffer than the laboratory-aged mixtures. The study did not have information of the type, capacity, etc. of the asphalt plants used in the experiment, so the reasons for the deviations could not be quantified. However, other studies have shown that mixing time, temperature, aggregate moisture content, and binder grade used affect the aging of asphalt binder and mixture during the plant mixing production.

Table 9-2. Average Stiffness Ratios of Aged Mixtures (Pellinen et. al, 1995).

Stiffness Ratio	SST $ G^* $ at 20°C & 10 Hz	ϵ_p from RSCH Test at 10°C
4 h aging / 2 h aging	1.23	1.49
2 h aging / Plant mix	0.94	0.62
4 h aging / Plant mix	1.16	1.00

9.1.3 Laboratory Binder Aging Study

In a study by Witczak and Bonaquist (2000), five binders used in the FHWA-ALF study (Stuart) were tested for conventional and Superpave binder properties. Tests were performed for four conditions: tank, RTFOT aged, PAV aged, and recovered from mix after laboratory short-term 4-hour oven aging. Figure 9-2 shows the viscosity ratios of aged and tank binder for different aging methods. Viscosity ratios were measured by first developing the binder A and VTS parameters, and then using binder temperature susceptibility, Eq. (4), to compute the viscosity of binder at 40°C.

The binders ranged from very soft (AC-5) to very stiff modified binders (Styrelf). The RTFOT aged and recovered binders gave similar stiffness ratios, being about 3 to 6 times more viscous than tank binders. The PAV aging indicated that binders might increase in viscosity up to 16 times. As the figure confirms, the RTFOT is indicative of the STOA aging of mixture. The PAV aging should be indicative of the long-term stiffening of binder and should be comparable to the LOA aging of mixtures.

Figure 9-3 shows the binder viscosity ratios relative to the soft AC-5 (PG58-28) binder at each condition. At tank condition, AC-20 (PG64-22) is 2.23, Novophalt (PG76-22) is 5.82, and Styrelf is 13.81 times more viscous than AC-5. AC-20 is one high-temperature PG grade stiffer than AC-5, Novophalt is 3, and Styrelf is 4 PG grades stiffer. The viscosity increase is then approximately 2.54 for one PG high-temperature grade of binder stiffness for the tank conditions. Similarly, the viscosity increase per one PG high-temperature grade is approximately 2.17, 2.32, and 2.91 for the RTFOT, recovered, and PAV aged binders, respectively.

Figure 9-2. Viscosity Ratios of Binder Aging.

Figure 9-3. Viscosity Increase Relative to AC-5 (PG58-28) binder.

Based on this study, the binder stiffness increase is approximately 2 to 2.5 for the RTFOT aged binder and short-term oven aged mixture per one high-temperature PG grade. For the PAV aged binder and then for the long term oven aged mixture, the stiffness increase is higher, being approximately 3 for one high-temperature PG grade.

9.1.4 In-place Binder Aging Study

Test results discussed below were obtained from Indiana SPS 9A study (Shah, (2004), described in more detail in Appendix 12. In this study, extracted binder properties were measured at tank condition and at different age intervals up to 48 months or 4 years of in-service. Figure 9-4 shows that based on measured penetration (25°C) values, the aging is most severe during mixing and lay-down and after 12 months, aging levels off substantially. The highest loss of penetration was for the softest binder of PG58-28. Figure 9-5 shows that the viscosity increase at 135°C indicated similar trends.

Figure 9-4. Penetration Decrease during in-place Aging of Binders.

Figure 9-6 compares the viscosity of tank and 48 months aged binders at 135°C. The figure shows that at tank conditions the PG64-28 is about 1.5, and PG76-28 is about 2 times stiffer than PG58-28. Also, surprisingly, the PG 64-28 binder did not age as much as PG58-28.

Figure 9-7 shows the viscosity difference at 40°C predicted from the A and VTS parameters obtained from the binder measurements. The stiffness ratio between PG58-28 and PG64-28 was 2 and PG76-28 and PG58-28 about 3. This is slightly less than

was measured for the modified binders in the FHWA-ALF study. PG64-16 is 7 times stiffer due to the low temperature grade difference compared to the PG64-28 or PG58-28. This indicates that the selection of performance testing temperature is extremely important. The PG 64-28 seems to have the same stiffness as PG58-28 after 48 months of service.

Figure 9-5. Viscosity Increase during in-place Aging of Binders.

Figure 9-6. Viscosity Ratios @ 135°C for Tank and 48 months in-place aged binders.

Figure 9-7. Viscosity Ratios @ 40°C for Tank and 48 months in-place aged binders.

Figure 9-8 shows the binder specific gravity increase as a function of aging for each of the binders. The specific gravity increase and loss of volatiles was highest during mixing and placement and leveled off after that. Overall, the modified binder PG76-28 had the highest specific gravity increase being 6.8%, while for PG64-22 the binder specific gravity increase was 3.3%, being highest of the non-modified binders. However, Figure 9-4 and Figure 9-5 show that PG64-28 did not age as severely as did the other non-modified binders and PG76-22.

Figure 9-9 shows the correlation between the binder temperature susceptibility parameter VTS and specific gravity increase of binder. It is clear that the VTS parameter explains some of the aging. However, there must be some other mechanisms that explain the odd aging behavior of the PG64-28 binder compared to the other binders studied.

Figure 9-8. Viscosity Ratios for Tank and 48 months in-place aged binders.

Figure 9-9. VTS and Specific Gravity Increase.

9.2 Viscosity of Study Binders

Table 9-3 summarizes the binder test results given in Appendix 19. The A and VTS values, given in Table 9-4, were estimated employing binder temperature susceptibility equations given above. Binder for SR64 was not tested due to lack of material and values for I74 were used instead. For all binders, regression was done using only viscosity and penetration data because the softening point data seemed to give erroneous results.

Table 9-3. Measured Binder Properties.

Road No.	Pen 0.1mm	T _{R&B} °C	η 175°C mPa-s	η 135°C mPa-s	η 120°C mPa-s
SR15	72.8	48.8	102.1	400.0	947.9
US24	65.0	48.0	93.8	635.4	958.3
SR161	55.0	51.0	100.0	410.4	1064.8
SR56	38.3	51.8	118.8	685.4	1641.8
US30	49.6	56.0	227.1	1058.5	2552.2
SR66	34.6	53.3	143.8	633.3	1625.0
SR135	44.0	53.0	152.1	635.4	1562.5
US31	53.3	66.0	412.5	1887.5	5166.7
I74	39.2	59.0	293.8	1620.7	4123.0
SR64	—	—	—	—	—
I65	41.6	73.5	287.5	1589.2	4764.7

Table 9-4. Estimated A and VTS values.

Road No.	Measured Tank		Predicted RTFO Global model visc _{t=0}	
	A	VTS	A	VTS
SR15	10.503	-3.5165	10.26369	-3.41816
US24	10.467	-3.5016	10.2287	-3.40368
SR161	10.738	-3.5971	10.49212	-3.49651
SR56	10.589	-3.5363	10.34728	-3.43741
US30	9.7503	-3.2312	9.532038	-3.14084
SR66	10.555	-3.5227	10.31423	-3.42419
SR135	10.351	-3.4512	10.11594	-3.35469
US31	9.0354	-2.9689	8.83713	-2.88587
I74	9.6311	-3.1815	9.416171	-3.09253
SR64	9.6311	-3.1815	9.416171	-3.09253
I65	9.5909	-3.1672	9.377095	-3.07863

Table 9-5 gives calculated viscosity values at testing temperature and at 50 mm deep in the pavement. Table 9-6 gives the back-calculated viscosity values obtained from the Hirsch predictive model for both $|G^*|$ and $|E^*|$. Figure 9-10 shows the correlation back-calculated binder viscosity obtained from the plant mixtures tested at 40°C and 54.4°C. Correlation is fair ($R^2 = 0.7401$ for $|G^*|$) and there is no bias in the 40°C test results, while the 54.4°C testing shows increasing bias for the stiffer binders and correlation for $|G^*|$ drops to 0.6357, see Figure 9-11.

Table 9-5. Predicted binder viscosity.

Road No.	Tank				RTFO (visc _{t=0})		
	η 40°C Pa-s	η 54.4°C Pa-s	C° Z=50mm	η z=50 Pa-s	η 40°C Pa-s	η 54.4°C Pa-s	η z=50 Pa-s
SR15	5,214	674	45.5	2,207	5,482	567	6,736
US24	7,699	568	45.6	2,581	6,642	674	7,933
SR161	13,562	996	47.2	2,556	8,985	823	7,854
SR56	23,215	2,426	47.2	4,921	16,769	1,468	15,576
US30	13,917	1,708	45.6	7,223	17,736	1,864	23,254
SR66	22,527	2,368	47.9	4,958	23,587	1,983	15,698
SR135	19,416	3,585	47.0	4,567	16,303	1,489	14,407
US31	10,680	1,602	46.5	8,699	10,353	1,535	28,236
I74	32,311	4,611	46.0	13,152	32,034	3,244	43,462
SR64	37,681	4,980	48.3	9,083	32,034	3,244	29,537
I65	27,319	4,059	47.8	9,580	24,642	2,699	31,228

Table 9-6. Predicted binder viscosity.

Road No.	Back Calculated from test data			
	η 40°C Pa-s	η 54.4°C Pa-s	C° Z=50mm	η z=50 Pa-s
	$ G^* $	$ G^* $	$ E^* $	$ E^* $
SR15	6169.24	478	4259.19	871
US24	6,580	536	8,817	600
SR161	16,004	934	11,121	1,058
SR56	22,556	2,355	23,874	2,496
US30	10,127	1,150	17,706	2,267
SR66	20,551	2,455	24,504	2,281
SR135	20,395	3,304	18,436	3,866
US31	11,301	1,205	10,059	1,999
I74	34,412	4,103	30,210	5,118
SR64	35,303	4,699	40,060	5,261
I65	29,178	4,365	25,460	3,753

Figure 9-10. Comparison of back-calculated and Measured Binder viscosity at 40°C.

Figure 9-11. Comparison of back-calculated and Measured Binder viscosity at 54.4°C.

10 PURDUE LABORATORY AGING STUDY

Although all laboratory fabricated specimens and field cores were sealed in plastic bags and stored in the cold room at 0°C temperature before testing, there was a concern that specimens may have aged when stored for longer times. Therefore, a special study was conducted at Purdue bituminous laboratory to investigate the laboratory aging effects on the dynamic modulus $|E^*|$ of the mixture.

Six specimens, 100 mm in diameter and 150 mm in height, were prepared using SR161 plant loose mixture, as explained in Chapter 3. All six specimens were tested in July 2004 at 40°C temperature. Then, specimens were separated into two groups: Group 1 samples were sealed in plastic bags and placed in the freezer at 0°C temperature, and Group 2 samples were stored in the laboratory shelves being exposed to the air oxidation at the ambient laboratory temperature.

The second testing of specimens was conducted at the end of March 2005, when approximately eight months had passed on the first testing. The results for the self-stored specimens are summarized in Table 10-1, and results for the freezer stored specimens are summarized in Table 10-2. Figure 10-1 shows the creep strain at the end of dynamic modulus testing.

Table 10-1. Test Results for Self Stored Specimens.

Self Stored Specimens	Specimen ID	Dynamic Modulus $ E^* $ (MPa)					
		Frequency (Hz)					
		25	10	5	1	0.5	0.1
First Testing	6S	3245	2368	1831	1084	897	677
	4S	2635	1997	1527	833	665	463
	10S	2622	1863	1474	808	630	430
	Average	2834	2076	1611	908	731	523
	St. Dev.	356.00	261.60	192.65	152.64	145.11	134.10
	CV%	12.56	12.60	11.96	16.80	19.86	25.62
Second Testing	6S	3458	2491	1928	1069	852	544
	4S	2595	1808	1357	757	599	407
	10S	3063	2184	1657	932	747	493
	Average	3039	2161	1647	919	733	481
	St. Dev.	432.01	342.08	285.62	156.39	127.11	69.24
	CV%	14.22	15.83	17.34	17.01	17.35	14.39

(1) F: stored in freezer; S: stored on shelf

(2) Standard deviation

Table 10-2. Test Results for Freezer Stored Specimens.

Freezer Stored Specimens	Specimen ID	Dynamic Modulus $ E^* $ (MPa)					
		Frequency (Hz)					
		25	10	5	1	0.5	0.1
First Testing	5F	3096	2135	1612	904	728	484
	1F	3079	2243	1722	980	790	512
	2F	2822	2091	1614	899	711	460
	Average	2999	2156	1649	928	743	485
	St. Dev.	153.52	78.21	62.94	45.39	41.58	26.03
	CV%	5.12	3.63	3.82	4.89	5.60	5.36
Second Testing	5F	2533	1748	1337	722	577	383
	1F	3595	2477	1842	989	790	527
	2F	2490	1709	1257	679	527	337
	Average	2873	1978	1479	797	631	416
	St. Dev.	625.93	432.59	317.19	167.95	139.67	99.12
	CV%	21.79	21.87	21.45	21.08	22.12	23.85

(3) F: stored in freezer; S: stored on shelf

(4) Standard deviation

Figure 10-1. Creep Strain at the End of Dynamic Modulus Test.

The tables above show that testing variation is quite high ranging from 12 to 25% for the self-stored samples, and from 5 to 23% for the freezer-stored specimens. Part of this variation comes from the sample preparation and part from testing itself.

In some cases, the second testing indicates increased stiffness and decreased stiffness for the specimens. The creep strain at the end of the testing indicates the amount of possible damage in the specimens. Figure 10-1 suggests that specimens 4S,

,6S, 2F, and 5F have some damage accumulation after the first testing because the creep strain is increased. To study the damage in the specimens, Figure 10-2 to Figure 10-5 show individual samples plotted to the Black space.

Figure 10-2. Black Space; Specimen 10S.

Figure 10-3. Black Space; Specimen 6S.

Figure 10-4. Black Space; Specimen 5F.

Figure 10-5. Black Space; Specimen 1F.

Figure 10-2 shows that specimen 10S has aged during storage and very little damage is present in the test results. Figure 10-3 shows that specimen 6S has more damage (increased face angle values) and aging effects are less (increase in stiffness).

Figure 10-4 shows that specimen 5F has some damage and specimen is softer than originally tested. Figure 10-5 shows that specimen 1F has aged in the freezer and there is some damage accumulation during testing .

Figure 10-6 shows the average stiffness differences, which indicates that there is about 12% difference between self-stored and freezer-stored specimens. This is calculated based on the slope of the regression lines given in the figure, $1.042/1.923 = 1.12$ or about 12%. The reason why the freezer-stored specimens tested slightly softer than the original testing indicates is unknown, and may be just a testing variation in terms of some systematic temperature errors in the testing.

It can be estimated that the aging was on the order of 16% for the 10S specimen that did not have any damage and clearly showed effects of aging in the test results.

Figure 10-6. Average Stiffness Differences.

Two-way ANOVA was performed to further investigate if the means (averages) of the groups are significantly different. Analysis results are given in Table

10-3, which shows that the differences between groups were not statistically significant.

Table 10-3. Two-Way ANOVA Results.

	1 st Testing	2 nd Testing	Group 1	Group 2
Group 1	No		N/A	
Group 2	No			
1 st Testing	N/A		No	
2 nd testing			No	

Based on the above analysis, it can be concluded that the damage accumulation in the test specimens was masking some of the aging effects in the laboratory aging study. However, there is approximately a 12 to 17% increase in the mixture stiffness due to aging of specimens stored in the laboratory shelves during an 8 month period compared to the specimens stored in the freezer at 0°C temperature. However, this difference is not statistically significant due to the large testing variation. The specimens stored in the freezer did not show aging relative to the original test results.

11 FORENSIC STUDY OF INTERSTATE I74

11.1 Background

The section of Interstate 74 located near Indianapolis suffered rutting failure in the eastbound lanes in Summer 1999. A study team was assembled by INDOT in Fall 1999 to study the failure. The forensic study conducted by the team included taking cores from the failed and survived section of the road in Fall 1999. A set of additional cores were taken in Spring 2002 for the Purdue University investigation, before the road was resurfaced in the same Spring.

The first set of cores, obtained in Fall 1999, were tested by Heritage Research Group, and the additional set of cores obtained in Spring 2002 were tested by Purdue University. All the background, mix design, and QC/QA information, as well as test results of the first set of cores presented in the following sections were gathered from the forensic data compiled by Heritage Research Group (communication with Gerry Huber, 2004 and “*I-74 Pavement Investigation, Contract: RS-23371*” report by D. Andrews, July 31, 2001). Figure 11-1 shows a schematic plan of pavement coring conducted in Fall 1999. Cores were obtained from Road Mark 69 to Road Mark 73.

Passing Lane		(Not in Scale)								
Driving Lane	Transverse Slab	Transverse Slab								
			x	x	x	x	x	x	x	Left Wheel path
			x	x	x	x	x	x	x	Center of Lane
			x	x	x					Right Wheel Path

Figure 11-1. A Schematic Coring Plan for I74 Pavement Investigation in 1999.

Based on the gathered information, Interstate I74 was constructed in 1998 by E&B Paving Inc. in two phases designated as Phase 1 and Phase 2. Table 11-1 shows

the construction schedule of the work. The Interstate rehabilitation work consisted of 2x76 mm (2x3”) of intermediate 19-mm Superpave base mixture placed in two lifts followed by 25 mm (1”) of 12.5-mm Superpave surface mixture with PG28-28 binder. The westbound (WB) lanes and the eastbound (EB) lanes were constructed by the same paving crew using the same equipment. There were no changes in the JMF of mixtures between WB and EB construction.

Table 11-1. Construction Schedule in 1998.

Construction Phase	Lane	Intermediate Base Mix	Surface Mix
Phase 1	WB	June10 – July 10	July 17 – July 18
Phase 2	EB	Sept.16 – Sept. 25	Oct. 29 – Oct. 31

During the Summer of 1999, the EB lanes developed 12 to 15 mm of rutting, while the WB lanes had only 1 to 3 mm of rutting. Transverse slabs cut from the pavement confirmed that the rutting occurred in the surface layer and in the first lift of the intermediate base layer, shown in Figure 11-2 and Figure 11-3. The WB lanes were constructed first during Phase 1 followed by the EB lanes in Phase 2, and during Phase 2 construction all interstate traffic was directed to the WB lanes.

The forensic study team investigated a number of factors that could have influenced the pavement rutting, including binder and mixture stiffness, aggregate properties, and mixture composition by collecting and analyzing QC/QA data and sampling and testing in-place materials.

The study team’s final report (D. Andrews, July 31, 2001) concluded that the failure of the EB lanes was due to the soft mixture caused by the soft binder and slightly higher binder and finer material contents compared to the WB lanes. The binder stiffness measured from the extracted binder in the EB lanes was approximately one binder grade lower than that of the survived WB lanes.

Figure 11-2. Cutting Trench in I74 (Courtesy of Heritage Research).

Figure 11-3. Rutting Failure in I74 (Courtesy of Heritage Research).

The study team recommendation was that the EB travel lane should be milled to a depth of 50 mm and resurfaced with 120 kg/m² of 12.5 mm nominal maximum aggregate size surface mix. In addition, mix design should be conducted using design traffic of 32 million ESALs, and PG 70-22 instead of PG64-28 should be used in the mix. The study team report also recommended the following items be considered for future INDOT construction projects:

1. Binder testing procedures should include testing of RTRO material
2. PG binder grade should be increased for traffic according to the latest AASHTO requirements.
3. Samples should be taken and tested by INDOT for volumetric properties and acceptance should be based on them. (A full implementation of volumetric acceptance was expected in 2003).

11.2 Mix Design Information

Both mixtures, the 12.5 mm surface mixture and 19 mm intermediate base mixture, were designed according to the Superpave mix design system. The design traffic was 12 million ESALs for both mixtures, and JMF report gave N_{des} of 109 SGC gyrations based on the Superpave mix design specification valid at the time. The PG binder grade specified for both mixtures was PG64-28 with no adjustments to the speed or traffic for high temperature grade based on the study team report. Adjustment for the traffic level based on the current MP2 is one binder grade.

Table 11-2 and Table 11-3 give information of the individual aggregate stockpiles and blended gradations, as well as gradation criteria prescribed in the Superpave specification. The surface mixture had Blast-Furnace slag while the intermediate mixture had 15% Reclaimed Asphalt (RAP).

Table 11-2. Aggregate Blending (I74 Forensic: Surface Mixture).

Material	B-L Slag	Dolomite	Dol. Sand	Nat. Sand	Adjusted Blend %	Spec. Limit %
Source	Levy Portage 2451	IMI Huntington 2211	IMI Huntington 2211	Benchmark Indianapolis 2312		
% Used	31	31	28	10		
Sieve (mm)	% Passing	% Passing	% Passing	% Passing		
12.5	100.0	100.0	100.0	100.0	100.0	
9.5	85.3	90.0	100.0	100.0	93.0	90-100
4.75	14.5	21.0	100.0	99.5	51.0	
2.36	6.0	8.0	92.0	90.5	42.0	32-47.2
1.18	5.0	6.0	62.0	70.0	30.0	≤31.6
0.6	4.0	4.2	36.0	46.0	20.0	≤23.5
0.3	3.8	3.8	18.0	14.0	11.0	≤18.7
0.15	3.0	3.0	6.8	3.0	7.0	
0.075	1.8	1.8	3.0	1.7	4.0	2-10
G _{sb}	2.443	2.670	2.699	2.603	2.596	

Table 11-3. Aggregate Blending (I74 Forensic: Intermediate Base Mixture).

Material	Crushed Stone	Crushed Stone	Stone Sand	RAP	Adjusted Blend %	Spec. Limit %
Source	Benchmark Indianapolis 2312	Benchmark Indianapolis 2312	Benchmark Indianapolis 2312	Benchmark Indianapolis 2312		
% Used	50	20	15	15		
Sieve (mm)	% Passing	% Passing	% Passing	% Passing		
25.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	89.0	100.0	100.0	84.0	93.0	90-100
12.5	49.0	100.0	100.0	75.0	73.0	≤90
9.5	30.0	100.0	100.0	69.0	62.0	
4.75	8.0	63.0	100.0	48.0	41.0	
2.36	4.5	18.0	92.0	40.0	28.0	23-34.6
1.18	4.0	4.5	62.0	25.0	18.0	≤22.3
0.6	3.5	4.3	36.0	15.0	13.0	≤16.7
0.3	3.5	3.6	18.0	9.0	9.0	≤13.7
0.15	3.5	3.0	7.5	6.5	7.5	
0.075	2.5	2.5	3.8	5.0	5.0	2.0-8.0
G _{sb}	2.592	2.582	2.589	2.773	2.615	

Figure 11-4 shows the aggregate blend gradations and the Maximum Density Line (MDL) for both mixtures. To quantify the gradation deviations, Table 11-4 shows the distance of the 2.36 and 4.75 mm sieves from the MDL in terms of percent passing. Based on calculations and visual inspection of gradation curves, the surface layer mixture had slightly S-shape gradation. Table 11-4 also shows the average gradation of both aggregate blends by averaging the percent passing of sieves 0.075, 0.6, 2.36, and 9.5 mm.

Figure 11-4. Gradation of Aggregate Blending (I74 Forensics).

Table 11-4. Avg. Gradations, Fineness, and Distance from the MDL ¹ (I74 Forensics).

Layer Mixture	Average Gradation (% passing)	Fineness Modulus FM_{300}	Distance from MDL 4.75 mm (% passing)	Distance from MDL 2.36 mm (% passing)	S-shape Gradation
Surface	39.8	22.0	13.7	5.2	Yes
Intermediate	27.0	21.5	6.4	6.6	No

(1) Maximum Density Line

The three Bailey method ratios of Coarse Aggregate Ratio (CA Ratio), Coarse Aggregate Ratio of Fine Aggregate (CA of FA_C), and Fine Aggregate Ratio of Fine

Aggregate (FA of FA_F) are shown in Table 11-5. The definitions and formulas for the ratios are the same as previously explained for study mixtures.

Table 11-5. The Bailey Method Gradation Ratios (I74 Forensics).

Layer Mixture	CA Ratio	CA FA _C Ratio	FA FA _F Ratio	Predicted VMA (%)	Predicted VCA _{mix} (%)
Surface	0.18	0.48	0.35	16.1	44.8
Intermediate	0.55	0.44	0.50	25.6	40.3

Table 11-6 gives the consensus aggregate properties measured from the aggregate blend and reported by the contractor. Specification criteria are dependent of the design traffic level, as Table 11-6 shows.

Table 11-6. Combined Aggregate Consensus Properties (I74 Forensics).

Layer Mixture	Actual Design ESALs (10 ⁶)	Uncompacted Voids in Fine Aggregate (%)		Coarse Aggregate Angularity (%)		Sand Equivalency, (%)	
		Actual	Criteria ¹	Actual	Criteria ¹	Actual	Criteria ¹
Surface	12	46.0	45	100.0/95.0	95/90 ²	75.0	45
Intermediate	12	47.0	45	100.0/95.0	95/90	76.7	45

(1) Minimum value

(2) 95/90 denotes that 95 percent of the coarse aggregate has one fractured face and 90 percent has two or more fractured faces.

Table 11-7 shows the actual design ESALs of the paving projects and SGC gyrations, as well as the relative density at the initial and maximum gyrations. The N_{des} gyrations used are slightly higher than required by the current specification. Table 11-8 presents the JMF Superpave mix design properties. In addition, Table 11-9 gives the binder absorption in the mixture by weight and volume, and the effective and total binder by volume.

Furthermore, Table 11-9 gives the aggregate surface area (SA) and binder film thickness calculated using the surface area and weight of effective binder. The surface area was calculated in the same way as described for study mixtures.

Table 11-7. Superpave Gyratory Compaction Effort (I74 Forensics).

Layer Mixture	PG	Actual Design ESALs (10 ⁶)	Specification Design ESALs (10 ⁶)	Actual Compaction					
				No. of Gyration			% G _{mm}		
				N _{ini}	N _{des}	N _{max}	N _{ini}	N _{des}	N _{max}
Surface	64-28	12	3 to < 30	8	109	174	85.4	96.0	97.6
Intermediate	64-28	12	3 to < 30	8	109	174	84.0	96.0	97.9

Table 11-8. JMF Mixture Design Properties (I74 Forensics).

Layer Mixture	NMA ¹ (mm)	P _b ²	P _b ³	Volumetrics @ N _{des} (%)			Specific Gravity			Dust/ P _{beff}	Tensile Strength Ratio ⁴ (%)
				V _a	VMA	VFA	G _{se}	G _{mm}	G _{mb @ N_{des}}		
Surface	9.5	6.5		4.0	15.8	74.6	2.691	2.435	2.337	0.8	93.6
Surface	9.5		6.2	4.0	15.5						
Interm.	12.5	4.8	4.5	4.0	13.9	71.3	2.650	2.463	2.365	1.2	87.4
Interm.	12.5		4.5	4.0							

(1) NMA¹ = Nominal Maximum Aggregate Size

(2) Binder recovery using ignition (by weight-%)

(3) Binder recovery using extraction (by weight-%)

(4) Tested from specimens with 7.0 ± 1.0 percent air voids.

Table 11-9. Binder Absorption¹, Surface Area, and Binder Film Thickness from JMF (I74 Forensics).

Layer Mixture	P _{ba} (%)	P _{beff} (%)	V _{ba} (%)	V _{beff} (%)	V _{b-total} (%)	Surface area SA (m ² /kg)	Film thickness (μm)
Surface	1.35	5.15	3.1	11.7	14.8	4.87	11.1
Intermediate	0.49	4.31	1.1	9.9	11.0	3.28	16.4

(1) All values calculated from “binder recovery using ignition values”.

11.3 Binder Stiffness Investigation

Both the QC and QA testing indicated that asphalt binder met the specification requirements for both high and low temperatures. The results given in Table 11-10 were obtained at 64°C for the high temperature and -18°C for the low temperature.

Standard deviation for the QC binder testing was twice as high for the RTFO aged binder (0.22) than for the original binder testing (0.11). Values ranged from 2.24 to 2.92 kPa for the RTFO binder and from 1.21 to 1.61 kPa for the original binder.

Table 11-10. Summary of QC/QA Binder Testing (1998).

Temperature	Test	Parameter	Binder Aging	Quality Control Result	Quality Assurance Result	MP1 Criteria
High (64°C)	DSR	$G^*/\sin\delta$ (kPa)	Original	1.42	1.17	1.00
			RTFO	2.57	2.64	2.20
Low (-18°C)	BBR	S (kPa)	PAV	233	249	300
		m		0.318	0.310	0.300

The Asphalt Institute performed forensic testing on extracted binder from cores taken from the WB and EB lanes. Table 11-11 shows test results for the binder graded as the Rolling Thin Film Oven (RTFO) material. It is evident that the binder in the WB lanes was about one grade stiffer than in the EB lanes, although the same PG grade was specified in the mix design. The binder in the WB lanes was graded as PG 70 while the binder in the EB lanes was graded as PG 64. Also for the WB lanes, the binder stiffness in the intermediate layer was higher than that of the surface layer.

Table 11-11. DSR Binder Testing Summary (I74 Forensic, 1999).

Asphalt Institute Testing	Eastbound Lanes			Westbound Lanes		
DSR	Surface Layer	Top Inter. Layer	Bottom Inter. Layer	Surface Layer	Top Inter. Layer	Bottom Inter. Layer
G^* (kPa) @ 64°C	2.12	2.43	2.75	4.31	7.0	4.18
δ (°) @ 64°C	85.6	84.9	84.5	82.8	81.8	83.3
$G^*/\sin\delta$ (kPa) @ 64°C	2.13	2.44	2.77	4.34	7.07	4.21
Failing Temperature (°C) Sec. RTFOT 2.2 kPa	63.8	64.8	65.8	68.8	72.7	68.9

Using binder stiffness $|G^*|$ and phase angle δ measured by Asphalt Institute, binder temperature susceptibility values A and VTS were developed using Eq. (39). The model coefficients used were for the RTFO aged binder. The developed values are given in Table 11-12. The table also gives the estimated tank binder properties using Global aging model (Mirza et al., 1995) with aging Code 1 used in the analysis. Table 11-13 gives the predicted binder viscosity values.

Table 11-12. Estimated A and VTS for I74 from recovered binder.

	Estimated Tank		Estimated RTFO	
Mix	A	VTS	A	VTS
I74 S EB	10.51567	-3.5291	10.276	-3.4304
I74 S WB	11.77385	-3.9721	11.499	-3.861
I74 INT EB	10.53727	-3.5351	10.297	-3.4362
I74 INT WB	11.39732	-3.8308	11.133	-3.7237

Table 11-13. Predicted Binder Viscosity.

Mix	Tank				RTFO (visc _{t=0})		
	η 40°C Pa-s	η 54.4°C Pa-s	C° Z=50mm	η z=50 Pa-s	η 40°C Pa-s	η 54.4°C Pa-s	η z=50 Pa-s
I74 S EB	2,580	296	46.0	991	7,930	819	2,914
I74 S WB	10,523	748	46.0	3,253	34,442	2,168	10,106
I74 INT EB	3,081	343	46.0	1,169	9,548	957	3,461
I74 INT WB	16,589	1,196	46.0	5,171	55,365	3,546	16,403

11.4 Mixture QC/QA and Forensic Testing

The QC/QA test data for the surface and intermediate base mixtures were obtained from the I74 forensic study data collected by Heritage Research Group in 1999. The aggregate blend gradations are given in Table 11-14 and Table 11-15 for the surface and the intermediate base mixture, respectively.

Table 11-16 shows the fineness modulus FM_{300} calculated for both mixtures. Both surface and intermediate mixture had more fines than the westbound mixtures. Mixture properties from QC and QA data are given in Table 11-17. In addition, some properties from the forensic study are available and included.

Table 11-14. Aggregate Gradation (I74 Forensic: Surface Mixture).

Sieve (mm)	% Passing by weight									
	Cold Feed			Main Line						
	QC		Design	QC		QA		Forensic ¹		Design
	EB	WB		EB	WB	EB	WB	EB	WB	
19	100.0	100.0	100.0	100.0	100.0	100.0	100.0			100.0
12.5	100.0	100.0	100.0	100.0	99.8	100.0	99.6			100.0
9.5	90.4	90.0	92.3	92.0	89.9	92.9	90.7			93.0
4.75	52.1	50.8	49.0	55.5	51.0	55.1	50.5			51.0
2.36	39.8	39.1	39.2	42.2	38.3	41.4	37.2	42.1	34.6	42.0
1.18	27.3	26.9	27.8	29.0	25.7	29.2	25.1			30.0
0.6	17.5	17.0	17.2	19.5	17.3	20.2	17.1			20.0
0.3	8.5	7.9	8.8	10.7	9.6	11.4	9.7			11.0
0.15	3.4	3.2	4.1	5.8	5.2	6.4	5.9			7.0
0.075	1.4	1.3	2.1	4.0	3.5	4.3	4.0	5.6	4.9	4.0

¹From Cores

Table 11-15. Aggregate Gradation (I74 Forensic: Intermediate Base Mixture).

Sieve (mm)	% Passing by weight									
	Cold Feed			Main Line						
	QC		Design	QC		QA		Forensic		Design
	EB	WB		EB	WB	EB	WB	EB	WB	
25	100.0	100.0	100	100.0	100.0	100.0	99.9			100
19	92.9	93.6	92.1	94.7	94.4	95.7	95.0			93
12.5	73.7	71.6	70.8	72.2	74.1	74.1	72.8			73
9.5	55.8	61.0	60.4	61.4	63.3	62.5	61.4			62
4.75	36.5	39.7	38.8	41.7	41.0	42.3	39.4			41
2.36	24.9	24.2	25.7	27.0	24.8	26.8	22.8	29.0	25.4	28
1.18	16.5	16.2	16	18.1	17.1	18.3	15.3			18
0.6	10.5	10.3	10.3	13.3	12.4	13.6	11.9			13
0.3	5.0	6.6	6.2	9.8	9.2	10.2	8.9			9.0
0.15	3.0	4.6	4.5	7.2	6.8	7.8	6.8			7.5
0.075	2.0	3.2	3.1	5.4	5.4	6.2	5.7	6.4	6.3	5.0

Table 11-16. Average Gradations and Fineness Modulus (I74 Forensic).

Layer Mixture	Direction	Test Type	Fineness Modulus FM ₃₀₀
Surface	EB	QC	20.5
		QA	22.1
	WB	QC	18.3
		QA	19.6
Intermediate	EB	QC	22.4
		QA	24.2
	WB	QC	21.4
		QA	21.4

Table 11-17. In-Place Mixture Properties (QA, QC, 1999).

Property	QC				QA			
	Surface		Intermediate		Surface		Intermediate	
	EB	WB	EB	WB	EB	WB	EB	WB
P _b	6.2	6.1	4.6	4.5	6.2	5.6	4.7	4.4
SGC Pill VMA ¹	15.5	14.6	14.0	13.4	—	—	—	—
SGC Pill V _a ¹	4.2	4.2	4.0	3.9	—	—	—	—
In -Place V _a ³	10.4 ³	8.1 ³	4.5 ³	7.3 ³	9.5	8.7	8.0	9.0
In-Place Density	2273	2266	2344	2288	2219	2268	2296	2261
G _{mm}	2.441 ²	2.465 ²	2.456 ²	2.468 ²	2.452	2.485	2.496	2.484

(1) From Sperpave gyratory compactor pills at design gyrations

(2) Based on calculated G_{mm} values.

(3) In-place air voids (density)

Table 11-18. In-Place Mixture Properties (I74 Forensic, 1999).

Property	Forensic ²			
	Surface		Intermediate	
	EB	WB	EB	WB
P _b	5.9 ² /6.2 ³	5.6 ² /6.2 ³	4.5 ² /4.7 ³	4.2 ² /4.4 ³
SGC Pill VMA ¹	—	—	—	—
SGC Pill V _a ¹	—	—	—	—
In -Place V _a	4.4	8.4	5.5	7.5
In-Place Density	2340	2283	2338	2303
G _{mm}	2.449	2.492	2.474	2.489

(1) From Superpave gyratory compactor pills at design gyrations

(2) From Heritage

(3) From Asphalt Institute

Table 11-19. Binder Absorption¹, Surface Area, and Binder Film Thickness from QC data for gyratory pills (I74 Forensics).

Layer Mixture	P _{ba} (%)	P _{beff} (%)	V _{ba} (%)	V _{beff} (%)	V _{b-total} (%)	Surface area SA (m ² /kg)	Film thickness (μm)
Surface EB	1.5	5.1	3.3	11.5	14.8	4.69	11.3
Surface WB	1.8	4.6	4.1	10.6	14.7	4.22	11.4
Intermediate EB	0.4	4.5	1.0	10.2	11.2	4.74	9.7
Intermediate WB	0.6	4.2	1.3	9.7	11.1	4.59	9.4

(1) All values calculated from “binder recovery using ignition values”.

Table 11-20. Binder Absorption¹, Surface Area, and Binder Film Thickness from QA data for gyratory pills (I74 Forensics)¹.

Layer Mixture	P _{ba} (%)	P _{beff} (%)	V _{ba} (%)	V _{beff} (%)	V _{b-total} (%)	Surface area SA (m ² /kg)	Film thickness (μm)
Surface EB	1.7	4.9	3.8	11.1	14.9	4.92	10.4
Surface WB	1.9	4.1	4.3	9.4	13.7	4.45	9.5
Intermediate EB	1.2	3.8	2.7	9.0	11.7	5.12	7.7
Intermediate WB	0.8	3.9	1.8	9.1	10.9	4.61	8.7

(1) QC data were used for air voids for Superpave gyratory compactor pills at design gyrations

(2) All values calculated from “binder recovery using ignition values”.

11.5 Pavement Cores Tested and Analyzed by Heritage Research Group

Heritage Research Group used Simple Shear Tester (SST) to measure shear resistance of surface and intermediate mixtures using Frequency Sweep at Constant Height (FSCH) test and Repeated Shear at Constant Height (RSCH) test. Specimens were prepared by stacking two thin cores to satisfy the requirement for test specimen height specified by the test protocol, if needed.

The SST shear frequency sweep testing was conducted at 30°C, 40°C and 50°C using fresh specimens at 40°C and retesting specimens at 30 and 50°C. The RSCH testing was conducted at 50°C using specimens already tested for the FSCH at 40°C. Table 11-21 summarizes the measured in-situ air voids content of the tested specimens. The actual test data are given in Appendix 20.

Table 11-21. Triaxial Shear Strength.

Layer Mixture	Lane Direction	Coring Location	Type of Test	Temp. (°C)	Air Voids (%)	G_{mm}	Number of Replicates ²
Surface	EB	LWP ¹	SST	40	3.2	2.449	5
		CL ¹		30, 50	5.3	2.449	6
		CL	RSCH	50	5.3	2.449	6
	WB	LWP	SST	40	6.5	2.507	1
		CL		30, 50	7.5	2.507	1
		CL	RSCH	50	7.5	2.507	1
Intermediate	EB	LWP	SST	40	4.2	2.474	12
		CL		30, 50	5.8	2.471	8
		CL	RSCH	50	5.8	2.471	6
	WB	LWP	SST	40	6.8	2.493	4
		CL		30, 50	6.6	2.489	8
		CL	RSCH	50	6.6	2.489	8

(1) LWP: left wheel path, CL: center of the lane

(2) Replicates are the same for SST shear test at 30°C and 50°C, and RSCH test. For eastbound intermediate layer mixture, 6 out of 8 replicates for SST shear test at 30°C & 50°C were used for RSCH test.

The original and air voids normalized shear stiffness $|G^*|$ results are summarized in Table 11-22 and Table 11-23, respectively, for the 10 and 5Hz test results. The normalization process is explained in Appendix 3. On average, survived WB lanes had 1.5 times higher shear modulus than the rutted EB lanes. When stiffness values are normalized to the 7.5% air voids content, see Table 11-23, the relative difference is twice as much due to the stiffness increase of the EB mixture because of mixture densification under traffic.

Table 11-22. Original Shear Modulus (I74 Forensic, 1999).

	Test Temp. (°C)	Surface Mixture				Intermediate Mixture			
		EB		WB		WB		EB	
		10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
$ G^* $ (MPa)	30	381	276	554	422	582	422	948	737
	40	170	118	238	170	179	120	322	222
	50	57	44	77	58	85	60	169	119
δ (degree)	30	45.3	48.1	38.3	40.8	42.3	46.2	35.6	39.2
	40	51.8	50.5	44.0	48.5	52.5	53.1	48.0	50.5
	50	42.3	40.5	44.6	43.1	47.4	45.7	49.6	49.1

Table 11-23. Normalized Shear Modulus (I74 Forensic, 1999).

Parameter	Test Temp. (°C)	Surface Mixture				Intermediate Mixture			
		EB		WB		EB		WB	
		10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
G* (MPa)	30	324	234	554	422	530	383	921	714
	40	118	82	220	157	141	95	315	218
	50	49	39	77	58	77	55	162	115

Table 11-24 summarizes test results for the RSCH. Testing was terminated after 5,000 cycles of loading, at which point the permanent strain shown was recorded. It is evident that the mixture of eastbound lanes experienced much higher permanent strain than that of westbound lanes. The actual test data are given in 20-4.

Table 11-24. Repeated Shear Test at Constant Height (I74 Forensic 1999).

Layer Mixture	Temp. (°C)	Permanent Strain ϵ_p (%)	
		EB	WB
Surface	50	2.38	1.25
Intermediate	50	3.99	1.32

11.6 Pavement Cores Tested and Analyzed by Purdue University

Thirty pavement cores, fifteen from each direction, were taken from the Interstate I74 lanes by INDOT in Spring 2002 for additional forensic testing. The purpose of the additional testing was to verify the original test results and to study if some additional mixture stiffening had occurred during the pavement service life. Exact coring locations were not reported to Purdue.

The first SST (FSCH) shear modulus |G*| testing at Purdue Pavement Laboratory was performed at the end of 2002, and the second testing was performed at the end of 2004. All samples were stored in the Purdue cold room between testing. The IDT strength testing was conducted in January 2005. The average air voids content of test specimens for each test are given in Table 11-25. Testing was conducted using two replicate cores. The actual test data is given in Appendix 20.

Table 11-25. Air Voids Contents (I74 Forensic, Purdue 2002).

Surface Mixture		Air Void Content, (%)			
		EB Lanes		WB Lanes	
		Average	Standard Deviation	Average	Standard Deviation
Shear Modulus	1 st Testing ¹	4.5	0.34	7.4	0.90
	2 nd Testing ¹	4.6	0.27	7.1	0.37
IDT Strength		5.1	0.21	7.0	0.28
Average		4.7	0.35	7.2	0.58

(1) 1st testing was performed in 2002 and 2nd testing was performed in 2004

The original and normalized SST shear modulus $|G^*|$ test results are summarized in Table 11-26 and Table 11-27, respectively, for 10 Hz and 5 Hz test data. The time difference between the first and second testing was approximately two years. At 40°C there is no significant stiffness increase, but at 54.4°C, on average, there was about 40% increase in shear stiffness. The stiffness increase is most likely due to binder aging in the cores even though they were stored in the cold room. The Purdue test results confirm the Heritage test results, as the tables show.

Table 11-26. Original Shear Modulus (I74 Forensic, Purdue 2002&2004).

Lanes Surface Mixture		$ G^* $ (MPa)				δ (degree)			
		40°		54.4°		40°		54.4°	
		10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
EB	1 st (2002)	139	101	41	30	57.05	56.48	60.54	58.05
	2 nd (2004)	147	96	55	47	65.40	64.23	59.28	48.85
WB	1 st (2002)	403	296	81	57	53.53	54.74	63.22	61.01
	2 nd (2004)	381	277	126	83	52.16	51.61	71.43	60.04

Table 11-27. Normalized Shear Modulus (I74 Forensic, Purdue 2002&2004).

Lanes Surface Mixture		$ G^* $ (MPa)				δ (degree)			
		40°		54.4°		40°		54.4°	
		10Hz	5Hz	10Hz	5Hz	10Hz	5Hz	10Hz	5Hz
EB	1 st (2002)	110	80	34	26	57.00	56.46	59.34	55.61
	2 nd (2004)	117	77	45	39	64.78	63.33	49.56	45.39
WB	1 st (2002)	400	294	80	56	54.00	55.15	63.40	61.46
	2 nd (2004)	370	269	122	81	51.89	52.13	69.48	63.39

Due to material availability, only two cores were tested for IDT tensile strength. Testing was performed at 35°C temperature using ram loading rate of 0.06 mm/min. Table 11-28 gives the test results normalized to 7.5% air voids using the procedure described in Appendix 3. The WB lanes were 2.8 times stronger than the EB lanes, as Table 11-28 shows.

Table 11-28. IDT Tensile Strength (I74 Forensic, Purdue 2005).

Lanes Surface Mixture	Original IDT Tensile Strength S_t (kPa)	Normalized IDT Tensile Strength S_t (kPa)	Strain at Failure (%)
EB	48.43	31.9	0.87
WB	98.86	90.6	1.08

12 INDIANA SPS 9A STUDY

As a part of an on-going program to validate the Superpave binder selection, Shah (2004) studied performance of six binders in six test sections constructed on interstate I70 east of Indianapolis in 1998. The spec recommended binder grade was PG58-16 at 50% reliability and 58-28 at 98% reliability. The selected grade was increased to PG64-28 due to expected traffic of 30 to 100 million ESALs for 20-years of service life. The study concluded that the standard Superpave grade PG64-28 was sufficient for this site.

Pavement temperature measurements with thermocouples imbedded in the asphalt mixture showed that 7-day maximum average air temperature ranged from 31.5 to 36.5°C and 7-day average pavement temperature at 20 mm deep ranged from 38.0 to 43.0°C. The closest weather station is Greenfield in Hancock County. Test sites were monitored for 4 years and rut depths were measured using a dipstick after 1.5 and 4 years of traffic loading.

12.1 Mix Design Information

Table 12-1 gives the mix design information, and Table 12-2 shows the design aggregate blends for the six surface and intermediate mixtures. Table 12-3 gives the gyratory compaction effort for the Superpave mixtures S2 to S6. Marshall mix design for S1 was done applying 75 blows with Marshall hammer. Table 12-4 gives the actual design binder contents, maximum specific gravity, and design volumetric properties, and Table 12-5 gives the binder absorption, surface area, and film thickness. The intermediate mixture had less binder absorption compared to the surface mixture with blast furnace slag and dolomite.

Table 12-1. Mix Design Information.

Mix Design	Test Section	Aggregate Type (Surface)	Aggregate Type (Intermediate)	Binder Grade
Marshall	S1	B-F Slag, crushed dolomite, and natural sand	Crushed stone and natural sand	AC-20
Superpave	S2 S3 S5 S6	B-F Slag, crushed dolomite, dolomitic sand, and ag. lime	Crushed stone and stone sand	PG64-28 PG58-28 PG70-28 PG64/16
Superpave (w/ RAP)	S4	B-F Slag, dolomite, dolomitic sand, and RAP	Crushed stone, stone sand and RAP	PG64-28 with 15% RAP

Table 12-2. Design Aggregate Blending.

Sieve Size, mm	% Passing					
	Section 1		Section 2, 3, 5, 6		Section 4	
	Surface	Interm.	Surface	Interm.	Surface	Interm.
25	100	100	100	100	100	100
19	100	92.8	100	94.6	100	92.2
12.5	100	70	100	77.5	100	73.8
9.5	93.5	56.5	90.6	67	89.3	62.4
4.75	61.4	32.7	49.9	43.5	49.8	38.7
2.36	50.9	26.7	40.7	28.9	39.3	29.6
1.18	39.7	21	28.9	16.5	27.2	17.2
0.6	25.4	13.9	19.4	10	18.2	10.5
0.3	14.3	8.2	11.7	6.5	11.1	6.7
0.15	3.7	3.1	7.5	4.7	6.7	4.9
0.075	2.5	2.5	5	3.3	4.1	3.5
G _{sb} blend	2.536	2.630	2.573	2.648	2.577	2.646

Table 12-3. Superpave Gyratory Compaction Effort.

Layer Mixture	Actual Design ESALs (10 ⁶)	Specification Design ESALs (10 ⁶)	Actual Compaction					
			No. of Gyrations			% G _{mm}		
			N _{ini}	N _{des}	N _{max}	N _{ini}	N _{des}	N _{max}
Surface	96	>30	9	126	204	84.2	96.0	97.6
Intermediate	96	>30	9	126	204	85.4	96.0	97.6

Table 12-4. Mix Design Properties.

Section	Surface Mix						Intermediate Mix					
	P _b ¹ (%)	P _b ² (%)	G _{mm}	V _a (%)	VMA (%)	VFA (%)	P _b (%)	P _b (%)	G _{mm}	V _a (%)	VMA (%)	VFA (%)
S1	6.6	6.2	2.412	6.0	16.4	63.3	4.5	4.3	2.498	6.0	14.7	59.2
S2	6.8	6.5	2.445	4.0	15.0	73.3	5.3	5.0	2.459	4.0	15.6	74.3
S3	6.8	6.5	2.445	4.0	15.0	73.3	5.3	5.0	2.459	4.0	15.6	74.3
S4	6.7	5.4	2.488	4.0	13.5	70.4	5.0	4.7	2.471	4.1	14.9	72.5
S5	6.8	6.5	2.445	4.0	15.0	73.3	5.3	5.0	2.459	4.0	15.6	74.3
S6	6.8	6.5	2.445	4.0	15.0	73.3	5.3	5.0	2.459	4.0	15.6	74.3

(1) Actual binder, Binder recovery using ignition (by weight-%)

(2) Effective binder, Binder recovery using extraction (by weight-%)

Table 12-5. Design Values for Absorption, Surface area and Film Thickness.

Section		P _{ba} (%)	P _{beff} (%)	V _{ba} (%)	V _{beff} (%)	V _{b-total} (%)	Surface area SA (m ² /kg)	Film thick. (μm)
Surface	S1	1.9	4.7	4.1	10.4	14.5	4.60	10.77
	S2	2.0	4.8	4.5	11.0	15.5	5.26	9.55
	S3	2.0	4.8	4.5	11.0	15.5	5.26	9.55
	S4	2.6	4.1	6.0	9.5	15.5	4.75	9.00
	S5	2.1	4.8	4.9	11.0	15.9	5.26	9.55
	S6	1.9	4.8	4.4	11.0	15.3	5.26	9.55
Interm.	S1	0.7	3.8	1.5	8.7	10.2	3.37	11.57
	S2	0.2	5.1	0.5	11.6	12.1	3.48	14.87
	S3	0.2	5.1	0.6	11.6	12.1	3.48	14.87
	S4	0.3	4.7	0.7	10.8	11.5	3.55	13.54
	S5	0.4	5.1	0.9	11.6	12.4	3.48	14.87
	S6	0.2	5.1	0.5	11.6	12.0	3.48	14.87

12.2 QC Data and In-place Properties

Table 12-6 shows the properties of gyratory compacted asphalt plant mixtures, and Table 12-7 shows the as-constructed properties. For surface mixture S2 the gyratory pill air voids content was lower than the design value, and for S1 it was higher. For the intermediate mixture all air void contents were less than the design value.

Table 12-8 gives the binder absorption, surface area, and film thickness for surface mixtures, Table 12-9 for intermediate mixtures, and Table 12-10 and Table 12-11 give the as-constructed gradation.

Table 12-6. Asphalt Plant Gyratory Pill QC Properties.

Section	Surface					Intermediate				
	P _b (%)	G _{mm}	V _a (%)	VMA (%)	VFA (%)	P _b (%)	G _{mm}	V _a (%)	VMA (%)	VFA (%)
S1	5.5	2.474	7.6	14.8	48.7	5.0	2.489	3.6	13.3	72.9
S2	6.8	2.438	3.0	14.4	79.1	5.4	2.459	2.2	14.1	84.4
S3	6.8	2.482	4.3	13.9	69.2	5.4	2.462	3.6	15.2	76.3
S4	6.3	2.484	4.4	13.5	67.6	4.2	2.499	2.0	11.4	82.5
S5	6.2	2.457	5.1	15.0	65.8	5.4	2.453	2.6	14.6	82.2
S6	6.6	2.439	5.5	14.5	61.9	4.6	2.480	3.2	13.5	76.3

Table 12-7. In-Place Properties.

Section	Surface					Intermediate				
	P _b (%)	G _{mm}	V _a (%)	VMA (%)	VFA (%)	P _b (%)	G _{mm}	V _a (%)	VMA (%)	VFA (%)
S1	5.5	2.474	7.6	14.8	48.7	5.0	2.489	3.6	13.4	74.4
S2	6.8	2.438	3	14.4	79.1	5.4	2.459	2.2	13.9	84.5
S3	6.8	2.482	4.3	13.9	69.2	5.4	2.462	3.6	14.2	74.4
S4	6.3	2.484	4.4	13.5	67.6	4.2	2.499	2.0	11.3	82.6
S5	6.2	2.457	5.1	15.0	65.8	5.4	2.453	2.6	14.5	82.2
S6	6.6	2.439	5.5	14.5	61.9	4.6	2.480	3.2	13.4	76.2

Table 12-8. Plant QC and As-constructed Properties, Surface Mix.

Section	Gyratory Pill QC Data						As-constructed Data				
	P _{ba} (%)	P _{beff} (%)	V _{ba} (%)	V _{beff} (%)	V _{b-total} (%)	SA (m ² /kg)	P _{ba} (%)	P _{beff} (%)	V _{ba} (%)	V _{beff} (%)	V _{b-total} (%)
S1	2.3	3.2	5.1	7.1	12.2	4.86	2.3	3.2	5.1	7.0	12.1
S2	1.8	4.9	4.2	11.3	15.6	5.33	1.8	4.9	4.2	11.2	15.4
S3	2.6	4.2	6.0	9.7	15.7	5.33	2.6	4.2	5.9	9.4	15.3
S4	2.3	4.0	5.4	9.1	14.5	5.45	2.3	4.0	5.2	8.9	14.1
S5	2.0	4.4	4.5	9.9	14.4	4.98	2.0	4.4	4.3	9.6	13.9
S6	1.7	4.8	3.8	10.8	14.6	5.45	2.6	3.9	5.7	8.6	14.4

Table 12-9. Plant QC and As- constructed Properties, Intermediate Mix.

Section	Gyratory Pill QC Data						As- constructed Data				
	P _{ba} (%)	P _{beff} (%)	V _{ba} (%)	V _{beff} (%)	V _{b-total} (%)	SA (m ² /kg)	P _{ba} (%)	P _{beff} (%)	V _{ba} (%)	V _{beff} (%)	V _{b-total} (%)
S1	0.8	4.2	1.9	9.7	11.6	3.63	2.3	3.2	5.3	7.3	12.5
S2	0.3	5.1	0.7	11.9	12.6	3.87	1.8	4.9	4.2	11.2	15.5
S3	0.4	5.0	0.8	11.6	12.4	4.10	2.6	4.2	6.0	9.7	15.7
S4	0.2	4.0	0.6	9.4	10.0	4.01	2.3	4.0	5.4	9.1	14.5
S5	0.3	5.2	0.8	12.0	12.8	3.91	2.0	4.4	4.4	9.8	14.3
S6	0.1	4.4	0.3	10.3	10.6	3.93	2.6	3.9	5.9	8.9	14.8

Table 12-10. In-Place Aggregate Gradation, Surface.

Sieve Size, mm	% Passing					
	S1	S2	S3	S4	S5	S6
4.75	62.5	60.4	59.0	56.0	50.2	56.7
0.075	3.3	5.1	5.1	5.5	4.8	5.5

Table 12-11. In-Place Aggregate Gradation, Intermediate.

Sieve Size, mm	% Passing					
	S1	S2	S3	S4	S5	S6
12.5	76.8	69.3	67.7	63.4	77.1	70.0
4.75	39.9	40.5	41.0	34.8	45.3	40.1
0.075	3.7	4.5	5.2	5.0	4.5	4.7

12.2.1 Binder Test Data

Table 12-12 to Table 12-16 show the conventional binder test data, and Table 12-16 gives the Superpave Dynamic Shear Rheometer test results for tank, RTFO and PAV data. Table 12-17 shows the computed A and VTS parameters for the six binders used in the mixtures. Parameters were calculated from the penetration and viscosity data shown.

Table 12-12. Penetration at 5°C.

Binder	Penetration Values (0.1 mm) @ 5°C						
	Tank	2 wks.	8 mo.	12 mo.	18 mo.	24 mo.	48 mo.
AC-20	26	13	15	8	6	6	6
PG64-28	36	27	21	19	18	16	16
PG58-28	53	36	34	25	21	20	21
PG64-28 w/ RAP	36	19	19	13	12	12	12
PG70-28	56	33	24	15	13	11	10
PG64-16	16	14	15	11	8	7	8

Table 12-13. Penetration at 25°C.

Binder	Penetration Values (0.1 mm) @ 25°C						
	Tank	2 wks.	8 mo.	12 mo.	18 mo.	24 mo.	48 mo.
AC-20	89	26	21	20	14	12	11
PG64-28	79	58	56	42	41	40	40
PG58-28	124	63	51	51	34	30	31
PG64-28 w/ RAP	79	37	35	27	23	16	17
PG70-28	68	40	32	20	19	15	15
PG64-16	31	23	24	12	11	5	6

Table 12-14. Absolute Viscosity at 60°C.

Binder	Absolute Viscosity (P) @60°C						
	Tank	2 wks.	8 mo.	12 mo.	18 mo.	24 mo.	48 mo.
AC-20	157	433	461	558	781	960	1,205
PG64-28	112	166	180	195	201	206	109*
PG58-28	66	131	135	137	326*	164	174
PG64-28 w/RAP	112	345	407	418	367	604	664
PG70-28	417	1,650	2,519	6,433*	1,265*	3,734	8,584
PG64-16	234	292	676	937	1,016	826	1,743

* Erroneous test result

Table 12-15. Rotational Viscosity at 135°C.

Binder	Rotational Viscosity (cP) @135°C						
	Tank	2 wks.	8 mo.	12 mo.	18 mo.	24 mo.	48 mo.
AC-20	456.3	750	775	825	937.5	975	1037.5
PG64-28	408.3	500	512.5	525	550	562.5	381.3*
PG58-28	272.9	437.5	450	462.5	612.5	625	506.3
PG64-28 w/ RAP	408.3	625	712.5	725	737.5	750	809.4
PG70-28	529.2	1104.3	1138	1650.0*	975.0*	1388	1971.5
PG64-16	425	462.5	750	800	875	900	987.5

* Erroneous test result

Table 12-16. Binder DSR Test Data.

DSR Test Data $G^*/\sin\delta$ (kPa)						
Aging	Temp. °C	AC-20	PG64-28	PG58-28	PG70-28	PG64-16
Tank	52			2.86		
	58	3.25	3.9	1.27		5.36
	64	1.31	1.73	0.53	2.77	1.99
	70	0.41	0.84		1.39	0.91
RTFO	52			5.7		
	58	6.34	4.88	2.4		5.76
	64	2.78	2.34	1.07	5.11	2.18
	70	1.11	1.09		2.84	1.26
	76				0.56	
PAV	31					4802
	28	2656				6716
	25	4010	2227			9367
	22	5902	3327	3565		
	19		5061	4991		
	16			7339		

Table 12-17. Binder A and VTS values obtained from Conventional Test Data.

Section	Tank		2 weeks. aged		18 mo. aged		48 mo. aged	
	A	VTS	A	VTS	A	VTS	A	VTS
S1	10.37394	-3.4707	11.02533	3.68977	11.29706	-3.77983	11.40407	-3.81456
S2	10.64346	-3.569	10.77717	3.61268	10.97309	-3.67925	10.96513	-3.67597
S3	10.83664	-3.6481	10.8681	3.64791	10.93702	-3.66552	11.00477	-3.6886
S4	10.73999	-3.6047	10.95437	3.66867	11.12706	-3.72636	11.32425	-3.79233
S5	10.73381	-3.5938	10.30751	3.42697	10.55322	-3.50619	10.5779	-3.50876
S6	11.76526	-3.9631	11.77861	3.96451	11.61357	-3.89154	11.96937	-4.01316

Table 12-18. Binder A and VTS values obtained from Test Data.

Section	Tank				2 weeks aged		
	η 40°C Pa-s	η 54.4°C Pa-s	C° Z=50mm	η z=50 Pa-s	η 40°C Pa-s	η 54.4°C Pa-s	η z=50 Pa-s
S1	4,962	535	46.2	46.2	31,043	2,222	9,315
S2	4,824	493	46.2	46.2	7,846	726	2,650
S3	2,079	230	46.2	46.2	6,313	591	2,142
S4	4,554	459	46.2	46.2	18,728	1,468	5,859
S5	10,771	962	46.2	46.2	38,144	3,155	12,269
S6	19,492	1,259	46.2	46.2	28,069	1,707	7,785

Table 12-19. Binder A and VTS values obtained from Test Data.

Section	18 mo. aged				48 mo. aged		
	η 40°C Pa-s	η 54.4°C Pa-s	C° Z=50mm	η z=50 Pa-s	η 40°C Pa-s	η 54.4°C Pa-s	η z=50 Pa-s
S1	82,623	4,785	46.2	22,472	134,558	7,045	34,929
S2	12,607	1,043	46.2	4,041	13,123	1,081	4,199
S3	13,443	1,110	46.2	4,307	15,802	1,255	4,972
S4	32,391	2,249	46.2	9,579	61,230	3,684	16,944
S5	120,802	8,007	46.2	35,092	260,929	15,428	71,951
S6	122,018	6,145	46.2	31,078	309,954	12,291	70,607

12.3 Mixture Performance Testing and Rut Measurements

Table 12-20 shows the SST test data for the long-term oven aged mixtures and measured rut depths at 1.5 years and 4 years of traffic.

Table 12-20. Long-Term Oven Aged Mixture Test Data.

Section	G* 40.5°C&10Hz (MPa)		Rut Depth, mm	
	Surface	Intermediate	1.5 years	4 years
S1	1,020	770	3.0	3.2
S2	1,897	502	3.2	5.2
S3	379	304	4.2	4.9
S4	2,202	867	3.9	4.9
S5	1,057	711	3.0	4.4
S6	1,515	1,332	2.5	4.2

13 PERFORMANCE CRITERIA LITERATURE REVIEW

13.1 Conceptual Stiffness Criteria based on Layered Elastic Analysis

A limited exercise of stiffness criteria development was done by Pellinen (2001) using the AYMA program, which is a relatively new mechanistic pavement design program developed by Ayres (1997). The AYMA program is capable of handling three distress types separately or together, including fatigue cracking, permanent deformation and low temperature cracking. The AYMA program was selected for the distress analysis because it incorporates climate (pavement temperature) and traffic speed in the mechanistic analysis. The rutting response model used in the AYMA program is based on the ratio of plastic and resilient strain (ϵ_p/ϵ_r) during cyclic loading, given in Eq. (42), where T is temperature and N is number of loading cycles.

$$\log\left(\frac{\epsilon_p}{\epsilon_r}\right) = -4.80661 + 2.58155 * \log T + 0.429561 \log N \quad (42)$$

Asphalt mix material characterization in the AYMA program was conducted using the Witczak et al. Dynamic Modulus Predictive Equation. The input data for this equation includes the A and VTS parameters for the binder, air voids, effective binder volume and aggregate gradation. The AYMA program uses the predictive equation to compute the stiffness of the asphalt mixture layers at different temperatures, rate of loading and aging conditions. The aging of asphalt mixture is achieved by incorporating the aging models, developed by Mirza and Witczak (1995), into the material characterization model.

Table 13-1 shows an example of the uniaxial stiffness criteria for a 150-mm (6") thick asphalt mix layer over a strong base. For implementation, the asphalt mixture stiffness, tested at the effective temperature for the design site, has to meet the minimum stiffness criteria presented in the tables. Three traffic levels were used: 1, 10, and 100 million ESALs over a 10-year design period. 50 km/h (30 miles/h) was chosen for the design traffic speed, which converts to 20 Hz loading rate in the

stiffness modulus computations. These criteria have not been verified by the field test results.

Table 13-1. Stiffness Criteria for 12.7 mm (0.5 inch) of Rutting.

Traffic	Minimum $ E^* $ (MPa) @ 20Hz @ T_{eff} (°C) (Strong Base with AC Mix Thickness > 6 inch)						
ESALs	15.5	21.1	26.7	32.2	37.8	43.3	48.9
10^6	83	145	234	358	517	730	993
10×10^6	276	469	745	1,117	1,607	2,241	3,026
100×10^6	910	1,531	2,400	3,535	5,075	6,985	9,349

13.2 Combined Stiffness and Strength Criteria

In a combined stiffness and strength criteria, Pellinen (2004) proposed to use the stiffness criteria presented above combined with the stability criteria proposed by McLeod (1948), in which both cohesion and friction angle contribute to the mix stability.

Figure 13-1 shows mixtures from MnRoad, RHWA-ALF, WesTrack, and ASTO (from Finland) experiments plotted as a function of stiffness and allowable surface pressure p . The stiffness of the mixtures was obtained from the dynamic modulus testing that was conducted at 54°C using 5 Hz loading rate. Triaxial testing was conducted at 54°C using 4 different confining pressures of 0, 137, 276, and 414 kPa to obtain the Mohr-Coulomb failure envelope. The ram rate used was 1.27 mm/min. This ram rate relates to the strain rates used in the early studies of the triaxial testing and it presents a relatively slow rate of loading.

The combined performance criteria must be related to the climatic conditions and traffic by limiting the allowable stiffness based on the critical or effective pavement temperature and traffic volume. The criteria lines shown in Figure 13-1 are based on the observed in-situ rutting behavior. The cold region refers to the T_{eff} less than 37°C.

The marginal mixtures (low stiffness and strength) shown in Figure 13-1 were mostly those MnRoad, ALF, and WesTrack mixtures that actually failed in-situ which, in part, verifies the presented performance concept. Figure 13-1 also shows the

delicate balance of the performance for the ASTO mixtures. Despite the fact that the ASTO mixtures had very low air void content, high binder volume, and soft binder, they performed satisfactorily in Finland; but they would not perform as well in the Arizona climate, which underlines the importance of climate in the selection of adequate material properties.

Figure 13-1. Stiffness and Strength Criteria (Pellinen, 2004).

13.3 Strength Criteria based on IDT and RSCH Test

In a study by Christensen et al. (2000), several asphalt mixtures used by Pennsylvania Department of Transportation were tested in the laboratory using the IDT strength test and unconfined compressive strength test. Test temperature was 35°C and the loading rate was 3.75 mm/min for the IDT strength test and 7.5 mm/min for the unconfined compressive test. The study also used SST Repeated Shear at Constant Height (RSCH) test to estimate the mixture's potential for rutting by measuring accumulative plastic strain ϵ_p . The SST testing was done at 58°C, applying 5,000 cycles of shear loading. All samples were laboratory fabricated and compacted with SGC for 4% target air voids content.

Based on the study, the authors proposed criteria for the permanent shear strain ϵ_p , the IDT strength, and friction angle as shown in Table 13-2 and Table 13-3. The authors used information from literature to establish the limit for rutting based on the RSCH testing, and IDT strength criteria was constructed based on the correlation between accumulated plastic strain γ_p and the IDT strength. The research did not give justification for the criteria for friction angle. The criteria presented below are only applicable for test results obtained at the test temperature and loading rate indicated in the table and it was not related to any traffic level.

Table 13-2. Guidelines of Evaluating Rut Resistance Using IDT Strength (Christensen et al, 2002).

Rut Resistance From literature	IDT Strength @ 35°C with 3.5mm/min ram rate (kPa)	SST - RSCH Permanent Sear Strain ϵ_p (%)
Excellent	> 440	<1.0
Good	> 320 to 440	1.0 to < 2.0
Fair	> 200 to 320	2.0 to < 3.0
Poor	200 $\geq$	≥ 3.0

Table 13-3. Guidelines of Evaluating Angle of Internal Friction (Christensen et al, 2002).

Angle of Internal Friction, ϕ @ 35°C with 7.5mm/min ram rate (Degrees)	Rating
> 45	Excellent
> 40 to 45	Good
> 35 to 40	Fair
35 $\geq$	Poor

The criteria presented by Christensen et al. were modified by the authors by adjusting the given criteria for the loading rate and temperature used in this study. Table 13-4 shows the converted criteria using conversion procedures shown in Appendix 3 for loading rate and air voids content. The criteria developed for mixture with 4% air voids was converted to mixture with 7.5% air voids content. The friction angle criteria were not converted because of the lack of methods for doing that.

However, it is evident that friction angle values given in Table 13-3 do not match the friction angles measured from the 11 Indiana mixtures because of a difference in the measurement procedure and data analysis. The values in Table 13-3 are too high compared to the values measured from the Indiana mixtures.

Table 13-4. Converted Guidelines of Evaluating Rut Resistance Using IDT Strength

IDT Strength @ 35°C with 0.06mm/min ram rate (kPa)	Rut Resistance Base on Literature
> 90	Excellent
> 66 to 90	Good
> 41 to 66	Fair
41 $\geq$	Poor

The modified criteria were transferred to different traffic levels by the authors as follows. To estimate the rutting criteria as a function of traffic level, a relationship between the RSCH test loading cycles and the actual traffic in ESALs presented by Christensen et al. (2002) was established, and the maximum permanent shear strain γ_p at 5,000 cycles at the end of the test was converted to an estimated rut depth. The Eq. (40) developed by Sousa et al. (1994) during SHRP program was used to predict rut depth:

$$Rut\ Depth\ (in.) = K \bullet \gamma_{p,max} \quad (43)$$

where:

$\gamma_{p,max}$ = maximum permanent shear strain at 5,000 cycles, in/in

K = 3 to 4 for a 100 mm (4 in) thick HMA layer, up to 11 for 380 mm (15 in) thick HMA layer, increasing as the HMA layer thickness increases

A shift factor must be applied to enable directly linking the laboratory loading cycles to the estimated field traffic, as defined by Eq. (41) and by Sousa et al. (1994):

$$N_{Demand} = SF \times (ESAL)_{TC} \quad (44)$$

where:

N_{Demand} = Laboratory equivalent repetition of loading

SF = Empirical shift factor

$(\text{ESAL})_{T_c}$ = Design ESAL adjusted to the critical temperature for the site in which the mixture is to be used

Nationally averaged temperature conversion factor and a regression model were used to obtain the following equation:

$$RSCH \text{ Cycle} = 0.0562 \times (\text{ESAL} \times 0.0725)^{0.924} \quad (45)$$

The proportionality between rut depth and ESAL was based on the square root because it gives a more reasonable traffic estimation compared to cubic root. The developed criteria are given in Table 13-5. Table 13-6 shows the converted criteria for study conditions, i.e., 7.5 mm/min loading time for triaxial testing and 0.06 mm/min loading time for IDT strength testing.

Table 13-5. Estimated Strength Criteria Based on 12.5 mm (0.5 in) Rut Depth.

Parameter	Minimum Strength Value (kPa)					
	ESALs, 10^6					
	<3	3~10	10~30	30~50	50~100	>100
c 35°C 7.5 mm/min	47	47~73	73~108	108~130	130~167	>167
S _t 35°C 7.5 mm/min	28	28~40	40~57	57~66	66~82	>82

Table 13-6. Converted Strength Criteria Based on 12.5 mm (0.5 in) Rut Depth.

Parameter	Minimum Strength Value (kPa)					
	ESALs, (10^6)					
	<3	3 - 10	10 - 30	30 - 50	50 - 100	>100
c 54°C, 7.5 mm/min	56	56 to 86	86 to 27	127 to 153	153 to 196	>196
S _t 35°C 0.06 mm/min	33	33 to 47	47 to 67	67 to 78	78 to 96	>96

13.4 Rutting Model based on IDT Strength, RSCH Test and Compaction Slope

Anderson, Christensen and Bonaquist (2003) suggested a model relating estimated rut depth to the IDT strength, compaction slope and voids in mineral aggregate. Compaction slope was hypothesized to be an indicator of the internal friction angle, which contributes to the rutting resistance of HMA mixtures providing frictional resistance.

$$Rut\ Depth = -0.0337 S_t + 4.37 VMA + 5.37 k - 0.337 VMA \times k - 46.83 \quad (46)$$

where:

Rut Depth = estimated rut depth from RSCH test, mm

S_t = IDT strength, kPa

VMA = voids in mineral aggregate, volume %

k = compaction slope, Eq. (47)

$$k = \frac{(\% G_{mm})_{N_{design}} - (\% G_{mm})_{N_{initial}}}{\log N_{design} - \log N_{initial}} \quad (47)$$

There are three limitations. First, the rut depth was estimated from laboratory testing and was not linked to actual traffic. Roughly, RSCH test with 5,000 cycles at 58°C is equivalent to 3 million ESALs (Sousa et al, 1994). Second, besides the IDT strength, VMA, compaction slope and their interaction play roles in rut depth, so it is impossible to establish criteria based on the IDT strength only. Third, the air voids of specimens tested for establishing the model varied from 1.2% to 4.1%, so the IDT strength among mixes are not comparable. Then, this model cannot be directly used to predict field rut depth under real traffic loading. However, this model can be used to identify mixtures with rutting potential if volumetric compositions and testing condition are comparable.

The volumetric compositions, compaction slope and the IDT strength are available for the I74 forensic study mixtures and four of eleven mixtures in this study, so this model can be used as a good tool. Again, normalization must be performed to convert the IDT strength in this study to the testing conditions used to develop the model that is the same testing conditions as those used by Christensen et al (2000). The results are given in Table 11-1.

Table 13-7. Estimated Rut Depth for Indiana Mixtures (Anderson et al. Model).

Mix	Design ESALs (10 ⁶)	Design VMA	k	Estimated IDT Strength (kPa)	Estimated Rut Depth ₁ (mm)
I74 Forensic EB	12.5	13.9	9.26	156	9.8
I74 Forensic WB	12.5	13.9	9.26	444	0.2
SR15	2.4	15.9	8.35	137	12.8
SR56	7.5	15.4	10.67	262	7.0
SR135	20	15.4	9.21	316	5.8
I65	155	17.8	9.30	709	-5.4

(1) Approximate 3 million ESALs.

Eastbound lanes of I74 had 12 to 15 mm measured rut depth after about 600,000 ESALs. In contrast, the estimated rut depth for I74 eastbound mixture is the second largest. Moreover, if the design ESALs are taken into consideration, I74 eastbound mixture is definitely the most susceptible mixture to rutting failure. The predicted negative values for I65 strengthen the suggestion that the model is not applicable to predict the real rut depth in the field.

14 DESCRIPTION OF RAW MATERIALS USED

14.1 Pictures of Raw Materials

Figure 14-1: SR15.

Figure 14-2: US24.

Figure 14-3: SR161.

Figure 14-4 SR56.

Figure 14-5: US30.

Figure 14-6: SR66.

Figure 14-7: SR135.

Figure 14-8: US31

Figure 14-9:I74.

Figure 14-10: SR64.

Figure 14-11:I65.

Road No.	Description	Source	% ^{1,2}	G _{sb}	Water Absorption	LA Abrasion
SR15	Aggregate	#11 Dolomite, IMI Huntington 2211	46	2.655	1.53%	30.40%
		#12 Dolomite, IMI Huntington 2211	12	2.669		
		#23 Nat Sand, IMI Huntington 2211	17	2.677		
		#24 Dol. Sand, IMI Huntington 2211	23	2.742	0.78%	
		Baghouse Fines	2	2.744		
	Asphalt Binder	PG 64-22, BP Amoco 7191	5.6			
US24	Aggregate	#11 B-F Slag, Beemsterboer Gary 2488	29	2.459	4.75%	40.01%
		#11 Dolomite, IMI Huntington 2211	29	2.665	1.53%	30.40%
		#23 Natural, Sand Aggr Serv Plymouth 2431	20	2.555	1.34%	
		#24 Mtg Sand, Stoneco Milner 2764	20	2.702	4.96%	
		Baghouse Fines	2	2.699		
	Asphalt Binder	PG 64-22, BP Amoco 7191	5.7			
SR161	Aggregate	#11 Stone-Mulzer, Cape Sandy 2621	38	2.640		
		QA 12 Stone-Mulzer 2621	27	2.635		
		QA Asphalt Sand-Mulzer, I-164 2688	23	2.610		
		QA #10 -Mulzer, Cape Sandy 2621	12	2.600		
	Asphalt Binder	PG 64-22, Marathon, Mt. Vernon 7187	5.4			
SR56	Aggregate	#11 Polish Resistant Aggregate, Sellersburg Stone 2542	16	2.688	1.19%	22.75%
		#11 Steel Slag, Sellersburg Stone 2542	26	3.355	2.54%	19.11%
		Man. Fine Aggregate(PRA), Sellersburg Stone 2542	40	2.682		
		QA #14 Stone Sand, Sellersburg Stone 2542	18	2.680	1.70%	
	Asphalt Binder	PG 70-22 Marathon/Ashland 7155	6.2			
US30	Aggregate	#24 Natural Phend&Brown, Inc 2217	11.5	2.640	1.37%	
		#24 Man. SS, Hanson 2232	12.5	2.742	1.37%	
		#12F Manufactured IMI 2211	6.5	2.732		
		#12L IMI IMI 2211	34	2.650		
		#11 B-F Slag, Beemsterboer 2248	34	2.514	4.75%	40.01%
		genfines	1.5	2.750		
SR66	Aggregate	PG 70-22 Koch 7106	6.2			
		#11 Sand Stone, Hastie Mining, Caveinrock, IL 2609	33	2.594	1.93%	20.63%
		#11 Dolomite Mulzer, Newberg redist 2970	10	2.613	2.19%	24.36%
		#12 Dolomite Mulzer, Newberg redist 2970	23	2.625		
		West Pit Mulzer I-164 2668	14	2.640		
		Man. Sand, Newberg redist 2970	20	2.645	2.05%	
SR135	Aggregate	PG 70-22 Marathon, Mt. Vernon IN 7202	5.7			
		#11 B-F Slag Beemsterboer 2488	27	2.498	4.75%	40.01%
		#11 Limestone Mar.Mar.River Ave.2389	27	2.606	2.23%	27.88%
		#24 QA Dolo Sand Mar.Mar. River Ave. 2389	34	2.620	1.85%	
		#23 Sand Mar.Mar. Waverly 2522	10	2.634	1.35%	
		Baghouse Fines	2	2.615		
U31	Aggregate	PG 70-22 Ashland Oil Co. 7171	6.4			
		#11 Steel Slag US Aggr Gary, IN 2718	80	3.526	1.44%	11.26%
	Mineral Filler	#24 Man. Cowles S&G 2432	12	2.727	1.80%	
		Mineral Filler QA No.80 IMI PCJ Swayzee 2355	8	2.600		
	Asphalt Binder	PG 76-22 Koch 7106	4.8			

Road No.	Description	Source	% ^{1,2}	G _{sb}	Water Absorption	LA Abrasion
I74	Aggregate	#11 Steel Slag, Whitesville Mill Service 2110	80	3.731	1.12%	16.29%
		Stone Sand, Handson #2312	10	2.604	1.99%	
	Mineral Filler	#16 Mineral Filler Meshbergerbros#2361	10	2.865		
	Fiber	Fiber Hi-Tech Asphalt Solutions	0.1			
	Asphalt Binder	PG 76-22 Asphalt Materials (7105) W. 86th St. INDPLS	5.5			
SR64	Aggregate	#11 Steel Slag Heritage 2781	87	3.386	1.44%	11.26%
		#24 Dolomite MFA 2970	8	2.615	2.05%	
	Mineral Filler	Mineral Filler, Gohman #3367	5	2.804		
	Fiber	Hi-Tech Asphalt Solutions	0.2			
I65	Asphalt Binder	Pg 76-22 Seneca Pet @ Jeffersonville 7208	5.5			
	Aggregate	QA 1/2" Slag, TFO-N. Vernon 2977	62	3.515	1.29%	
		QA 3/8" Slag, TFO-N. Vernon 2977	26	3.218	5.12%	
		QA Stone Sand, Hanson-N. Vernon 2977	12	2.689	1.46%	
	Fiber	Hi-Tech Asphalt Solutions-Mechanicsville, Va.	0.25			
	Asphalt Binder	PG 76-22 Asland / Marathon Cincinnati, Ohio 7107	5.9			

Sieve Size		% Passing (by Weight)											
		SR15						US24					
inch	mm	#11 Dolomite	#12 Dolomite	#23 Nat. Sand	#24 Dol. Sand	Baghouse Fines	Combined	#11 B-F Slag	#11 Dolomite	#23 Nat. Sand	#24 Man Sand	Baghouse Fines	Combined
3/4	19.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100
1/2	12.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100
3/8	9.5	85.8	100.0	100.0	100.0	100.0	93.5	82.5	86.8	100.0	100.0	100.0	91.1
# 4	4.75	19.0	69.0	100.0	100.0	100.0	59.0	15.0	20.0	100.0	100.0	100.0	52.2
# 8	2.36	4.0	6.0	88.0	94.0	95.0	41.0	6.0	7.5	88.0	70.0	100.0	37.5
#16	1.18	3.5	4.5	68.0	63.0	90.0	30.0	4.7	5.0	75.0	35.0	100.0	26.8
#30	0.6	3.2	4.3	50.0	38.0	87.0	21.0	4.0	4.0	58.0	19.5	100.0	19.8
#50	0.3	2.8	3.5	19.0	19.0	85.0	11.0	3.5	3.5	23.0	10.5	95.0	10.6
#100	0.15	2.5	2.5	7.0	9.0	83.0	6.4	2.0	3.0	6.0	8.5	90.0	6.2
# 200	0.075	1.5	1.8	1.0	4.0	80.0	3.6	1.5	2.7	2.0	5.0	85.0	4.3

Sieve Size		% Passing (by Weight)											
		SR161						SR56					
inch	mm	#11 Stone-Mulzer	#12 Stone-Mulzer	Asphalt Sand-Mulzer	#10 - Mulzer		Combined	#11 PRA	#11 Steel Slag	Man Fine PRA	#14 Stone Sand		Combined
3/4	19.5	100.0	100.0	100.0	100.0		100.0	100.0	100.0	100.0	100.0		100.0
1/2	12.5	100.0	100.0	100.0	100.0		100.0	100.0	100.0	100.0	100.0		100.0
3/8	9.5	87.0	100.0	100.0	100.0		96.0	83.0	73.0	100.0	100.0		90.3
# 4	4.75	21.0	73.0	97.8	96.2		63.0	22.0	20.0	97.0	99.0		65.3
# 8	2.36	3.5	26.0	92.6	47.0		36.8	4.5	10.0	68.0	30.0		35.9
#16	1.18	1.6	9.2	84.1	22.8		26.7	4.0	8.0	40.0	14.5		21.3
#30	0.6	1.3	5.1	68.8	15.7		21.1	3.8	6.0	23.0	8.5		12.9
#50	0.3	1.2	3.7	19.0	12.3		8.8	3.6	4.0	12.5	5.0		7.5
#100	0.15	1.0	3.2	1.1	10.3		4.2	3.3	3.0	7.0	2.8		4.6
# 200	0.075	0.9	2.9	0.4	8.7		3.8	3.0	2.5	4.5	2.5		3.4

Sieve Size		% Passing (by Weight)											
		SR135						SR66					
inch	mm	#11 B-F Slag	#11 Limestone	#23 Sand	#24 Dol. Sand	Baghouse Fines	Combined	#11 Sand Stone	#11 Dol. Mulzer	#12 Dol. Mulzer	West Pit Mulzer	Man Sand	Combined
3/4	19.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2	12.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8	9.5	83.9	85.2	100.0	100.0	100.0	91.7	88.4	88.5	100.0	100.0	100.0	95.0
# 4	4.75	17.7	19.3	100.0	99.6	100.0	55.9	27.4	22.7	74.1	96.0	92.6	60.3
# 8	2.36	5.4	3.8	96.0	80.1	100.0	41.3	8.7	6.6	25.8	85.0	70.1	35.4
#16	1.18	4.2	1.6	76.0	49.6	100.0	28.2	6.0	4.3	15.1	73.0	49.2	25.9
#30	0.6	3.7	1.4	52.8	29.0	100.0	18.5	5.2	3.3	12.1	58.0	33.4	19.6
#50	0.3	3.2	1.3	12.5	18.3	100.0	10.0	4.9	3.1	10.7	12.0	19.2	9.9
#100	0.15	2.0	1.1	2.4	8.3	100.0	5.9	4.5	2.8	9.7	1.1	10.6	6.3
# 200	0.075	1.3	1.0	1.3	4.8	100.0	4.4	3.3	2.6	8.3	0.5	6.5	4.6

Sieve Size		% Passing (by Weight)											
		US30							US31				
inch	mm	#11 Steel Slag	#12L	#12F	#24 Nat Sand	#24 Man Sand	Genfines	Combined	#11 Steel Slag	#24 Man Sand	Mineral Filler		Combined
3/4	19.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		100.0
1/2	12.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		100.0
3/8	9.5	80.0	100.0	100.0	100.0	100.0	100.0	93.2	82.6	100.0	100.0		86.1
# 4	4.75	18.0	72.0	84.0	99.0	99.9	100.0	61.4	20.0	100.0	100.0		36.0
# 8	2.36	5.0	18.0	60.0	84.0	94.5	100.0	34.7	6.3	82.0	100.0		22.9
#16	1.18	2.0	10.0	42.0	65.0	62.8	100.0	23.6	3.5	46.2	100.0		16.3
#30	0.6	2.0	4.0	30.0	45.0	34.3	100.0	15.0	3.0	30.0	100.0		14.0
#50	0.3	2.0	3.0	22.0	16.0	15.0	100.0	8.3	2.8	16.0	97.0		11.9
#100	0.15	1.5	2.0	17.0	3.0	5.0	100.0	4.8	2.7	8.0	80.0		9.5
# 200	0.075	1.5	2.0	12.0	1.0	3.0	100.0	4.0	2.7	4.0	67.0		8.0

Sieve Size		% Passing (by Weight)											
		I74				SR64				I65			
inch	mm	#11 B-F Slag	Stone Sand	Mineral Filler	Combined	#11 Steel Slag	#24 Dol. MFA	#11 Steel Slag	Combined	QA 1/2" Slag	QA 3/8" Slag	Stone Sand	Combined
3/4	19.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2	12.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8	9.5	79.5	100.0	100.0	83.6	83.0	100.0	100.0	85.2	78.0	100.0	100.0	87.0
# 4	4.75	18.5	99.0	100.0	34.7	23.0	95.0	100.0	32.6	16.0	80.0	100.0	43.0
# 8	2.36	3.2	93.0	100.0	21.9	9.0	75.0	100.0	18.8	6.0	40.0	84.0	24.5
#16	1.18	1.8	56.4	100.0	17.1	5.0	45.0	100.0	13.0	5.0	19.0	69.0	16.5
#30	0.6	1.6	32.5	100.0	14.5	4.0	22.0	100.0	10.2	4.0	13.0	59.0	13.5
#50	0.3	1.2	16.4	98.0	12.4	3.8	11.0	100.0	9.2	4.0	10.0	52.0	12.0
#100	0.15	1.1	6.8	95.0	11.1	3.4	6.0	99.0	8.4	3.0	8.0	46.0	10.0
# 200	0.075	0.8	3.5	74.6	8.5	3.0	4.0	93.0	7.6	3.0	5.0	38.0	8.0

Road No.	Measrued G_{mm}					JFM G_{mm}	Difference
	Sample 1	Sample 2	Average	StDev.	CV%		
SR15	2.523	2.529	2.526	0.004	0.17	2.488	0.038
US24	2.481	2.477	2.479	0.003	0.11	2.417	0.062
SR161	2.451	2.469	2.460	0.013	0.52	2.457	0.003
SR56	2.648	2.650	2.649	0.001	0.05	2.659	0.010
US30	2.484	2.489	2.487	0.004	0.14	2.455	0.031
SR66	2.457	2.465	2.461	0.006	0.23	2.457	0.004
SR135	2.440	2.446	2.443	0.004	0.17	2.431	0.012
US31	2.979	2.967	2.973	0.008	0.29	2.980	0.007
I74	3.140	3.114	3.127	0.018	0.59	3.154	0.027
SR64	2.938	2.959	2.949	0.015	0.50	2.966	0.018
I65	2.973	2.962	2.968	0.008	0.26	3.017	0.049

Road No.	Test Method	Specimen ID	G _{mb}	V _a (%)	Average V _a (%)	Standard Deviation (%)	Coefficient of Variation (%)
SR15	Unconfined Dynamic Modulus	SR15R-02	2.325	8.0	7.8	0.2	2.0
		SR15R-03	2.331	7.7			
		SR15R-04	2.329	7.8			
	Shear Modulus	SR15R-08-01	2.333	7.6	7.5	0.2	2.9
		SR15R-08-02	2.330	7.7			
		SR15R-09-01	2.341	7.3			
		SR15R-09-02	2.342	7.3			
	Triaxial Strength	SR15R-01	2.327	7.9	7.8	0.2	2.18
		SR15R-02	2.325	8.0			
		SR15R-05	2.334	7.6			
		SR15R-06	2.330	7.8			
	IDT Strength	SR15R-07-01	2.306	8.7	8.8	0.4	4.7
		SR15R-07-02	2.292	9.3			
		SR15R-07-03	2.311	8.5			
US24	Unconfined Dynamic Modulus	US24R-01	2.288	7.7	7.6	0.1	1.3
		US24R-04	2.290	7.6			
		US24R-05	2.292	7.5			
	Shear Modulus	US24R-09-01	2.288	7.7	7.8	0.2	3.0
		US24R-09-02	2.291	7.6			
		US24R-10-01	2.280	8.0			
	Triaxial Strength	US24R-02	2.291	7.6	7.7	0.2	2.3
		US24R-03	2.290	7.6			
		US24R-05	2.292	7.5			
		US24R-06	2.283	7.9			
	IDT Strength	US24R-07-01	2.260	8.8	8.6	0.5	6.2
		US24R-07-02	2.249	9.3			
		US24R-07-03	2.282	7.9			
		US24R-08-01	2.261	8.8			
		US24R-08-02	2.260	8.8			
		US24R-08-03	2.265	8.6			
		US24R-10-02	2.285	7.8			
SR161	Unconfined Dynamic Modulus	SR161R-02	2.268	7.8	7.6	0.2	2.7
		SR161R-03	2.271	7.7			
		SR161R-04	2.279	7.4			
	Shear Modulus	SR161R-08-01	2.268	7.8	7.6	0.2	2.6
		SR161R-08-02	2.271	7.7			
		SR161R-09-01	2.277	7.4			
		SR161R-09-02	2.279	7.4			
	Triaxial Strength	SR161R-01	2.275	7.5	7.6	0.1	1.7
		SR161R-03	2.271	7.7			
		SR161R-04	2.279	7.4			
		SR161R-05	2.273	7.6			
	IDT Strength	SR161R-07-01	2.25	8.5	8.4	0.4	4.3
		SR161R-07-02	2.245	8.7			
		SR161R-07-03	2.262	8.0			
	Unconfined Dynamic	SR56R-01	2.448	7.6	7.6	0.3	3.3
		SR56R-02	2.453	7.4			

Road No.	Test Method	Specimen ID	G _{mb}	V _a (%)	Average V _a (%)	Standard Deviation (%)	Coefficient of Variation (%)
SR56	Modulus	SR56R-03	2.438	7.9			
	Shear Modulus	SR56R-08-01	2.442	7.8	7.7	0.3	3.7
		SR56R-08-02	2.438	7.9			
		SR56R-09-01	2.452	7.4			
	Triaxial Strength	SR56R-01	2.448	7.6	7.5	0.1	1.7
		SR56R-04	2.453	7.4			
		SR56R-05	2.449	7.5			
		SR56R-06	2.454	7.3			
	IDT Strength	SR56R-07-01	2.471	6.7	8.0	1.1	13.2
		SR56R-07-02	2.403	9.3			
		SR56R-07-03	2.437	8.0			
		SR56R-09-02	2.435	8.1			
US30	Unconfined Dynamic Modulus	US30R-01	2.315	6.9	6.8	0.1	0.8
		US30R-04	2.319	6.8			
		US30R-06	2.317	6.8			
	Shear Modulus	US30R-08-01	2.295	7.7	7.8	0.7	9.3
		US30R-08-02	2.274	8.6			
		US30R-09-01	2.31	7.1			
	Triaxial Strength	US30R-01	2.315	6.9	7.1	0.2	3.1
		US30R-02	2.314	7.0			
		US30R-03	2.304	7.4			
		US30R-05	2.312	7.0			
	IDT Strength	US30R-07-01	2.291	7.9	7.9	0.7	9.0
		US30R-07-02	2.266	8.9			
		US30R-07-03	2.302	7.4			
		US30R-09-02	2.303	7.4			
SR66	Unconfined Dynamic Modulus	SR66R-01	2.279	7.4	7.3	0.1	1.6
		SR66R-03	2.284	7.2			
		SR66R-04	2.285	7.2			
	Shear Modulus	SR66R-08-01	2.283	7.2	7.5	0.2	2.2
		SR66R-08-02	2.275	7.5			
		SR66R-09-01	2.273	7.6			
		SR66R-09-02	2.278	7.4			
	Triaxial Strength	SR66R-01	2.279	7.4	7.5	0.0	0.7
		SR66R-02	2.277	7.5			
		SR66R-05	2.277	7.5			
		SR66R-06	2.284	7.5			
	IDT Strength	SR66R-07-01	2.269	7.8	8.1	0.4	4.5
		SR66R-07-02	2.251	8.5			
		SR66R-07-03	2.263	8.0			
SR135	Unconfined Dynamic Modulus	SR135R-01	2.262	7.4	7.4	0.1	1.4
		SR135R-02	2.264	7.3			
		SR135R-03	2.260	7.5			
	Shear Modulus	SR135R-08-01	2.260	7.5	7.6	0.2	2.3
		SR135R-09-01	2.260	7.5			
		SR135R-09-02	2.252	7.8			
	Triaxial	SR135R-02	2.264	7.3	7.4	0.1	1.6
		SR135R-04	2.265	7.3			

Road No.	Test Method	Specimen ID	G _{mb}	V _a (%)	Average V _a (%)	Standard Deviation (%)	Coefficient of Variation (%)
	Strength	SR135R-05	2.262	7.5	8.4	0.4	4.3
		SR135R-06	2.259	7.5			
	IDT Strength	SR135R-07-01	2.236	8.5			
		SR135R-07-02	2.240	8.3			
		SR135R-07-03	2.227	8.8			
		SR135R-08-02	2.249	7.9			
US31	Unconfined Dynamic Modulus	US31R-01	2.749	7.5	7.7	0.2	2.6
		US31R-02	2.743	7.7			
		US31R-03	2.737	7.9			
	Shear Modulus	US31R-07-01	2.72	8.5	8.4	0.4	4.8
		US31R-07-02	2.71	8.8			
		US31R-08-02	2.735	8.0			
	Triaxial Strength	US31R-03	2.737	7.9	7.8	0.2	1.9
		US31R-04	2.747	7.6			
		US31R-05	2.738	7.9			
		US31R-06	2.743	7.7			
	IDT Strength	US31R-07-03	2.743	7.7	7.7	0.3	3.3
		US31R-08-01	2.743	7.7			
		US31R-09-01	2.756	7.3			
		US31R-09-02	2.737	7.9			
I74	Unconfined Dynamic Modulus	I74R-01	2.880	7.9	8.3	0.5	5.7
		I74R-02	2.852	8.8			
		I74R-05	2.873	8.1			
	Shear Modulus	I74R-07-01	2.877	8.0	8.2	0.2	1.9
		I74R-07-02	2.871	8.2			
		I74R-09-02	2.869	8.3			
	Triaxial Strength	I74R-02	2.852	8.8	8.1	0.5	6.3
		I74R-03	2.889	7.6			
		I74R-05	2.873	8.1			
		I74R-06	2.881	7.9			
	IDT Strength	I74R-03	2.889	7.6	7.7	0.1	1.3
		I74R-08-01	2.888	7.6			
		I74R-08-02	2.882	7.8			
		I74R-09-01	2.888	7.6			
SR64	Unconfined Dynamic Modulus	SR64R-01	2.721	7.7	7.6	0.4	5.3
		SR64R-02	2.737	7.2			
		SR64R-06	2.714	8.0			
	Shear Modulus	SR64R-07-01	2.736	7.2	7.5	0.4	4.7
		SR64R-07-02	2.716	7.9			
		SR64R-07-03	2.728	7.5			
	Triaxial Strength	SR64R-02	2.737	7.2	7.5	0.2	3.3
		SR64R-03	2.73	7.4			
		SR64R-04	2.721	7.7			
		SR64R-05	2.723	7.7			
	IDT Strength	SR64R-08-01	2.734	7.3	7.4	0.3	3.4
		SR64R-08-02	2.723	7.7			
		SR64R-09-01	2.739	7.1			
		SR64R-09-02	2.735	7.3			

Road No.	Test Method	Specimen ID	G _{mb}	V _a (%)	Average V _a (%)	Standard Deviation (%)	Coefficient of Variation (%)
I65	Unconfined Dynamic Modulus	I65R-03	2.762	6.9	6.7	0.3	4.3
		I65R-04	2.779	6.4			
		I65R-06	2.764	6.9			
	Shear Modulus	I65R-07-01	2.724	8.2	6.9	1.1	16.3
		I65R-08-01	2.785	6.2			
		I65R-08-02	2.782	6.3			
	Triaxial Strength	I65R-01	2.758	7.1	7.1	0.2	2.4
		I65R-02	2.752	7.3			
		I65R-03	2.762	6.9			
		I65R-05	2.761	7.0			
	IDT Strength	I65R-07-02	2.735	7.9	7.2	0.7	9.3
		I65R-07-03	2.748	7.4			
		I65R-09-01	2.780	6.3			
		I65R-09-02	2.753	7.2			

Mix	Sample ID	Temp. °C	V _a %	Unconfined Dynamic (Complex) Modulus E* (MPa)						Phase Angle φ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
SR15 (Mix 1)	SR15R-02	40	8.0	2262.0	1699.0	1284.0	787.0	681.0	494.0	33.49	26.07	32.62	28.78	26.78	23.05
	SR15R-03	40	7.7	2575.0	1858.0	1403.0	825.0	686.0	487.0	32.03	32.84	32.55	30.09	28.12	24.38
	SR15R-04	40	7.8	2185.0	1553.0	1204.0	733.0	613.0	457.0	32.86	33.26	32.29	28.36	26.57	22.25
	Average	40	7.8	2340.7	1703.3	1297.0	781.7	660.0	479.3	32.79	30.72	32.49	29.08	27.16	23.23
	STDV	40	0.2	206.6	152.5	100.1	46.2	40.8	19.7	0.73	4.04	0.17	0.90	0.84	1.08
	CV, %	40	2.0	8.8	9.0	7.7	5.9	6.2	4.1	2.2	13.1	0.5	3.1	3.1	4.6
US24 (Mix 2)	US24R-01	40	7.7	2584.0	1912.0	1475.0	848.0	686.0	459.0	30.35	32.16	32.50	30.20	28.73	24.96
	US24R-04	40	7.6	2975.0	2263.0	1765.0	1059.0	889.0	620.0	30.06	28.17	31.64	29.75	28.19	24.76
	US24R-05	40	7.5	3666.0	2701.0	2143.0	1232.0	988.0	676.0	30.47	33.01	32.95	31.54	29.98	27.03
	Average	40	7.6	3075.0	2292.0	1794.3	1046.3	854.3	585.0	30.29	31.11	32.36	30.50	28.97	25.58
	STDV	40	0.1	547.9	395.3	335.0	192.3	154.0	112.7	0.21	2.58	0.67	0.93	0.92	1.26
	CV, %	40	1.3	17.8	17.2	18.7	18.4	18.0	19.3	0.7	8.3	2.1	3.1	3.2	4.9
SR161 (Mix 4)	SR161R-02	40	7.8	2091.0	1511.0	1149.0	667.0	556.0	360.0	33.37	34.04	33.91	32.87	31.29	28.00
	SR161R-03	40	7.7	2384.0	1745.0	1313.0	693.0	564.0	442.0	37.92	38.05	37.06	36.54	35.20	29.69
	SR161R-04	40	7.4	2828.0	1901.0	1418.0	749.0	592.0	380.0	35.66	35.80	36.00	35.12	33.66	30.58
	Average	40	7.6	2434.3	1719.0	1293.3	703.0	570.7	394.0	35.65	35.96	35.66	34.84	33.38	29.42
	STDV	40	0.2	371.1	196.3	135.6	41.9	18.9	42.8	2.28	2.01	1.60	1.85	1.97	1.31
	CV, %	40	2.7	15.2	11.4	10.5	6.0	3.3	10.9	6.4	5.6	4.5	5.3	5.9	4.5
SR56 (Mix 5)	SR56R-01	40	7.6	3670.0	2716.0	2139.0	1314.0	1074.0	726.0	26.48	28.33	29.23	29.95	29.41	27.18
	SR56R-02	40	7.4	3951.0	3106.0	2533.0	1536.0	1265.0	871.0	26.22	27.95	29.09	29.79	29.39	26.80
	SR56R-03	40	7.9	3627.0	2757.0	2205.0	1357.0	1119.0	773.0	26.64	28.06	29.05	29.95	29.40	26.95
	Average	40	7.6	3749.3	2859.7	2292.3	1402.3	1152.7	790.0	26.45	28.11	29.12	29.90	29.40	26.98
	STDV	40	0.3	176.0	214.3	211.0	117.7	99.9	74.0	0.21	0.20	0.09	0.09	0.01	0.19
	CV, %	40	3.3	4.7	7.5	9.2	8.4	8.7	9.4	0.8	0.7	0.3	0.3	0.0	0.7
US30 (Mix 9)	US30R-01	40	6.9	4069.0	3160.0	2582.0	1687.0	1466.0	1153.0	28.46	28.83	28.23	25.49	23.84	20.40
	US30R-04	40	6.8	3858.0	2766.0	2173.0	1316.0	1091.0	792.0	31.84	32.95	32.39	30.33	29.22	26.00
	US30R-06	40	6.8	5241.0	4011.0	3246.0	1884.0	1517.0	1114.0	25.50	27.93	28.40	31.10	30.61	27.42
	Average	40	6.8	4389.3	3312.3	2667.0	1629.0	1358.0	1019.7	28.60	29.90	29.67	28.97	27.89	24.61
	STDV	40	0.1	745.1	636.3	541.5	288.4	232.6	198.1	3.17	2.68	2.35	3.04	3.58	3.71
	CV, %	40	0.8	17.0	19.2	20.3	17.7	17.1	19.4	11.1	9.0	7.9	10.5	12.8	15.1

Mix	Sample ID	Temp. °C	V _a %	Unconfined Dynamic (Complex) Modulus E* (MPa)						Phase Angle φ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
SR66 (Mix 11)	SR66R-01	40	7.4	3787.0	2936.0	2346.0	1383.0	1109.0	814.0	26.80	28.55	29.01	29.57	29.22	26.58
	SR66R-03	40	7.2	3589.0	2754.0	2197.0	1340.0	1101.0	778.0	28.11	29.77	30.00	29.06	28.04	24.31
	SR66R-04	40	7.2	3693.0	2732.0	2060.0	1218.0	987.0	694.0	29.60	31.78	32.52	32.58	31.58	29.12
	Average	40	7.3	3689.7	2807.3	2201.0	1313.7	1065.7	762.0	28.17	30.03	30.51	30.40	29.61	26.67
	STDV	40	0.1	99.0	112.0	143.0	85.6	68.2	61.6	1.40	1.63	1.81	1.90	1.80	2.41
	CV, %	40	1.6	2.7	4.0	6.5	6.5	6.4	8.1	5.0	5.4	5.9	6.3	6.1	9.0
SR135 (Mix 12)	SR135R-01	40	7.4	2583.0	1964.0	1606.0	1021.0	851.0	606.0	27.63	29.05	29.12	28.20	26.90	24.18
	SR135R-02	40	7.3	3822.0	2919.0	2329.0	1418.0	1173.0	836.0	27.29	28.76	29.24	29.92	28.93	25.72
	SR135R-03	40	7.5	3702.0	2800.0	2262.0	1419.0	1199.0	868.0	26.77	28.17	28.50	27.05	25.79	22.08
	Average	40	7.4	3369.0	2561.0	2065.7	1286.0	1074.3	770.0	27.23	28.66	28.95	28.39	27.21	23.99
	STDV	40	0.1	683.3	520.4	399.5	229.5	193.8	142.9	0.43	0.45	0.40	1.44	1.59	1.83
	CV, %	40	1.4	20.3	20.3	19.3	17.8	18.0	18.6	1.6	1.6	1.4	5.1	5.9	7.6
US31 (Mix 8S)	US31R-01	40	7.5	2484.0	1835.0	1473.0	955.0	809.0	597.0	33.03	32.83	31.87	28.73	26.91	23.51
	US31R-02	40	7.7	2686.0	1989.0	1682.0	1028.0	872.0	665.0	32.17	32.03	32.66	29.23	27.57	24.62
	US31R-03	40	7.9	2135.0	1598.0	1321.0	850.0	729.0	553.0	30.94	30.78	29.87	27.47	25.97	23.11
	Average	40	7.7	2435.0	1807.3	1492.0	944.3	803.3	605.0	32.05	31.88	31.47	28.48	26.82	23.75
	STDV	40	0.2	278.7	197.0	181.2	89.5	71.7	56.4	1.05	1.03	1.44	0.91	0.80	0.78
	CV, %	40	2.6	11.4	10.9	12.1	9.5	8.9	9.3	3.3	3.2	4.6	3.2	3.0	3.3
I74 (Mix 9S)	I74R-01	40	7.9	3069.0	2407.0	1957.0	1257.0	1119.0	856.0	28.15	29.00	28.48	26.36	24.85	21.52
	I74R-02	40	8.8	2984.0	2126.0	2958.0	217.0	901.0	640.0	27.71	29.26	36.82	36.62	28.59	26.69
	I74R-05	40	8.1	3457.0	2698.0	2192.0	1434.0	1229.0	945.0	28.74	29.43	28.99	26.81	25.15	21.69
	Average	40	8.3	3170.0	2410.3	2369.0	969.3	1083.0	813.7	28.20	29.23	31.43	29.93	26.20	23.30
	STDV	40	0.5	252.2	286.0	523.4	657.5	166.9	156.8	0.52	0.22	4.67	5.80	2.08	2.94
	CV, %	40	5.7	8.0	11.9	22.1	67.8	15.4	19.3	1.8	0.7	14.9	19.4	7.9	12.6
SR64 (Mix 11S)	SR64R-01	40	7.7	5442.0	4057.0	3305.0	2084.0	1711.0	1164.0	24.35	26.36	27.07	27.60	27.00	25.06
	SR64R-02	40	7.2	5044.0	3752.0	3090.0	1894.0	1564.0	1085.0	27.62	28.98	29.44	28.55	27.30	24.40
	SR64R-06	40	8.0	5216.0	4012.0	3281.0	2071.0	1741.0	1257.0	25.68	27.81	28.47	28.97	28.19	26.08
	Average	40	7.6	5234.0	3940.3	3225.3	2016.3	1672.0	1168.7	25.88	27.72	28.33	28.37	27.50	25.18
	STDV	40	0.4	199.6	164.6	117.8	106.1	94.7	86.1	1.64	1.31	1.19	0.70	0.62	0.85
	CV, %	40	5.3	3.8	4.2	3.7	5.3	5.7	7.4	6.4	4.7	4.2	2.5	2.3	3.4

Mix	Sample ID	Temp. °C	V _a %	Unconfined Dynamic (Complex) Modulus E* (MPa)						Phase Angle φ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
I65 (Mix 12S)	I65R-03	40	6.9	2891.0	2203.0	1812.0	1124.0	938.0	675.0	28.69	29.90	30.14	29.12	28.16	25.36
	I65R-04	40	6.4	3571.0	2707.0	2247.0	1396.0	1168.0	848.0	26.55	28.07	28.44	28.29	27.51	25.19
	I65R-06	40	6.9	5762.0	4283.0	3377.0	2070.0	1708.0	1213.0	26.97	27.94	28.19	27.46	26.43	23.42
	Average	40	6.7	4074.7	3064.3	2478.7	1530.0	1271.3	912.0	27.40	28.64	28.92	28.29	27.37	24.66
	STDV	40	0.3	1500.3	1085.1	807.8	487.0	395.3	274.7	1.13	1.10	1.06	0.83	0.87	1.07
	CV, %	40	4.3	36.8	35.4	32.6	31.8	31.1	30.1	4.1	3.8	3.7	2.9	3.2	4.4
SR15 (Mix 1)	SR15R-02	54.4	8.0	625.0	486.0	413.0	319.0	297.0	271.0	29.06	26.49	24.44	19.62	18.54	17.59
	SR15R-03	54.4	7.7	993.0	741.0	631.0	462.0	417.0	344.0	33.22	27.79	30.25	24.98	23.76	21.75
	SR15R-04	54.4	7.8	780.0	589.0	491.0	364.0	335.0	299.0	32.60	29.97	27.64	22.03	20.49	18.22
	Average	54.4	7.8	799.3	605.3	511.7	381.7	349.7	304.7	31.63	28.08	27.44	22.21	20.93	19.19
	STDV	54.4	0.2	184.8	128.3	110.5	73.1	61.3	36.8	2.24	1.76	2.91	2.68	2.64	2.24
	CV, %	54.4	2.0	23.1	21.2	21.6	19.2	17.5	12.1	7.1	6.3	10.6	12.1	12.6	11.7
US24 (Mix 2)	US24R-01	54.4	7.7	696.0	508.0	417.0	301.0	273.0	229.0	34.47	31.81	29.00	23.26	21.34	18.54
	US24R-04	54.4	7.6	1336.0	977.0	785.0	538.0	477.0	400.0	32.80	31.58	30.14	26.08	24.26	21.33
	US24R-05	54.4	7.5	1199.0	880.0	724.0	511.0	450.0	375.0	31.49	29.89	27.91	23.61	22.21	19.51
	Average	54.4	7.6	1077.0	788.3	642.0	450.0	400.0	334.7	32.92	31.09	29.02	24.32	22.60	19.79
	STDV	54.4	0.1	337.0	247.6	197.2	129.7	110.8	92.4	1.49	1.05	1.12	1.54	1.50	1.42
	CV, %	54.4	1.3	31.3	31.4	30.7	28.8	27.7	27.6	4.5	3.4	3.8	6.3	6.6	7.2
SR161 (Mix 4)	SR161R-02	54.4	7.8	825.0	592.0	455.0	313.0	275.0	230.0	34.82	146.74	28.58	26.01	24.20	21.15
	SR161R-03	54.4	7.7	687.0	492.0	400.0	291.0	265.0	217.0	34.60	147.79	29.59	23.71	22.33	20.27
	SR161R-04	54.4	7.4	1010.0	701.0	537.0	336.0	286.0	224.0	35.07	145.68	87.37	27.91	26.22	22.94
	Average	54.4	7.6	840.7	595.0	464.0	313.3	275.3	223.7	34.83	146.74	48.51	25.88	24.25	21.45
	STDV	54.4	0.2	162.1	104.5	68.9	22.5	10.5	6.5	0.24	1.06	33.65	2.10	1.95	1.36
	CV, %	54.4	2.7	19.3	17.6	14.9	7.2	3.8	2.9	0.7	0.7	69.4	8.1	8.0	6.3
SR56 (Mix 5)	SR56R-01	54.4	7.6	1299.0	994.0	803.0	532.0	455.0	334.0	30.69	30.01	28.93	25.92	24.83	22.59
	SR56R-02	54.4	7.4	1286.0	972.0	799.0	563.0	505.0	406.0	30.76	29.64	28.12	24.31	22.90	20.68
	SR56R-03	54.4	7.9	1302.0	1000.0	825.0	575.0	506.0	391.0	28.36	27.87	26.85	23.42	22.05	19.49
	Average	54.4	7.6	1295.7	988.7	809.0	556.7	488.7	377.0	29.94	29.17	27.97	24.55	23.26	20.92
	STDV	54.4	0.3	8.5	14.7	14.0	22.2	29.2	38.0	1.37	1.14	1.05	1.27	1.42	1.56
	CV, %	54.4	3.3	0.7	1.5	1.7	4.0	6.0	10.1	4.6	3.9	3.7	5.2	6.1	7.5

Mix	Sample ID	Temp. °C	V _a %	Unconfined Dynamic (Complex) Modulus E* (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
US30 (Mix 9)	US30R-01	54.4	6.9	1545.0	1204.0	1031.0	801.0	742.0	650.0	25.59	23.88	21.94	18.25	17.02	14.87
	US30R-04	54.4	6.8	1564.0	1215.0	1027.0	778.0	709.0	606.0	27.34	26.05	24.46	21.00	19.84	17.52
	US30R-06	54.4	6.8	2560.0	2014.0	1692.0	1334.0	1236.0	1054.0	24.67	23.58	22.44	19.98	19.37	17.85
	Average	54.4	6.8	1889.7	1477.7	1250.0	971.0	895.7	770.0	25.87	24.50	22.95	19.74	18.74	16.75
	STDV	54.4	0.1	580.6	464.5	382.8	314.6	295.2	246.9	1.36	1.35	1.33	1.39	1.51	1.63
	CV, %	54.4	0.8	30.7	31.4	30.6	32.4	33.0	32.1	5.2	5.5	5.8	7.0	8.1	9.8
SR66 (Mix 11)	SR66R-01	54.4	7.4	1267.0	948.0	772.0	547.0	491.0	409.0	29.72	27.86	26.46	22.61	21.12	18.52
	SR66R-03	54.4	7.2	1153.0	863.0	718.0	518.0	461.0	384.0	28.59	27.29	25.52	21.47	20.14	17.96
	SR66R-04	54.4	7.2	1253.0	905.0	717.0	507.0	438.0	353.0	31.72	30.03	28.27	23.62	22.10	19.82
	Average	54.4	7.3	1224.3	905.3	735.7	524.0	463.3	382.0	30.01	28.39	26.75	22.57	21.12	18.77
	STDV	54.4	0.1	62.2	42.5	31.5	20.7	26.6	28.1	1.59	1.45	1.40	1.08	0.98	0.95
	CV, %	54.4	1.6	5.1	4.7	4.3	3.9	5.7	7.3	5.3	5.1	5.2	4.8	4.6	5.1
SR135 (Mix 12)	SR135R-01	54.4	7.4	881.0	687.0	574.0	432.0	393.0	322.0	28.82	26.96	25.05	20.47	19.12	17.15
	SR135R-02	54.4	7.3	1152.0	898.0	770.0	557.0	515.0	451.0	28.20	27.11	25.58	21.43	19.95	17.63
	SR135R-03	54.4	7.5	1496.0	1122.0	921.0	648.0	581.0	486.0	27.66	26.60	25.05	20.76	19.38	17.08
	Average	54.4	7.4	1176.3	902.3	755.0	545.7	496.3	419.7	28.23	26.89	25.23	20.89	19.48	17.29
	STDV	54.4	0.1	308.2	217.5	174.0	108.4	95.4	86.4	0.58	0.26	0.31	0.49	0.42	0.30
	CV, %	54.4	1.4	26.2	24.1	23.0	19.9	19.2	20.6	2.1	1.0	1.2	2.4	2.2	1.7
US31 (Mix 8S)	US31R-01	54.4	7.5	836.0	663.0	579.0	451.0	423.0	368.0	27.46	24.99	23.16	19.84	18.80	16.84
	US31R-02	54.4	7.7	1141.0	924.0	769.0	579.0	527.0	441.0	29.45	26.99	25.41	22.78	21.41	20.05
	US31R-03	54.4	7.9	819.0	676.0	595.0	465.0	428.0	366.0	27.13	25.27	23.48	20.72	19.97	18.77
	Average	54.4	7.7	932.0	754.3	647.7	498.3	459.3	391.7	28.01	25.75	24.02	21.11	20.06	18.55
	STDV	54.4	0.2	181.2	147.1	105.4	70.2	58.7	42.7	1.26	1.08	1.22	1.51	1.31	1.62
	CV, %	54.4	2.6	19.4	19.5	16.3	14.1	12.8	10.9	4.5	4.2	5.1	7.1	6.5	8.7
I74 (Mix 9S)	I74R-01	54.4	7.9	1680.0	1342.0	1168.0	905.0	828.0	738.0	25.56	23.93	21.87	18.04	17.15	15.87
	I74R-02	54.4	8.8	1151.0	895.0	758.0	579.0	527.0	448.0	26.99	25.44	23.58	19.96	18.62	16.76
	I74R-05	54.4	8.1	1028.0	820.0	691.0	511.0	460.0	388.0	28.29	26.36	24.80	21.12	20.18	19.22
	Average	54.4	8.3	1286.3	1019.0	872.3	665.0	605.0	524.7	26.95	25.24	23.42	19.71	18.65	17.28
	STDV	54.4	0.5	346.4	282.2	258.2	210.6	196.0	187.2	1.37	1.23	1.47	1.56	1.52	1.74
	CV, %	54.4	5.7	26.9	27.7	29.6	31.7	32.4	35.7	5.1	4.9	6.3	7.9	8.1	10.0

Mix	Sample ID	Temp. °C	V _a %	Unconfined Dynamic (Complex) Modulus E* (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
SR64 (Mix 11S)	SR64R-01	54.4	7.7	1530.0	1154.0	931.0	612.0	521.0	388.0	28.91	29.04	28.53	27.22	26.54	25.32
	SR64R-02	54.4	7.2	2289.0	1737.0	1429.0	1011.0	890.0	716.0	27.07	26.00	24.97	22.15	21.10	19.29
	SR64R-06	54.4	8.0	1549.0	1256.0	1007.0	716.0	653.0	484.0	28.04	27.75	26.58	24.44	23.49	22.72
	Average	54.4	7.6	1789.3	1382.3	1122.3	779.7	688.0	529.3	28.01	27.60	26.69	24.60	23.71	22.44
	STDV	54.4	0.4	432.8	311.4	268.3	207.0	187.0	168.6	0.92	1.53	1.78	2.54	2.73	3.02
	CV, %	54.4	5.3	24.2	22.5	23.9	26.5	27.2	31.9	3.3	5.5	6.7	10.3	11.5	13.5
I65 (Mix 12S)	I65R-03	54.4	6.9	1048.0	843.0	719.0	517.0	467.0	385.0	28.89	27.96	26.76	23.40	22.20	20.03
	I65R-04	54.4	6.4	1636.0	1290.0	1083.0	769.0	684.0	556.0	28.51	27.11	25.93	23.30	22.35	20.90
	I65R-06	54.4	6.9	1803.0	1414.0	1197.0	864.0	776.0	629.0	25.07	24.31	23.47	21.31	20.36	18.61
	Average	54.4	6.7	1495.7	1182.3	999.7	716.7	642.3	523.3	27.49	26.46	25.39	22.67	21.64	19.85
	STDV	54.4	0.3	396.6	300.3	249.7	179.3	158.7	125.2	2.10	1.91	1.71	1.18	1.11	1.16
	CV, %	54.4	4.3	26.5	25.4	25.0	25.0	24.7	23.9	7.7	7.2	6.7	5.2	5.1	5.8

Mix	Sample ID	Temp. °C	V _a %	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR15 (Mix 1)	SR15R-08-01	40	7.6	423.1	305.3	195.8	139.2	99.6	66.8	52.2	44.2	37.8	36.7
	SR15R-08-02	40	7.7	341.9	248.5	151.9	103.6	72.1	48.0	36.7	29.7	24.7	23.4
	SR15R-09-01	40	7.3	487.3	359.5	229.8	163.7	114.9	76.3	59.0	47.8	38.6	36.3
	SR15R-09-02	40	7.3	480.2	349.5	222.2	152.8	106.1	67.7	49.7	38.1	29.2	26.9
	Average	40	7.5	433.1	315.7	199.9	139.8	98.2	64.7	49.4	40.0	32.6	30.9
	STDV	40	0.2	67.3	50.6	35.2	26.1	18.5	11.9	9.3	7.9	6.8	6.7
	CV, %	40	2.9	15.5	16.0	17.6	18.7	18.8	18.4	18.9	19.8	20.8	21.8
US24 (Mix 2)	US24R-09-01	40	7.7	565.4	438.8	296.0	216.9	156.7	105.7	81.0	64.7	50.4	45.3
	US24R-09-02	40	7.6	859.4	612.8	386.1	283.7	197.7	127.7	90.3	67.8	50.0	42.3
	US24R-10-01	40	8.0	1146.6	892.2	605.7	439.0	310.6	192.0	131.9	92.1	59.9	46.0
	Average	40	7.8	857.1	647.9	429.2	313.2	221.6	141.8	101.1	74.9	53.4	44.5
	STDV	40	0.2	290.6	228.7	159.3	114.0	79.7	44.8	27.1	15.0	5.6	2.0
	CV, %	40	3.0	33.9	35.3	37.1	36.4	36.0	31.6	26.8	20.0	10.5	4.5
SR161 (Mix 4)	SR161R-08-01	40	7.8	414.1	305.3	196.8	135.3	96.9	61.3	45.4	35.7	28.7	27.5
	SR161R-08-02	40	7.7	559.0	418.9	272.4	196.6	144.4	99.7	75.2	58.8	45.6	39.8
	SR161R-09-01	40	7.4	682.9	527.7	362.1	260.0	186.5	123.3	88.8	66.0	45.9	36.6
	SR161R-09-02	40	7.4	622.5	466.8	302.2	215.1	153.5	100.4	73.4	54.3	37.6	31.2
	Average	40	7.6	569.6	429.7	283.4	201.8	145.3	96.2	70.7	53.7	39.5	33.8
	STDV	40	0.2	115.3	94.1	68.7	51.7	37.0	25.7	18.2	12.9	8.1	5.5
	CV, %	40	2.6	20.2	21.9	24.3	25.6	25.5	26.7	25.7	24.1	20.6	16.3
SR56 (Mix 5)	SR56R-08-01	40	7.8	865.2	665.5	484.2	366.3	272.1	180.8	133.3	99.1	66.9	51.3
	SR56R-08-02	40	7.9	1219.9	972.3	703.4	535.7	391.6	265.1	193.8	144.1	97.1	70.4
	SR56R-09-01	40	7.4	1748.7	1355.1	1014.1	786.8	602.7	419.6	313.6	236.1	160.2	116.9
	Average	40	7.7	1277.9	997.7	733.9	562.9	422.1	288.5	213.5	159.7	108.1	79.5
	STDV	40	0.3	444.6	345.5	266.2	211.6	167.4	121.1	91.7	69.8	47.6	33.8
	CV, %	40	3.7	34.8	34.6	36.3	37.6	39.7	42.0	43.0	43.7	44.0	42.5
US30 (Mix 9)	US30R-08-01	40	7.7	800.3	613.4	431.6	322.2	239.2	163.0	123.4	96.7	70.4	58.8
	US30R-08-02	40	8.6	599.0	437.7	292.2	213.1	156.6	104.9	80.4	62.6	48.2	41.2
	US30R-09-01	40	7.1	835.0	657.4	463.7	351.8	266.9	184.7	138.0	104.7	75.1	59.9
	Average	40	7.8	744.8	569.5	395.8	295.7	220.9	150.9	113.9	88.0	64.6	53.3
	STDV	40	0.7	127.4	116.2	91.2	73.1	57.4	41.3	29.9	22.4	14.4	10.5
	CV, %	40	9.3	17.1	20.4	23.0	24.7	26.0	27.4	26.3	25.4	22.3	19.7
SR66 (Mix 11)	SR66R-08-01	40	7.2	787.4	634.7	441.1	340.2	266.4	185.5	144.1	112.2	83.1	65.6
	SR66R-08-02	40	7.5	653.3	509.6	349.7	274.2	209.7	146.9	113.2	91.3	70.5	61.5
	SR66R-09-01	40	7.6	752.6	596.8	417.2	314.0	234.7	160.2	121.4	93.0	66.3	54.0
	SR66R-09-02	40	7.4	807.7	634.1	445.9	339.5	257.2	173.7	129.1	98.3	68.5	52.4
	Average	40	7.5	750.2	593.8	413.4	317.0	242.0	166.6	126.9	98.7	72.1	58.4
	STDV	40	0.2	68.5	58.9	44.3	31.0	25.3	16.7	13.2	9.5	7.5	6.2
SR135 (Mix 12)	SR135R-08-01	40	7.5	1000.1	777.8	553.1	411.9	309.4	211.6	155.6	117.7	83.3	69.7
	SR135R-09-01	40	7.5	779.9	619.7	452.5	361.8	293.0	211.1	165.9	131.9	100.7	80.8
	SR135R-09-02	40	7.8	776.8	593.6	401.1	299.0	222.7	146.7	109.9	83.5	61.0	50.5
	Average	40	7.6	852.3	663.7	468.9	357.6	275.0	189.8	143.8	111.0	81.7	67.0
	STDV	40	0.2	128.0	99.7	77.3	56.5	46.0	37.3	29.8	24.8	19.9	15.3
	CV, %	40	2.3	15.0	15.0	16.5	15.8	16.7	19.7	20.7	22.4	24.4	22.9

Mix	Sample ID	Temp. °C	V _a %	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
US31 (Mix 8S)	US31R-07-01	40	8.5	364.2	263.2	172.2	126.0	92.9	62.5	48.6	38.2	29.1	23.8
	US31R-07-02	40	8.8	377.5	281.4	196.0	150.4	114.6	83.2	65.2	52.6	40.9	34.9
	US31R-08-02	40	8.0	436.6	316.9	205.3	148.7	107.2	71.6	54.5	42.3	30.8	25.7
	Average	40	8.4	392.8	287.1	191.2	141.7	104.9	72.4	56.1	44.4	33.6	28.2
	STDV	40	0.4	38.5	27.3	17.1	13.6	11.1	10.4	8.4	7.4	6.4	5.9
	CV, %	40	4.8	9.8	9.5	8.9	9.6	10.6	14.4	15.0	16.7	19.0	21.0
I74 (Mix 9S)	I74R-07-01	40	8.0	399.0	298.2	200.7	145.3	108.0	74.9	57.2	44.4	32.5	27.5
	I74R-07-02	40	8.2	391.2	293.5	195.2	144.4	106.8	71.2	54.8	42.2	30.5	25.5
	I74R-09-02	40	8.3	414.1	306.4	199.4	143.9	105.8	71.4	53.8	41.3	30.3	24.8
	Average	40	8.2	401.4	299.3	198.4	144.5	106.9	72.5	55.3	42.7	31.1	25.9
	STDV	40	0.2	11.7	6.5	2.9	0.7	1.1	2.1	1.7	1.6	1.2	1.4
	CV, %	40	1.9	2.9	2.2	1.4	0.5	1.0	2.9	3.1	3.8	3.9	5.4
SR64 (Mix 11S)	SR64R-07-01	40	7.2	758.4	596.5	406.8	306.6	229.4	153.0	115.5	84.9	58.4	45.1
	SR64R-07-02	40	7.9	714.0	560.5	390.2	296.2	226.5	155.9	118.5	88.4	63.1	49.5
	SR64R-07-03	40	7.5	642.1	487.7	340.4	258.2	192.1	131.5	97.6	74.1	52.6	41.4
	Average	40	7.5	704.8	548.2	379.1	287.0	216.0	146.8	110.5	82.5	58.0	45.3
	STDV	40	0.4	58.7	55.4	34.6	25.5	20.7	13.3	11.3	7.5	5.3	4.0
	CV, %	40	4.7	8.3	10.1	9.1	8.9	9.6	9.1	10.2	9.1	9.1	8.9
I65 (Mix 12S)	I65R-07-01	40	8.2	526.8	399.9	274.0	212.0	161.9	114.1	88.4	69.7	52.3	42.9
	I65R-08-01	40	6.2	637.1	502.2	362.1	281.3	220.9	159.9	128.8	103.1	77.9	62.5
	I65R-08-02	40	6.3	613.8	476.4	337.7	260.3	200.1	143.9	112.8	88.7	66.0	53.5
	Average	40	6.9	592.6	459.5	324.6	251.2	194.3	139.3	110.0	87.2	65.4	53.0
	STDV	40	1.1	58.2	53.2	45.5	35.5	29.9	23.3	20.4	16.8	12.8	9.8
	CV, %	40	16.3	9.8	11.6	14.0	14.1	15.4	16.7	18.5	19.3	19.6	18.5
SR15 (Mix 1)	SR15R-08-01	54.4	7.6	106.7	70.0	37.3	25.6	22.7	16.7	14.1	13.0	11.9	12.3
	SR15R-08-02	54.4	7.7	103.9	68.6	40.0	32.2	23.9	18.2	16.1	15.3	13.9	14.2
	SR15R-09-01	54.4	7.3	127.5	85.9	49.0	33.3	28.7	20.4	17.2	15.4	13.4	13.3
	SR15R-09-02	54.4	7.3	128.4	86.6	54.4	37.8	26.6	18.5	16.2	15.1	13.1	12.4
	Average	54.4	7.5	116.6	77.8	45.2	32.2	25.5	18.5	15.9	14.7	13.1	13.1
	STDV	54.4	0.2	13.1	9.8	7.9	5.0	2.7	1.5	1.3	1.1	0.8	0.9
US24 (Mix 2)	CV, %	54.4	2.9	11.2	12.6	17.5	15.6	10.6	8.2	8.2	7.8	6.4	6.7
	US24R-09-01	54.4	7.7	174.7	133.2	81.0	59.1	50.2	47.7	45.9	39.6	42.5	48.9
	US24R-09-02	54.4	7.6	145.5	112.5	63.2	46.5	48.8	42.6	40.7	39.2	41.8	45.4
	US24R-10-01	54.4	8.0	202.0	134.8	76.0	54.8	38.0	25.4	20.4	17.1	15.0	16.3
	Average	54.4	7.8	174.1	126.8	73.4	53.5	45.7	38.6	35.7	32.0	33.1	36.8
	STDV	54.4	0.2	28.3	12.4	9.2	6.4	6.7	11.7	13.5	12.9	15.7	17.9
SR161 (Mix 4)	CV, %	54.4	3.0	16.2	9.8	12.5	11.9	14.7	30.4	37.8	40.4	47.3	48.6
	SR161R-08-01	54.4	7.8	89.7	62.0	37.9	27.4	19.2	14.4	11.8	10.8	10.3	11.4
	SR161R-08-02	54.4	7.7	147.9	101.4	65.1	45.4	33.7	24.0	19.7	15.2	14.1	13.7
	SR161R-09-01	54.4	7.4	133.4	92.5	56.2	41.0	28.4	21.2	17.5	14.5	12.3	11.8
	SR161R-09-02	54.4	7.4	183.8	132.0	78.5	56.3	40.6	28.7	23.9	21.0	20.8	23.8
	Average	54.4	7.6	138.7	97.0	59.4	42.5	30.5	22.1	18.2	15.4	14.3	15.2
	STDV	54.4	0.2	39.0	28.8	17.0	11.9	9.0	6.0	5.0	4.2	4.6	5.9
	CV, %	54.4	2.6	28.1	29.7	28.7	28.1	29.7	27.2	27.5	27.6	31.9	38.7

Mix	Sample ID	Temp. °C	V _a %	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR56 (Mix 5)	SR56R-08-01	54.4	7.8	232.3	169.9	108.2	77.7	58.4	41.3	33.4	27.0	23.0	21.4
	SR56R-08-02	54.4	7.9	192.4	140.0	87.3	61.6	44.6	29.5	22.6	17.9	14.3	12.5
	SR56R-09-01	54.4	7.4	238.7	176.8	121.6	90.9	69.6	51.7	42.5	36.8	31.1	28.5
	Average	54.4	7.7	221.1	162.2	105.7	76.7	57.5	40.8	32.8	27.2	22.8	20.8
	STDV	54.4	0.3	25.1	19.5	17.3	14.7	12.5	11.1	9.9	9.5	8.4	8.0
	CV, %	54.4	3.7	11.3	12.0	16.4	19.1	21.7	27.2	30.2	34.9	36.8	38.5
US30 (Mix 9)	US30R-08-01	54.4	7.7	184.1	130.4	86.7	63.1	48.6	35.9	30.2	26.5	22.7	21.6
	US30R-08-02	54.4	8.6	225.8	157.5	101.8	73.6	52.6	38.4	31.2	27.0	22.5	20.9
	US30R-09-01	54.4	7.1	157.5	113.7	74.5	52.3	40.3	29.3	24.5	21.4	18.8	17.7
	Average	54.4	7.8	189.1	133.9	87.7	63.0	47.2	34.5	28.6	24.9	21.3	20.1
	STDV	54.4	0.7	34.4	22.1	13.7	10.6	6.3	4.7	3.6	3.1	2.2	2.1
	CV, %	54.4	9.3	18.2	16.5	15.6	16.9	13.3	13.7	12.5	12.5	10.4	10.3
SR66 (Mix 11)	SR66R-08-01	54.4	7.2	199.8	156.3	105.3	79.8	65.2	57.3	53.5	50.1	50.0	51.7
	SR66R-08-02	54.4	7.5	290.0	231.5	154.4	121.9	97.1	76.7	64.6	61.3	61.0	67.2
	SR66R-09-01	54.4	7.6	279.0	212.1	153.8	117.6	97.2	75.1	66.6	63.8	62.9	67.7
	SR66R-09-02	54.4	7.4	262.8	186.7	122.5	85.9	62.2	41.3	31.3	25.3	20.4	18.1
	Average	54.4	7.5	257.9	196.7	134.0	101.3	80.4	62.6	54.0	50.1	48.6	51.2
	STDV	54.4	0.2	40.3	32.6	24.3	21.5	19.3	16.7	16.2	17.6	19.7	23.3
SR135 (Mix 12)	SR135R-08-01	54.4	7.5	356.3	263.0	167.7	126.7	92.1	65.8	53.9	44.3	36.4	32.5
	SR135R-09-01	54.4	7.5	235.1	184.6	127.4	100.6	89.0	68.6	66.7	64.5	62.2	66.1
	SR135R-09-02	54.4	7.8	185.7	130.2	78.0	53.7	39.2	26.9	21.8	16.8	14.1	12.2
	Average	54.4	7.6	259.0	192.6	124.4	93.7	73.4	53.8	47.5	41.9	37.6	36.9
	STDV	54.4	0.2	87.8	66.7	44.9	37.0	29.7	23.3	23.2	24.0	24.0	27.2
	CV, %	54.4	2.3	33.9	34.6	36.1	39.5	40.5	43.3	48.8	57.2	63.9	73.7
US31 (Mix 8S)	US31R-07-01	54.4	8.5	107.4	77.0	48.6	37.2	29.3	22.3	19.5	17.2	15.0	14.4
	US31R-07-02	54.4	8.8	106.6	78.5	51.1	35.8	27.6	20.6	21.0	20.1	17.7	18.3
	US31R-08-02	54.4	8.0	114.8	84.3	53.8	38.3	29.9	23.0	20.6	20.8	19.6	19.8
	Average	54.4	8.4	109.6	79.9	51.2	37.1	29.0	22.0	20.4	19.4	17.4	17.5
	STDV	54.4	0.4	4.5	3.8	2.6	1.2	1.2	1.2	0.8	1.9	2.3	2.8
	CV, %	54.4	4.8	4.1	4.8	5.0	3.2	4.1	5.6	3.9	9.9	13.4	16.0
I74 (Mix 9S)	I74R-07-01	54.4	8.0	96.0	68.6	42.4	36.2	28.1	21.5	18.3	16.2	14.1	13.5
	I74R-07-02	54.4	8.2	113.3	81.4	51.0	35.4	29.6	21.5	18.0	15.2	13.0	13.4
	I74R-09-02	54.4	8.3	113.8	82.9	55.5	38.5	30.6	21.9	20.8	18.9	17.4	17.4
	Average	54.4	8.2	107.7	77.7	49.6	36.7	29.4	21.7	19.1	16.8	14.8	14.8
	STDV	54.4	0.2	10.2	7.9	6.7	1.6	1.2	0.2	1.5	1.9	2.3	2.3
	CV, %	54.4	1.9	9.4	10.1	13.4	4.5	4.2	0.9	8.0	11.5	15.4	15.6
SR64 (Mix 11S)	SR64R-07-01	54.4	7.2	184.0	133.1	90.1	64.9	47.5	33.4	27.0	22.1	18.1	17.6
	SR64R-07-02	54.4	7.9	165.1	121.7	77.0	54.5	39.7	31.6	24.6	19.4	17.7	17.3
	SR64R-07-03	54.4	7.5	146.9	106.8	68.3	47.9	33.9	29.5	23.9	20.7	18.1	18.4
	Average	54.4	7.5	165.3	120.5	78.5	55.8	40.4	31.5	25.2	20.8	18.0	17.8
	STDV	54.4	0.4	18.5	13.2	11.0	8.6	6.8	2.0	1.6	1.4	0.3	0.5
	CV, %	54.4	4.7	11.2	10.9	14.0	15.4	16.9	6.2	6.4	6.5	1.4	3.0
I65 (Mix 12S)	I65R-07-01	54.4	8.2	158.1	125.9	85.5	68.3	54.0	41.3	35.0	30.6	26.8	24.8
	I65R-08-01	54.4	6.2	198.3	151.2	104.1	82.3	65.0	49.3	41.1	35.4	29.7	27.7
	I65R-08-02	54.4	6.3	180.9	134.0	96.0	71.2	55.5	44.9	39.3	34.3	29.7	27.4
	Average	54.4	6.9	179.1	137.1	95.2	74.0	58.2	45.2	38.5	33.4	28.7	26.6
	STDV	54.4	1.1	20.2	12.9	9.3	7.4	5.9	4.0	3.1	2.5	1.7	1.6
	CV, %	54.4	16.3	11.3	9.4	9.8	10.0	10.2	8.8	8.0	7.6	5.8	6.2

Mix	Sample ID	Temp °C	V _a %	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR15 (Mix 1)	SR15R-08-01	40	7.6	53.72	54.83	53.43	54.46	53.93	53.44	53.06	52.16	50.83	51.02
	SR15R-08-02	40	7.7	54.79	55.33	56.70	58.56	58.26	57.70	58.08	57.59	58.79	58.55
	SR15R-09-01	40	7.3	49.89	51.31	52.80	54.92	55.62	54.55	54.05	54.18	53.68	53.18
	SR15R-09-02	40	7.3	49.11	50.51	52.90	56.16	57.45	57.21	58.45	58.00	58.15	58.82
	Average	40	7.5	51.88	53.00	53.96	56.03	56.32	55.73	55.91	55.48	55.36	55.39
	STDV	40	0.2	2.8	2.4	1.8	1.8	1.9	2.1	2.8	2.8	3.8	3.9
US24 (Mix 2)	CV, %	40	2.9	5.4	4.6	3.4	3.3	3.4	3.7	4.9	5.0	6.8	7.0
	US24R-09-01	40	7.7	43.43	43.75	47.12	49.85	51.21	50.93	49.34	48.95	49.35	49.40
	US24R-09-02	40	7.6	45.86	48.65	50.88	50.62	54.45	53.93	54.83	54.23	53.87	53.76
	US24R-10-01	40	8.0	37.27	38.75	42.12	44.87	47.24	50.02	51.74	52.27	54.99	55.44
	Average	40	7.8	42.19	43.72	46.71	48.45	50.97	51.63	51.97	51.82	52.74	52.87
	STDV	40	0.2	4.4	5.0	4.4	3.1	3.6	2.0	2.8	2.7	3.0	3.1
SR161 (Mix 4)	CV, %	40	3.0	10.5	11.3	9.4	6.4	7.1	4.0	5.3	5.2	5.7	5.9
	SR161R-08-01	40	7.8	49.92	51.55	53.80	57.30	56.41	58.41	59.40	59.90	60.80	60.84
	SR161R-08-02	40	7.7	45.12	46.31	48.67	49.61	49.57	50.61	50.67	50.57	51.37	52.09
	SR161R-09-01	40	7.4	40.19	40.89	44.09	46.25	47.73	48.72	50.06	50.90	52.73	53.70
	SR161R-09-02	40	7.4	43.69	45.36	48.23	48.80	50.24	52.02	51.49	51.59	53.10	53.98
	Average	40	7.6	44.73	46.03	48.70	50.49	50.99	52.44	52.91	53.24	54.50	55.15
SR56 (Mix 5)	STDV	40	0.2	4.0	4.4	4.0	4.8	3.8	4.2	4.4	4.5	4.3	3.9
	CV, %	40	2.6	9.0	9.5	8.2	9.4	7.4	8.0	8.3	8.4	7.8	7.0
	SR56R-08-01	40	7.8	33.83	35.25	36.99	39.67	41.55	44.03	44.65	46.04	48.98	51.79
	SR56R-08-02	40	7.9	33.86	33.99	36.49	38.18	40.42	41.48	42.79	43.55	45.52	47.31
	SR56R-09-01	40	7.4	30.41	30.43	31.45	34.04	35.16	37.66	38.61	40.64	42.99	45.92
	Average	40	7.7	32.70	33.22	34.98	37.30	39.04	41.06	42.02	43.41	45.83	48.34
US30 (Mix 9)	STDV	40	0.3	2.0	2.5	3.1	2.9	3.4	3.2	3.1	2.7	3.0	3.1
	CV, %	40	3.7	6.1	7.5	8.8	7.8	8.7	7.8	7.4	6.2	6.6	6.3
	US30R-08-01	40	7.7	40.51	39.86	40.05	41.30	41.89	41.88	40.77	39.70	39.83	40.91
	US30R-08-02	40	8.6	45.29	45.38	44.92	46.09	45.58	45.24	44.34	43.67	43.22	45.52
	US30R-09-01	40	7.1	35.18	36.19	39.07	39.69	41.68	43.71	45.18	46.33	48.83	50.79
	Average	40	7.8	40.33	40.48	41.35	42.36	43.05	43.61	43.43	43.23	43.96	45.74
SR66 (Mix 11)	STDV	40	0.7	5.1	4.6	3.1	3.3	2.2	1.7	2.3	3.3	4.5	4.9
	CV, %	40	9.3	12.5	11.4	7.6	7.9	5.1	3.9	5.4	7.7	10.3	10.8
	SR66R-08-01	40	7.2	35.17	36.50	38.69	38.98	40.09	42.15	41.92	42.86	44.21	45.12
	SR66R-08-02	40	7.5	39.53	40.48	42.20	41.99	44.21	45.06	45.42	45.50	46.53	47.30
	SR66R-09-01	40	7.6	37.19	38.10	40.50	42.08	43.55	44.83	46.11	46.93	48.98	49.27
	SR66R-09-02	40	7.4	35.19	36.78	40.03	41.20	42.61	45.32	46.89	47.51	50.04	52.45
SR135 (Mix 12)	Average	40	7.5	36.77	37.97	40.36	41.06	42.62	44.34	45.09	45.70	47.44	48.54
	STDV	40	0.2	2.1	1.8	1.4	1.4	1.8	1.5	2.2	2.1	2.6	3.1
	CV, %	40	2.2	5.6	4.8	3.6	3.5	4.2	3.3	4.9	4.5	5.5	6.4
	SR135R-08-01	40	7.5	36.04	37.43	39.99	41.46	43.35	46.41	47.49	49.34	51.92	52.88
	SR135R-09-01	40	7.5	34.18	35.06	35.56	35.55	37.07	37.95	38.31	39.40	40.47	42.61
	SR135R-09-02	40	7.8	39.33	40.95	44.47	45.49	46.92	49.24	49.29	50.32	52.16	54.07
	Average	40	7.6	36.52	37.81	40.01	40.83	42.45	44.53	45.03	46.35	48.18	49.85
	STDV	40	0.2	2.6	3.0	4.5	5.0	5.0	5.9	5.9	6.0	6.7	6.3
	CV, %	40	2.3	7.1	7.8	11.1	12.2	11.7	13.2	13.1	13.0	13.9	12.6

Mix	Sample ID	Temp. °C	V _a %	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
US31 (Mix 8S)	US31R-07-01	40	8.5	48.36	47.99	47.36	47.10	46.82	46.36	45.86	46.18	46.66	48.01
	US31R-07-02	40	8.8	44.36	43.48	42.35	41.82	41.90	40.59	40.74	40.90	41.27	42.86
	US31R-08-02	40	8.0	49.88	48.82	48.33	47.54	46.78	46.63	45.82	46.08	46.06	49.23
	Average	40	8.4	47.53	46.76	46.01	45.49	45.17	44.53	44.14	44.39	44.66	46.70
	STDV	40	0.4	2.9	2.9	3.2	3.2	2.8	3.4	2.9	3.0	3.0	3.4
	CV, %	40	4.8	6.0	6.1	7.0	7.0	6.3	7.7	6.7	6.8	6.6	7.2
I74 (Mix 9S)	I74R-07-01	40	8.0	46.23	44.91	44.49	45.65	45.89	45.36	46.16	47.82	50.30	54.32
	I74R-07-02	40	8.2	47.11	45.54	45.67	45.41	45.87	46.60	46.06	47.88	51.31	51.88
	I74R-09-02	40	8.3	47.51	46.42	46.68	46.71	46.87	47.72	48.05	49.43	51.29	54.91
	Average	40	8.2	46.95	45.62	45.61	45.92	46.21	46.56	46.76	48.38	50.97	53.70
	STDV	40	0.2	0.7	0.8	1.1	0.7	0.6	1.2	1.1	0.9	0.6	1.6
	CV, %	40	1.9	1.4	1.7	2.4	1.5	1.2	2.5	2.4	1.9	1.1	3.0
SR64 (Mix 11S)	SR64R-07-01	40	7.2	38.75	38.98	39.96	41.02	42.79	44.65	44.68	46.59	48.76	51.17
	SR64R-07-02	40	7.9	38.28	38.24	38.73	39.00	40.34	41.78	42.31	43.85	46.49	49.25
	SR64R-07-03	40	7.5	39.53	39.29	40.25	40.91	42.16	43.25	43.97	44.65	46.45	49.17
	Average	40	7.5	38.85	38.84	39.65	40.31	41.76	43.23	43.65	45.03	47.23	49.86
	STDV	40	0.4	0.6	0.5	0.8	1.1	1.3	1.4	1.2	1.4	1.3	1.1
	CV, %	40	4.7	1.6	1.4	2.0	2.8	3.0	3.3	2.8	3.1	2.8	2.3
I65 (Mix 12S)	I65R-07-01	40	8.2	43.15	41.40	40.64	41.20	41.11	40.96	40.08	40.17	40.98	42.15
	I65R-08-01	40	6.2	37.53	36.00	36.24	36.28	35.79	36.15	35.32	35.42	36.12	37.72
	I65R-08-02	40	6.3	39.03	38.49	38.12	39.46	39.36	39.39	38.94	38.96	39.83	41.13
	Average	40	6.9	39.90	38.63	38.33	38.98	38.75	38.83	38.11	38.18	38.98	40.33
	STDV	40	1.1	2.9	2.7	2.2	2.5	2.7	2.5	2.5	2.5	2.5	2.3
	CV, %	40	16.3	7.3	7.0	5.8	6.4	7.0	6.3	6.5	6.5	6.5	5.8
SR15 (Mix 1)	SR15R-08-01	54.4	7.6	65.89	58.97	61.31	57.30	56.21	55.59	54.19	53.40	52.96	54.01
	SR15R-08-02	54.4	7.7	64.82	60.42	56.56	55.84	52.53	51.20	48.47	48.53	48.66	48.97
	SR15R-09-01	54.4	7.3	60.70	59.61	56.91	54.02	52.76	49.24	48.60	47.03	49.18	51.02
	SR15R-09-02	54.4	7.3	57.85	58.09	53.84	54.22	50.56	47.62	47.67	44.17	45.82	44.48
	Average	54.4	7.5	62.32	59.27	57.16	55.35	53.02	50.91	49.73	48.28	49.16	49.62
	STDV	54.4	0.2	3.7	1.0	3.1	1.5	2.3	3.4	3.0	3.9	2.9	4.0
US24 (Mix 2)	US24R-09-01	54.4	7.7	60.95	59.51	61.99	59.01	56.86	49.50	46.70	46.11	46.21	43.40
	US24R-09-02	54.4	7.6	63.47	60.78	59.24	56.84	51.07	46.91	44.59	45.13	44.07	43.75
	US24R-10-01	54.4	8.0	61.49	61.12	59.83	60.23	59.27	58.09	56.82	56.44	56.51	55.23
	Average	54.4	7.8	61.97	60.47	60.35	58.69	55.73	51.50	49.37	49.23	48.93	47.46
	STDV	54.4	0.2	1.3	0.8	1.4	1.7	4.2	5.9	6.5	6.3	6.7	6.7
	CV, %	54.4	3.0	2.1	1.4	2.4	2.9	7.6	11.4	13.2	12.7	13.6	14.2
SR161 (Mix 4)	SR161R-08-01	54.4	7.8	62.94	61.12	61.11	59.29	54.54	62.98	59.45	56.95	55.61	57.21
	SR161R-08-02	54.4	7.7	60.70	59.19	56.74	57.83	55.82	54.84	55.44	60.15	56.24	55.66
	SR161R-09-01	54.4	7.4	58.38	57.11	54.99	53.43	52.08	50.99	49.20	49.97	52.09	51.22
	SR161R-09-02	54.4	7.4	58.67	58.34	58.77	58.65	59.05	58.62	57.93	57.61	57.54	55.35
	Average	54.4	7.6	60.17	58.94	57.90	57.30	55.37	56.86	55.51	56.17	55.37	54.86
	STDV	54.4	0.2	2.1	1.7	2.6	2.6	2.9	5.1	4.5	4.4	2.3	2.6
SR161 (Mix 4)	CV, %	54.4	2.6	3.5	2.9	4.6	4.6	5.2	9.0	8.1	7.8	4.2	4.7

Mix	Sample ID	Temp. °C	V _a %	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR56 (Mix 5)	SR56R-08-01	54.4	7.8	53.07	50.95	50.14	50.80	48.29	47.00	45.84	45.10	45.62	47.18
	SR56R-08-02	54.4	7.9	55.95	54.55	54.54	55.47	53.95	54.04	53.46	54.42	52.48	53.44
	SR56R-09-01	54.4	7.4	51.29	48.81	46.90	46.24	45.10	42.71	41.85	41.98	42.08	42.69
	Average	54.4	7.7	53.44	51.44	50.53	50.84	49.11	47.92	47.05	47.17	46.73	47.77
	STDV	54.4	0.3	2.4	2.9	3.8	4.6	4.5	5.7	5.9	6.5	5.3	5.4
	CV, %	54.4	3.7	4.4	5.6	7.6	9.1	9.1	11.9	12.5	13.7	11.3	11.3
US30 (Mix 9)	US30R-08-01	54.4	7.7	55.11	51.32	48.84	47.42	44.58	43.74	42.28	42.01	42.74	44.48
	US30R-08-02	54.4	8.6	55.52	53.01	52.58	50.23	51.09	48.71	47.76	47.22	49.79	49.11
	US30R-09-01	54.4	7.1	56.38	52.65	51.26	52.04	48.79	48.44	47.74	48.72	48.96	50.54
	Average	54.4	7.8	55.67	52.33	50.89	49.90	48.15	46.96	45.93	45.98	47.16	48.04
	STDV	54.4	0.7	0.6	0.9	1.9	2.3	3.3	2.8	3.2	3.5	3.9	3.2
	CV, %	54.4	9.3	1.2	1.7	3.7	4.7	6.9	6.0	6.9	7.7	8.2	6.6
SR66 (Mix 11)	SR66R-08-01	54.4	7.2	55.42	52.80	53.96	51.74	49.88	51.24	50.22	46.05	44.81	46.06
	SR66R-08-02	54.4	7.5	56.04	52.15	56.28	55.64	55.50	51.04	48.84	42.72	38.59	35.68
	SR66R-09-01	54.4	7.6	55.96	54.41	53.72	51.68	49.78	48.40	45.42	42.71	40.92	38.99
	SR66R-09-02	54.4	7.4	51.33	50.61	50.20	51.86	51.44	51.61	53.00	52.39	53.05	55.22
	Average	54.4	7.5	54.69	52.49	53.54	52.73	51.65	50.57	49.37	45.97	44.34	43.99
	STDV	54.4	0.2	2.3	1.6	2.5	1.9	2.7	1.5	3.2	4.6	6.3	8.6
SR135 (Mix 12)	SR135R-08-01	54.4	7.5	51.86	51.38	52.04	52.61	52.92	51.26	49.78	50.26	49.58	50.05
	SR135R-09-01	54.4	7.5	54.48	49.36	53.40	51.49	47.60	44.07	43.94	42.76	41.51	41.17
	SR135R-09-02	54.4	7.8	57.05	55.50	54.10	55.49	55.30	53.90	52.55	52.99	51.47	56.12
	Average	54.4	7.6	54.46	52.08	53.18	53.20	51.94	49.74	48.76	48.67	47.52	49.11
	STDV	54.4	0.2	2.6	3.1	1.0	2.1	3.9	5.1	4.4	5.3	5.3	7.5
	CV, %	54.4	2.3	4.8	6.0	2.0	3.9	7.6	10.2	9.0	10.9	11.1	15.3
US31 (Mix 8S)	US31R-07-01	54.4	8.5	58.06	54.76	52.05	51.31	48.58	46.66	47.28	47.00	49.24	51.05
	US31R-07-02	54.4	8.8	57.86	54.65	50.60	49.94	45.69	47.98	50.25	49.07	51.81	51.84
	US31R-08-02	54.4	8.0	57.51	54.70	49.58	49.98	47.80	41.86	42.61	49.68	48.72	49.24
	Average	54.4	8.4	57.81	54.70	50.74	50.41	47.36	45.50	46.71	48.58	49.92	50.71
	STDV	54.4	0.4	0.3	0.1	1.2	0.8	1.5	3.2	3.9	1.4	1.7	1.3
	CV, %	54.4	4.8	0.5	0.1	2.4	1.5	3.2	7.1	8.2	2.9	3.3	2.6
I74 (Mix 9S)	I74R-07-01	54.4	8.0	58.59	56.41	54.39	51.46	50.86	51.33	51.55	50.46	51.33	53.98
	I74R-07-02	54.4	8.2	57.47	56.71	54.56	55.82	53.16	53.91	53.89	54.08	53.62	56.12
	I74R-09-02	54.4	8.3	59.50	55.94	55.14	55.75	54.42	50.01	51.68	49.95	51.46	53.19
	Average	54.4	8.2	58.52	56.35	54.70	54.34	52.81	51.75	52.37	51.50	52.14	54.43
	STDV	54.4	0.2	1.0	0.4	0.4	2.5	1.8	2.0	1.3	2.3	1.3	1.5
	CV, %	54.4	1.9	1.7	0.7	0.7	4.6	3.4	3.8	2.5	4.4	2.5	2.8
SR64 (Mix 11S)	SR64R-07-01	54.4	7.2	55.45	53.95	51.33	51.43	51.97	51.96	51.87	51.74	53.23	53.20
	SR64R-07-02	54.4	7.9	55.57	52.82	52.26	53.13	54.36	52.55	53.36	54.53	55.04	56.13
	SR64R-07-03	54.4	7.5	56.94	55.20	53.88	53.80	53.63	52.22	53.35	52.89	54.05	55.80
	Average	54.4	7.5	55.99	53.99	52.49	52.79	53.32	52.24	52.86	53.05	54.11	55.04
	STDV	54.4	0.4	0.8	1.2	1.3	1.2	1.2	0.3	0.9	1.4	0.9	1.6
	CV, %	54.4	4.7	1.5	2.2	2.5	2.3	2.3	0.6	1.6	2.6	1.7	2.9
I65 (Mix 12S)	I65R-07-01	54.4	8.2	51.07	46.52	45.41	44.77	43.20	41.40	41.04	40.75	41.43	43.62
	I65R-08-01	54.4	6.2	49.62	46.47	44.76	43.72	43.02	41.75	41.44	42.10	43.42	46.55
	I65R-08-02	54.4	6.3	52.91	50.28	47.51	45.84	44.70	44.63	43.96	43.81	46.31	46.78
	Average	54.4	6.9	51.20	47.76	45.89	44.78	43.64	42.59	42.15	42.22	43.72	45.65
	STDV	54.4	1.1	1.6	2.2	1.4	1.1	0.9	1.8	1.6	1.5	2.5	1.8
	CV, %	54.4	16.3	3.2	4.6	3.1	2.4	2.1	4.2	3.8	3.6	5.6	3.9

Road No.	Sample ID	Air Voids (%)	Temperature (°C)	Confining Pressure (kPa)	Max. Deviatoric Stress σ_d (kPa)	Max. Normal Stress σ_1 (kPa)	Strain at Failure (%)
SR15	SR15R-02	8.0	54.4	0	410.93	410.9	1.23
SR15	SR15R-04	7.8	54.4	138.265	1361.13	1499.4	2.94
SR15	SR15R-05	7.6	54.4	276.622	2046.602	2323.2	3.93
SR15	SR15R-06	7.8	54.4	415.07	2605.007	3020.1	5.62
US24	US24R-05	7.5	54.4	0	506.597	506.6	1.19
US24	US24R-02	7.6	54.4	138.247	1298.628	1436.9	2.83
US24	US24R-03	7.6	54.4	276.64	2064.46	2341.1	3.94
US24	US24R-06	7.9	54.4	415.033	2567.23	2982.3	5.01
SR161	SR161R-03	7.7	54.4	0	349.8	349.8	1.19
SR161	SR161R-01	7.5	54.4	138.302	1193.835	1332.1	3.65
SR161	SR161R-04	7.4	54.4	276.603	1823.868	2100.5	5.53
SR161	SR161R-05	7.6	54.4	415.051	2330.465	2745.5	7.20
SR56	SR56R-01	7.6	54.4	0	765.2	765.2	1.26
SR56	SR56R-04	7.4	54.4	138.247	1648.035	1786.3	3.67
SR56	SR56R-05	7.5	54.4	276.585	2225.868	2502.5	6.18
SR56	SR56R-06	7.3	54.4	415.015	2876.899	3291.9	6.61
US30	US30R-01	6.9	54.4	0	1023.497	1023.5	1.67
US30	US30R-02	7.0	54.4	138.265	1869.788	2008.1	2.91
US30	US30R-03	7.4	54.4	276.603	2419.362	2696.0	4.75
US30	US30R-05	7.0	54.4	415.051	2938.911	3354.0	5.31
SR66	SR66R-01	7.4	54.4	0	587.939	587.9	1.63
SR66	SR66R-02	7.5	54.4	138.247	1385.072	1523.3	4.00
SR66	SR66R-05	7.5	54.4	276.64	1822.494	2099.1	4.77
SR66	SR66R-06	7.5	54.4	415.051	2440.36	2855.4	9.58
SR135	SR135R-02	7.3	54.4	0	709.511	709.5	1.49
SR135	SR135R-04	7.3	54.4	138.265	1269.878	1408.1	2.04
SR135	SR135R-05	7.5	54.4	276.658	2037.084	2313.7	6.58
SR135	SR135R-06	7.5	54.4	414.997	2592.643	3007.6	8.10
US31	US31R-03	7.9	54.4	0	792.913	792.9	2.40
US31	US31R-04	7.6	54.4	138.283	1391.155	1529.4	3.97
US31	US31R-05	7.9	54.4	276.622	1852.225	2128.8	8.44
US31	US31R-06	7.7	54.4	415.015	2501.489	2916.5	10.42
I74	I74R-02	8.8	54.4	0	576.263	576.3	1.64
I74	I74R-03	7.6	54.4	138.265	1180.588	1318.9	5.04
I74	I74R-05	8.1	54.4	276.658	1662.95	1939.6	6.85
I74	I74R-06	7.9	54.4	415.015	2184.461	2599.5	15.71
SR64	SR64R-02	7.2	54.4	0	678.9	678.9	1.21
SR64	SR64R-03	7.4	54.4	138.247	1093.261	1231.5	8.16
SR64	SR64R-04	7.7	54.4	276.64	1712.795	1989.4	9.07
SR64	SR64R-05	7.7	54.4	414.997	2217.528	2632.5	14.21
I65	I65R-03	6.9	54.4	0	709.805	709.8	1.30
I65	I65R-01	7.1	54.4	138.265	1325.218	1463.5	5.83
I65	I65R-02	7.3	54.4	276.603	1874.4	2151.0	8.22
I65	I65R-05	7.0	54.4	414.96	2393.851	2808.8	11.97

Road No.	Sample ID	Diameter (mm)	Thickness (mm)	Air Voids (%)	Temp. (°C)	Loading Rate (mm/min)	Max. Compressive Force (kN)	Tensile Strength (kPa)	Strain at Failure (%)
SR15	SR15R-07-01	149.98	51.50	8.7	35	0.06	0.366	30.16	1.22
SR15	SR15R-07-02	150.17	50.81	9.3	35	0.06	0.33	27.53	1.55
SR15	SR15R-07-03	149.87	48.59	8.5	35	0.06	0.343	29.98	1.44
US24	US24R-07-01	150.00	52.30	8.8	35	0.06	0.698	56.64	1.09
US24	US24R-07-02	149.99	49.56	9.3	35	0.06	0.586	50.19	1.13
US24	US24R-07-03	150.01	48.91	7.9	35	0.06	0.649	56.31	1.13
US24	US24R-08-01	150.17	51.29	8.8	35	0.06	0.511	42.24	1.03
US24	US24R-08-02	149.97	50.87	8.8	35	0.06	0.512	42.73	1.30
US24	US24R-08-03	149.84	49.16	8.6	35	0.06	0.507	43.82	1.07
SR161	SR161R-07-01	150.10	50.22	8.5	35	0.06	0.325	27.45	1.18
SR161	SR161R-07-02	150.12	52.23	8.7	35	0.06	0.321	26.06	1.53
SR161	SR161R-07-03	150.21	49.31	8.0	35	0.06	0.31	26.65	1.18
SR56	SR56R-07-01	149.93	49.52	6.7	35	0.06	1.393	119.43	1.51
SR56	SR56R-07-02	150.12	52.01	9.3	35	0.06	1.262	102.90	1.89
SR56	SR56R-07-03	150.16	47.63	8.0	35	0.06	1.270	113.04	1.81
SR56	SR56R-09-02	150.11	52.20	8.1	35	0.06	1.298	105.46	2.20
US30	US30R-07-01	149.83	50.82	7.9	35	0.06	1.402	117.21	1.43
US30	US30R-07-02	149.81	52.71	8.9	35	0.06	1.408	113.52	1.68
US30	US30R-07-03	149.86	46.74	7.4	35	0.06	1.26	114.52	1.47
US30	US30R-09-02	149.90	51.41	7.4	35	0.06	0.996	82.28	2.83
SR66	SR66R-07-01	150.31	50.71	7.8	35	0.06	0.788	65.81	1.99
SR66	SR66R-07-02	150.18	49.87	8.5	35	0.06	0.812	69.02	1.88
SR66	SR66R-07-03	150.13	49.53	8.0	35	0.06	0.767	65.67	1.74
SR135	SR135R-07-01	149.83	49.58	8.5	35	0.06	0.893	76.54	1.86
SR135	SR135R-07-02	149.93	50.48	8.3	35	0.06	0.925	77.82	1.98
SR135	SR135R-07-03	149.98	49.54	8.8	35	0.06	0.784	67.18	1.82
SR135	SR135R-08-02	150.13	46.62	7.9	35	0.06	0.916	83.32	2.05
US31	US31R-07-03	150.23	51.69	7.7	35	0.06	1.436	117.72	2.16
US31	US31R-08-01	149.94	48.06	7.7	35	0.06	1.429	126.24	2.11
US31	US31R-09-01	150.20	48.76	7.3	35	0.06	1.470	127.79	2.94
US31	US31R-09-02	150.34	50.03	7.9	35	0.06	1.251	105.88	2.00
I74	I74R-07-03	150.48	52.04	7.6	35	0.06	0.913	74.22	2.16
I74	I74R-08-01	150.11	50.99	7.6	35	0.06	0.915	76.10	2.38
I74	I74R-08-02	150.54	49.54	7.8	35	0.06	1.13	96.47	2.73
I74	I74R-09-01	150.02	50.41	7.6	35	0.06			
SR64	SR64R-08-01	150.80	50.03	7.3	35	0.06	0.91	76.79	3.33
SR64	SR64R-08-02	150.21	51.06	7.7	35	0.06	0.965	80.11	2.17
SR64	SR64R-09-01	150.47	49.96	7.1	35	0.06	0.947	80.20	2.36
SR64	SR64R-09-02	150.35	49.98	7.3	35	0.06	1.015	86.00	1.94
I65	I65R-07-02	149.75	52.79	7.9	35	0.06	1.679	135.21	2.11
I65	I65R-07-03	149.94	49.03	7.4	35	0.06	1.341	116.12	3.07
I65	I65R-09-01	149.68	55.51	6.3	35	0.06	2.001	153.31	1.47
I65	I65R-09-02	149.76	49.09	7.2	35	0.06	1.292	111.89	2.01

Road No.	Test Method	Specimen ID	G _{mb}	V _a (%)	Average V _a (%)	Standard Deviation (%)	Coefficient of Variation (%)
SR15	Unconfined Dynamic Modulus	SR15-01t	2.309	7.2	7.4	0.3	3.4
		SR15-07	2.297	7.7			
		SR15-08	2.303	7.4			
	Confined Dynamic Modulus	SR15-05	2.309	7.2	7.4	0.2	2.8
		SR15-06	2.302	7.5			
		SR15-09	2.300	7.6			
	Shear Modulus	SR15-01-02	2.306	7.3	7.7	0.3	4.2
		SR15-02-02	2.294	7.8			
		SR15-03-02	2.291	7.9			
	Triaxial Strength	SR15-13	2.294	7.8	7.7	0.1	1.5
		SR15-14	2.300	7.6			
		SR15-15	2.298	7.6			
	Triaxial Strength	SR15-10	2.308	7.2	7.7	0.4	4.7
		SR15-11	2.300	7.6			
		SR15-12	2.288	8.0			
		SR15-13	2.292	7.9			
	IDT Strength	SR15-01-01	2.292	7.9	7.7	0.4	5.3
		SR15-02-01	2.309	7.2			
		SR15-03-01	2.291	7.9			
US24	Unconfined Dynamic Modulus	US24-01	2.233	7.6	7.8	0.2	2.0
		US24-02	2.229	7.8			
		US24-06	2.226	7.9			
	Confined Dynamic Modulus	US24-03	2.226	7.9	7.8	0.1	1.5
		US24-05	2.230	7.7			
		US24-07	2.231	7.7			
	Shear Modulus	US24-14-02	2.231	7.7	7.7	0.4	4.6
		US24-15-01	2.222	8.0			
		US24-16-01	2.241	7.3			
	Triaxial Strength	US24-23	2.244	7.2	7.4	0.2	2.2
		US24-24	2.238	7.4			
		US24-25	2.237	7.4			
		US24-26	2.234	7.6			
	Triaxial Strength	US24-08	2.229	7.8	7.9	0.2	2.8
		US24-09	2.220	8.2			
		US24-10	2.229	7.8			
		US24-11	2.231	7.7			
	IDT Strength	US24-14-01	2.237	7.4	7.7	0.3	4.0
		US24-17-01	2.223	8.0			
		US24-17-02	2.234	7.6			
	Unconfined Dynamic Modulus	SR161-01	2.264	7.9	7.6	0.2	3.0
		SR161-03	2.272	7.5			
		SR161-05	2.273	7.5			
	Confined Dynamic Modulus	SR161-02	2.262	7.9	7.7	0.2	2.7
		SR161-04	2.266	7.8			
		SR161-06	2.274	7.5			
	Shear Modulus	SR161-15-01	2.263	7.9	7.6	0.3	3.5
		SR161-16-01	2.274	7.4			

Road No.	Test Method	Specimen ID	G _{mb}	V _a (%)	Average V _a (%)	Standard Deviation (%)	Coefficient of Variation (%)
SR161	Triaxial Strength	SR161-17-02	2.273	7.5	7.7	0.2	2.3
		SR161-22	2.262	7.9			
		SR161-23	2.271	7.6			
		SR161-24	2.273	7.5			
		SR161-25	2.270	7.6			
	Triaxial Strength	SR161-07	2.265	7.8	7.9	0.2	2.8
		SR161-08	2.266	7.8			
		SR161-09	2.269	7.7			
		SR161-10	2.256	8.2			
	IDT Strength	SR161-14-02	2.265	7.8	7.7	0.2	2.0
		SR161-15-02	2.272	7.5			
		SR161-13-01	2.267	7.7			
SR56	Unconfined Dynamic Modulus	SR56-02	2.466	7.3	7.4	0.2	2.1
		SR56-03	2.461	7.4			
		SR56-07	2.458	7.6			
	Confined Dynamic Modulus	SR56-04	2.467	7.2	7.4	0.3	4.3
		SR56-04t	2.465	7.3			
		SR56-08	2.454	7.8			
	Shear Modulus	SR56-03-01	2.474	7.0	7.3	0.2	3.2
		SR56-04-01	2.463	7.4			
		SR56-05-02	2.462	7.4			
	Triaxial Strength	SR56-09	2.454	7.7	7.7	0.2	2.2
		SR56-10	2.457	7.6			
		SR56-11	2.448	7.9			
		SR56-12	2.459	7.5			
	Triaxial Strength	SR56-09	2.461	7.4	7.5	0.4	5.5
		SR56-10	2.474	7.0			
		SR56-11	2.460	7.5			
		SR56-12	2.447	8.0			
	IDT Strength	SR56-03-02	2.455	7.7	7.3	0.4	4.9
		SR56-04-02	2.473	7.0			
		SR56-05-01	2.467	7.2			
US30	Unconfined Dynamic Modulus	US30-03	2.277	7.3	7.4	0.1	0.8
		US30-05	2.273	7.4			
		US30-07	2.273	7.4			
	Confined Dynamic Modulus	US30-01t	2.280	7.1	7.3	0.2	2.7
		US30-02	2.271	7.5			
		US30-06	2.277	7.3			
	Shear Modulus	US30-01-01	2.273	7.4	7.5	0.1	1.3
		US30-02-01	2.271	7.5			
		US30-03-02	2.268	7.6			
	Triaxial Strength	US30-07	2.272	7.5	7.4	0.1	1.3
		US30-08	2.274	7.4			
		US30-09	2.277	7.3			
		US30-10	2.276	7.3			
	Triaxial Strength	US30-08	2.272	7.5	7.6	0.1	1.7
		US30-09	2.269	7.6			
		US30-10	2.266	7.7			

Road No.	Test Method	Specimen ID	G _{mb}	V _a (%)	Average V _a (%)	Standard Deviation (%)	Coefficient of Variation (%)
	IDT Strength	US30-11	2.274	7.4	7.5	0.2	2.7
		US30-01-02	2.276	7.3			
		US30-03-01	2.266	7.7			
		US30-02-02	2.270	7.5			
SR66	Unconfined Dynamic Modulus	SR66-01	2.282	7.2	7.5	0.4	4.8
		SR66-03	2.276	7.4			
		SR66-06	2.264	7.9			
	Confined Dynamic Modulus	SR66-02	2.274	7.4	7.5	0.2	2.3
		SR66-02t	2.276	7.4			
		SR66-08	2.267	7.7			
	Shear Modulus	SR66-11-02	2.268	7.7	7.9	0.2	1.9
		SR66-12-02	2.264	7.9			
		SR66-13-02	2.260	8.0			
	Triaxial Strength	SR66-17	2.277	7.3	7.4	0.3	3.4
		SR66-18	2.277	7.3			
		SR66-19	2.278	7.3			
		SR66-20	2.266	7.8			
	Triaxial Strength	SR66-04	2.273	7.5	7.4	0.1	2.0
		SR66-05	2.273	7.5			
		SR66-07	2.277	7.3			
		SR66-09	2.279	7.2			
	IDT Strength	SR66-11-01	2.275	7.4	7.6	0.2	2.0
		SR66-12-01	2.268	7.7			
		SR66-13-01	2.271	7.6			
SR135	Unconfined Dynamic Modulus	SR135-01	2.260	7.0	7.2	0.2	2.8
		SR135-04	2.251	7.4			
		SR135-07	2.255	7.2			
	Confined Dynamic Modulus	SR135-03	2.253	7.3	7.2	0.2	2.9
		SR135-06	2.252	7.4			
		SR135-08	2.260	7.0			
	Shear Modulus	SR135-16-01	2.255	7.2	7.4	0.3	3.4
		SR135-17-02	2.243	7.7			
		SR135-19-02	2.252	7.4			
	Triaxial Strength	SR135-25	2.247	7.6	7.6	0.1	1.7
		SR135-26	2.244	7.7			
		SR135-27	2.250	7.4			
		SR135-28	2.247	7.6			
	Triaxial Strength	SR135-09	2.259	7.1	7.5	0.3	3.9
		SR135-10	2.248	7.5			
		SR135-11	2.250	7.4			
		SR135-12	2.241	7.8			
	IDT Strength	SR135-15-02	2.255	7.2	7.5	0.3	3.5
		SR135-19-01	2.245	7.7			
		SR135-18-01	2.246	7.6			
	Unconfined Dynamic Modulus	US31-01	2.762	7.3	7.0	0.3	3.6
		US31-03	2.777	6.8			
		US31-05	2.771	7.0			
	Confined	US31-02	2.756	7.5			

Road No.	Test Method	Specimen ID	G _{mb}	V _a (%)	Average V _a (%)	Standard Deviation (%)	Coefficient of Variation (%)
US31	Dynamic Modulus	US31-07	2.77	7.0	7.2	0.3	4.0
		US31-09	2.772	7.0			
	Shear Modulus	US31-15-01	2.777	6.8	7.3	0.7	9.6
		US31-17-01	2.772	7.0			
		US31-17-02	2.739	8.1			
	Triaxial Strength	US31-21	2.77	7.0	7.0	0.0	0.0
		US31-22	2.77	7.0			
		US31-23	2.771	7.0			
		US31-24	2.771	7.0			
	Triaxial Strength	US31-04	2.755	7.6	7.4	0.2	2.8
		US31-06	2.760	7.4			
		US31-10	2.761	7.3			
		US31-12	2.767	7.1			
	IDT Strength	US31-15-02	2.756	7.5	7.4	0.1	0.8
		US31-16-01	2.758	7.4			
		US31-16-02	2.759	7.4			
I74	Unconfined Dynamic Modulus	I74-01	2.928	7.2	7.3	0.2	2.4
		I74-02	2.918	7.5			
		I74-09	2.928	7.2			
	Confined Dynamic Modulus	I74-04	2.918	7.5	7.3	0.3	3.6
		I74-06	2.920	7.4			
		I74-07	2.933	7.0			
	Shear Modulus	I74-12-01	2.929	7.1	7.0	0.1	1.6
		I74-12-02	2.931	7.1			
		I74-13-02	2.936	6.9			
	Triaxial Strength	I74-21	2.915	7.6	7.4	0.2	3.0
		I74-22	2.918	7.5			
		I74-23	2.931	7.1			
		I74-24	2.924	7.3			
	Triaxial Strength	I74-14	2.935	6.9	7.4	0.6	7.5
		I74-16	2.933	7.0			
		I74-17	2.901	8.0			
		I74-20	2.907	7.8			
	IDT Strength	I74-11-01	2.914	7.6	7.1	0.4	6.1
		I74-13-01	2.939	6.8			
		I74-11-02	2.936	6.9			
SR64	Unconfined Dynamic Modulus	SR64-01	2.746	7.4	7.4	0.2	2.7
		SR64-02	2.740	7.6			
		SR64-03	2.752	7.2			
	Confined Dynamic Modulus	SR64-10	2.752	7.2	7.4	0.3	3.6
		SR64-17	2.748	7.3			
		SR64-18	2.737	7.7			
	Shear Modulus	SR64-13-01	2.763	6.8	7.3	0.6	8.6
		SR64-13-02	2.728	8.0			
		SR64-15-01	2.755	7.1			
	Triaxial Strength	SR64-23	2.736	7.8	7.5	0.4	4.8
		SR64-24	2.740	7.6			
		SR64-25	2.758	7.0			

Road No.	Test Method	Specimen ID	G _{mb}	V _a (%)	Average V _a (%)	Standard Deviation (%)	Coefficient of Variation (%)
	Triaxial Strength	SR64-26	2.737	7.7	7.0	0.1	1.4
		SR64-16	2.755	7.1			
		SR64-17	2.759	7.0			
		SR64-18	2.756	7.1			
		SR64-22	2.761	6.9			
	IDT Strength	SR64-14-01	2.746	7.4	7.4	0.1	0.8
		SR64-14-02	2.750	7.3			
		SR64-15-02	2.746	7.4			
I65	Unconfined Dynamic Modulus	I65-01	2.784	7.7	7.6	0.1	0.8
		I65-03	2.787	7.6			
		I65-04	2.789	7.6			
	Confined Dynamic Modulus	I65-02	2.776	8.0	7.8	0.3	4.1
		I65-05	2.794	7.4			
		I65-06	2.777	7.9			
	Shear Modulus	I65-15-01	2.802	7.1	7.4	0.2	3.1
		I65-16-02	2.792	7.5			
		I65-17-01	2.790	7.5			
	Triaxial Strength	I65-15	2.779	7.9	7.7	0.2	2.2
		I65-16	2.783	7.8			
		I65-17	2.792	7.5			
		I65-18	2.786	7.7			
	Triaxial Strength	I65-07	2.781	7.8	7.7	0.0	0.6
		I65-08	2.784	7.7			
		I65-09	2.786	7.7			
		I65-10	2.784	7.7			
	IDT Strength	I65-15-02	2.804	7.1	7.4	0.3	4.1
		I65-17-02	2.786	7.7			
		I65-16-01	2.797	7.3			

Mix	Sample ID	Temp. °C	V _a %	Unconfined Dynamic (Complex) Modulus E* (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
SR15 (Mix 1)	SR15-01t	40	7.2	1594.0	1097.0	832.0	482.0	398.0	290.0	37.13	37.15	36.41	31.57	29.17	24.34
	SR15-07	40	7.7	1415.0	985.0	750.0	445.0	373.0	367.0	38.43	37.61	36.20	30.36	28.02	21.79
	SR15-08	40	7.4	1588.0	1099.0	830.0	486.0	415.0	330.0	37.11	37.03	36.02	31.33	28.78	24.27
	Average	40	7.4	1532.3	1060.3	804.0	471.0	395.3	329.0	37.56	37.26	36.21	31.09	28.66	23.47
	STDV	40	0.3	101.7	65.2	46.8	22.6	21.1	38.5	0.76	0.31	0.20	0.64	0.58	1.45
	CV, %	40	3.4	6.6	6.2	5.8	4.8	5.3	11.7	2.0	0.8	0.5	2.1	2.0	6.2
US24 (Mix 2)	US24-01	40	7.6	1848.0	1338.0	1076.0	691.0	581.0	437.0	31.58	31.35	30.09	25.56	23.47	20.02
	US24-02	40	7.8	2567.0	1867.0	1462.0	890.0	744.0	550.0	30.86	31.67	31.21	27.51	25.27	20.98
	US24-06	40	7.9	1681.0	1227.0	948.0	549.0	460.0	333.0	32.68	33.62	33.00	29.01	26.51	22.46
	Average	40	7.8	2032.0	1477.3	1162.0	710.0	595.0	440.0	31.71	32.21	31.43	27.36	25.08	21.15
	STDV	40	0.2	470.8	342.0	267.6	171.3	142.5	108.5	0.92	1.23	1.47	1.73	1.53	1.23
	CV, %	40	2.0	23.2	23.1	23.0	24.1	24.0	24.7	2.9	3.8	4.7	6.3	6.1	5.8
SR161 (Mix 4)	SR161-01	40	7.9	3388.0	2434.0	1856.0	1062.0	879.0	563.0	30.80	32.54	33.19	31.79	30.04	28.25
	SR161-03	40	7.5	2093.0	1453.0	1094.0	628.0	495.0	326.0	33.47	34.92	35.17	33.01	31.39	26.48
	SR161-05	40	7.5	2053.0	1403.0	1054.0	589.0	485.0	318.0	36.96	37.86	37.77	35.03	32.82	27.81
	Average	40	7.6	2511.3	1763.3	1334.7	759.7	619.7	402.3	33.74	35.11	35.38	33.28	31.42	27.51
	STDV	40	0.2	759.5	581.4	451.9	262.6	224.6	139.2	3.09	2.66	2.30	1.64	1.39	0.92
	CV, %	40	3.0	30.2	33.0	33.9	34.6	36.3	34.6	9.2	7.6	6.5	4.9	4.4	3.3
SR56 (Mix 5)	SR56-02	40	7.3	3033.0	2294.0	1861.0	1155.0	968.0	687.0	30.13	31.45	31.59	29.80	28.22	24.46
	SR56-03	40	7.4	3598.0	2706.0	2118.0	1286.0	1060.0	753.0	29.09	30.52	30.57	28.84	27.51	23.55
	SR56-07	40	7.6	3606.0	2713.0	2184.0	1388.0	1163.0	844.0	27.39	29.37	29.95	28.42	26.73	22.53
	Average	40	7.4	3412.3	2571.0	2054.3	1276.3	1063.7	761.3	28.87	30.45	30.70	29.02	27.49	23.51
	STDV	40	0.2	328.5	239.9	170.7	116.8	97.6	78.8	1.38	1.04	0.83	0.71	0.75	0.97
	CV, %	40	2.1	9.6	9.3	8.3	9.2	9.2	10.4	4.8	3.4	2.7	2.4	2.7	4.1
US30 (Mix 9)	US30-03	40	7.3	2502.0	1872.0	1503.0	962.0	831.0	637.0	30.91	31.48	30.54	27.91	26.06	22.83
	US30-05	40	7.4	3309.0	2540.0	2001.0	1223.0	1018.0	729.0	28.14	29.15	29.04	27.87	26.63	23.84
	US30-07	40	7.4	2780.0	2144.0	1753.0	1206.0	1064.0	858.0	28.75	28.59	27.17	22.98	21.08	17.78
	Average	40	7.4	2863.7	2185.3	1752.3	1130.3	971.0	741.3	29.27	29.74	28.92	26.25	24.59	21.48
	STDV	40	0.1	410.0	335.9	249.0	146.0	123.4	111.0	1.46	1.53	1.69	2.83	3.05	3.25
	CV, %	40	0.8	14.3	15.4	14.2	12.9	12.7	15.0	5.0	5.2	5.8	10.8	12.4	15.1

Mix	Sample ID	Temp. °C	V _a %	Unconfined Dynamic (Complex) Modulus E* (MPa)						Phase Angle φ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
SR66 (Mix 11)	SR66-01	40	7.2	3290.0	2435.0	1916.0	1125.0	907.0	580.0	30.19	30.79	31.36	31.36	30.49	27.91
	SR66-03	40	7.4	3139.0	2381.0	1921.0	1147.0	935.0	620.0	30.02	31.03	31.90	31.42	30.35	27.21
	SR66-06	40	7.9	4083.0	3048.0	2372.0	1380.0	1127.0	794.0	30.29	31.13	31.86	31.86	30.74	27.33
	Average	40	7.5	3504.0	2621.3	2069.7	1217.3	989.7	664.7	30.17	30.98	31.71	31.55	30.53	27.48
	STDV	40	0.4	507.1	370.5	261.8	141.3	119.8	113.8	0.14	0.17	0.30	0.27	0.20	0.37
	CV, %	40	4.8	14.5	14.1	12.7	11.6	12.1	17.1	0.5	0.6	0.9	0.9	0.6	1.4
SR135 (Mix 12)	SR135-01	40	7.0	3767.0	2808.0	2292.0	1418.0	1156.0	813.0	28.79	29.94	29.80	27.80	26.50	22.73
	SR135-04	40	7.4	2693.0	2012.0	1651.0	1029.0	840.0	617.0	28.49	29.96	30.14	28.43	26.85	23.06
	SR135-07	40	7.2	2691.0	1967.0	1562.0	980.0	814.0	556.0	29.43	31.24	31.68	30.17	28.86	25.95
	Average	40	7.2	3050.3	2262.3	1835.0	1142.3	936.7	662.0	28.90	30.38	30.54	28.80	27.40	23.91
	STDV	40	0.2	620.7	473.1	398.3	240.0	190.4	134.3	0.48	0.74	1.00	1.23	1.27	1.77
	CV, %	40	2.8	20.3	20.9	21.7	21.0	20.3	20.3	1.7	2.5	3.3	4.3	4.6	7.4
US31 (Mix 8S)	US31-01	40	7.3	2109.0	1561.0	1247.0	834.0	716.0	535.0	31.68	30.25	29.40	27.05	25.90	23.75
	US31-03	40	6.8	1933.0	1448.0	1141.0	742.0	638.0	505.0	32.70	31.37	30.03	26.81	25.45	22.89
	US31-05	40	7.0	2270.0	1708.0	1401.0	905.0	792.0	610.0	32.13	31.32	30.25	27.83	26.65	24.51
	Average	40	7.0	2104.0	1572.3	1263.0	827.0	715.3	550.0	32.17	30.98	29.89	27.23	26.00	23.72
	STDV	40	0.3	168.6	130.4	130.7	81.7	77.0	54.1	0.51	0.63	0.44	0.53	0.61	0.81
	CV, %	40	3.6	8.0	8.3	10.4	9.9	10.8	9.8	1.6	2.0	1.5	2.0	2.3	3.4
I74 (Mix 9S)	I74-01	40	7.4	3217.0	2383.0	1898.0	1221.0	1039.0	750.0	28.16	29.34	29.23	28.93	28.37	26.65
	I74-02	40	7.6	3641.0	2713.0	2242.0	1420.0	1160.0	814.0	27.54	28.70	28.99	28.17	27.42	25.16
	I74-09	40	7.2	4274.0	3199.0	2545.0	1572.0	1277.0	902.0	27.10	28.51	29.29	29.68	28.93	26.82
	Average	40	7.4	3710.7	2765.0	2228.3	1404.3	1158.7	822.0	27.60	28.85	29.17	28.93	28.24	26.21
	STDV	40	0.2	531.9	410.5	323.7	176.0	119.0	76.3	0.53	0.43	0.16	0.76	0.76	0.91
	CV, %	40	2.7	14.3	14.8	14.5	12.5	10.3	9.3	1.9	1.5	0.5	2.6	2.7	3.5
SR64 (Mix 11S)	SR64-01	40	7.7	3357.0	2561.0	2078.0	1323.0	1096.0	766.0	28.46	29.92	30.20	29.81	29.09	27.05
	SR64-02	40	7.6	5285.0	4052.0	3360.0	2020.0	1666.0	1088.0	26.10	27.87	28.79	31.83	32.38	32.29
	SR64-03	40	7.6	3683.0	2846.0	2230.0	1361.0	1124.0	747.0	29.44	30.31	30.12	29.75	29.11	27.62
	Average	40	7.6	4108.3	3153.0	2556.0	1568.0	1295.3	867.0	28.00	29.37	29.70	30.46	30.19	28.99
	STDV	40	0.1	1032.0	791.5	700.4	391.9	321.3	191.6	1.72	1.31	0.79	1.18	1.89	2.87
	CV, %	40	0.8	25.1	25.1	27.4	25.0	24.8	22.1	6.1	4.5	2.7	3.9	6.3	9.9

Mix	Sample ID	Temp. °C	V _a %	Unconfined Dynamic (Complex) Modulus E* (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
I65 (Mix 12S)	I65-01	40	7.7	3634.0	2743.0	2167.0	1334.0	1116.0	789.0	29.70	30.12	30.50	30.25	29.96	27.70
	I65-03	40	7.6	3215.0	2387.0	1927.0	1189.0	990.0	704.0	29.83	30.62	30.61	29.04	27.96	24.79
	I65-04	40	7.6	3336.0	2359.0	1888.0	1152.0	955.0	688.0	32.04	32.44	31.60	29.96	28.89	26.34
	Average	40	7.6	3395.0	2496.3	1994.0	1225.0	1020.3	727.0	30.52	31.06	30.90	29.75	28.94	26.28
	STDV	40	0.1	215.6	214.1	151.1	96.2	84.7	54.3	1.32	1.22	0.61	0.63	1.00	1.46
	CV, %	40	0.8	6.4	8.6	7.6	7.9	8.3	7.5	4.3	3.9	2.0	2.1	3.5	5.5
SR15 (Mix 1)	SR15-01t	54.4	7.2	594.0	458.0	381.0	290.0	276.0	247.0	32.31	29.65	27.56	22.11	20.15	17.10
	SR15-07	54.4	7.7	647.0	515.0	445.0	357.0	336.0	319.0	31.05	27.43	24.70	19.73	18.57	15.66
	SR15-08	54.4	7.4	538.0	425.0	373.0	313.0	283.0	262.0	32.79	29.68	26.53	22.67	21.70	21.92
	Average	54.4	7.4	593.0	466.0	399.7	320.0	298.3	276.0	32.05	28.92	26.26	21.50	20.14	18.23
	STDV	54.4	0.3	54.5	45.5	39.5	34.0	32.8	38.0	0.90	1.29	1.45	1.56	1.57	3.28
	CV, %	54.4	3.4	9.2	9.8	9.9	10.6	11.0	13.8	2.8	4.5	5.5	7.3	7.8	18.0
US24 (Mix 2)	US24-01	54.4	7.6	431.0	331.0	276.0	215.0	200.0	173.0	31.32	28.50	25.57	19.67	18.24	16.41
	US24-02	54.4	7.8	708.0	555.0	464.0	358.0	330.0	281.0	28.55	26.22	23.66	18.92	17.80	16.85
	US24-06	54.4	7.9	438.0	328.0	259.0	195.0	181.0	156.0	34.99	33.07	30.68	24.12	22.11	19.73
	Average	54.4	7.8	525.7	404.7	333.0	256.0	237.0	203.3	31.62	29.26	26.64	20.90	19.38	17.66
	STDV	54.4	0.2	157.9	130.2	113.8	88.9	81.1	67.8	3.23	3.49	3.63	2.81	2.37	1.80
	CV, %	54.4	2.0	30.0	32.2	34.2	34.7	34.2	33.3	10.2	11.9	13.6	13.4	12.2	10.2
SR161 (Mix 4)	SR161-01	54.4	7.9	993.0	754.0	616.0	450.0	412.0	366.0	33.14	30.25	27.69	22.61	21.10	17.96
	SR161-03	54.4	7.5	596.0	431.0	346.0	244.0	221.0	176.0	36.42	34.11	31.54	25.61	23.98	21.21
	SR161-05	54.4	7.5	537.0	393.0	315.0	227.0	211.0	177.0	37.61	34.40	32.14	25.81	23.82	20.74
	Average	54.4	7.6	708.7	526.0	425.7	307.0	281.3	239.7	35.72	32.92	30.46	24.68	22.97	19.97
	STDV	54.4	0.2	248.0	198.4	165.6	124.1	113.3	109.4	2.32	2.32	2.41	1.79	1.62	1.76
	CV, %	54.4	3.0	35.0	37.7	38.9	40.4	40.3	45.7	6.5	7.0	7.9	7.3	7.0	8.8
SR56 (Mix 5)	SR56-02	54.4	7.3	964.0	762.0	643.0	505.0	457.0	413.0	30.95	29.07	26.34	23.25	22.52	21.90
	SR56-03	54.4	7.4	935.0	731.0	617.0	473.0	437.0	378.0	31.64	29.76	27.31	23.34	22.00	20.27
	SR56-07	54.4	7.6	1042.0	819.0	688.0	505.0	451.0	365.0	31.31	29.80	27.68	25.27	24.54	24.46
	Average	54.4	7.4	980.3	770.7	649.3	494.3	448.3	385.3	31.30	29.54	27.11	23.95	23.02	22.21
	STDV	54.4	0.2	55.3	44.6	35.9	18.5	10.3	24.8	0.35	0.41	0.69	1.14	1.34	2.11
	CV, %	54.4	2.1	5.6	5.8	5.5	3.7	2.3	6.4	1.1	1.4	2.6	4.8	5.8	9.5

Mix	Sample ID	Temp. °C	V _a %	Unconfined Dynamic (Complex) Modulus E* (MPa)						Phase Angle φ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
US30 (Mix 9)	US30-03	54.4	7.3	614.0	492.0	423.0	325.0	295.0	246.0	29.45	27.27	24.93	22.08	21.27	20.07
	US30-05	54.4	7.4	972.0	780.0	658.0	485.0	444.0	370.0	29.47	27.47	25.80	22.75	21.60	19.73
	US30-07	54.4	7.4	1085.0	885.0	789.0	605.0	566.0	488.0	29.00	26.70	24.33	21.01	19.89	18.25
	Average	54.4	7.4	890.3	719.0	623.3	471.7	435.0	368.0	29.31	27.15	25.02	21.95	20.92	19.35
	STDV	54.4	0.1	245.9	203.5	185.4	140.5	135.7	121.0	0.27	0.40	0.74	0.88	0.91	0.97
	CV, %	54.4	0.8	27.6	28.3	29.8	29.8	31.2	32.9	0.9	1.5	3.0	4.0	4.3	5.0
SR66 (Mix 11)	SR66-01	54.4	7.2	917.0	700.0	565.0	395.0	349.0	284.0	32.29	30.87	29.08	24.45	22.99	20.16
	SR66-03	54.4	7.4	903.0	666.0	548.0	380.0	343.0	287.0	32.99	31.61	29.61	24.48	22.41	18.44
	SR66-06	54.4	7.9	1172.0	879.0	729.0	538.0	495.0	437.0	32.05	30.22	27.96	22.86	20.82	17.70
	Average	54.4	7.5	997.3	748.3	614.0	437.7	395.7	336.0	32.44	30.90	28.88	23.93	22.07	18.77
	STDV	54.4	0.4	151.4	114.4	100.0	87.2	86.1	87.5	0.49	0.70	0.84	0.93	1.12	1.26
	CV, %	54.4	4.8	15.2	15.3	16.3	19.9	21.8	26.0	1.5	2.3	2.9	3.9	5.1	6.7
SR135 (Mix 12)	SR135-01	54.4	7.0	1852.0	1444.0	1229.0	935.0	847.0	729.0	27.55	25.64	23.42	18.81	17.61	15.56
	SR135-04	54.4	7.4	946.0	726.0	616.0	469.0	429.0	365.0	28.74	26.49	24.30	19.81	18.46	16.31
	SR135-07	54.4	7.2	962.0	724.0	630.0	463.0	420.0	351.0	30.38	28.71	26.53	22.57	21.32	19.22
	Average	54.4	7.2	1253.3	964.7	825.0	622.3	565.3	481.7	28.89	26.95	24.75	20.40	19.13	17.03
	STDV	54.4	0.2	518.5	415.1	349.9	270.8	244.0	214.3	1.42	1.59	1.60	1.95	1.94	1.93
	CV, %	54.4	2.8	41.4	43.0	42.4	43.5	43.2	44.5	4.9	5.9	6.5	9.5	10.2	11.4
US31 (Mix 8S)	US31-01	54.4	7.3	743.0	610.0	540.0	431.0	402.0	353.0	27.15	24.33	22.72	20.33	19.67	18.55
	US31-03	54.4	6.8	788.0	643.0	557.0	437.0	401.0	337.0	27.97	24.88	23.31	20.43	19.66	18.91
	US31-05	54.4	7.0	835.0	700.0	619.0	473.0	434.0	370.0	28.15	25.68	23.90	21.46	20.74	19.16
	Average	54.4	7.0	788.7	651.0	572.0	447.0	412.3	353.3	27.76	24.96	23.31	20.74	20.02	18.87
	STDV	54.4	0.3	46.0	45.5	41.6	22.7	18.8	16.5	0.53	0.68	0.59	0.63	0.62	0.31
	CV, %	54.4	3.6	5.8	7.0	7.3	5.1	4.6	4.7	1.9	2.7	2.5	3.0	3.1	1.6
I74 (Mix 9S)	I74-01	54.4	7.4	1300.0	994.0	814.0	575.0	505.0	410.0	28.07	27.32	26.20	23.93	22.93	21.18
	I74-02	54.4	7.6	1350.0	1033.0	868.0	621.0	551.0	445.0	28.80	27.29	25.72	22.40	21.16	19.11
	I74-09	54.4	7.2	1617.0	1179.0	998.0	679.0	607.0	532.0	32.33	30.75	29.16	27.11	25.92	21.92
	Average	54.4	7.4	1422.3	1068.7	893.3	625.0	554.3	462.3	29.73	28.45	27.03	24.48	23.34	20.74
	STDV	54.4	0.2	170.4	97.5	94.6	52.1	51.1	62.8	2.28	1.99	1.86	2.40	2.41	1.46
	CV, %	54.4	2.7	12.0	9.1	10.6	8.3	9.2	13.6	7.7	7.0	6.9	9.8	10.3	7.0

Mix	Sample ID	Temp. °C	V _a %	Unconfined Dynamic (Complex) Modulus E* (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
SR64 (Mix 11S)	SR64-01	54.4	7.7	1259.0	958.0	806.0	561.0	487.0	393.0	30.65	29.45	28.23	24.97	23.75	21.76
	SR64-02	54.4	7.6	1687.0	1255.0	1048.0	730.0	654.0	523.0	29.54	28.53	27.33	25.67	24.87	24.04
	SR64-03	54.4	7.6	1295.0	1008.0	839.0	606.0	541.0	448.0	30.13	28.05	26.62	23.74	23.00	22.06
	Average	54.4	7.6	1413.7	1073.7	897.7	632.3	560.7	454.7	30.11	28.68	27.39	24.79	23.87	22.62
	STDV	54.4	0.1	237.4	159.0	131.2	87.5	85.2	65.3	0.56	0.71	0.81	0.98	0.94	1.24
	CV, %	54.4	0.8	16.8	14.8	14.6	13.8	15.2	14.4	1.8	2.5	2.9	3.9	3.9	5.5
I65 (Mix 12S)	I65-01	54.4	7.7	1129.0	874.0	722.0	504.0	450.0	382.0	31.81	29.87	29.65	28.41	27.62	24.76
	I65-03	54.4	7.6	1154.0	902.0	758.0	522.0	463.0	381.0	30.57	29.19	27.66	24.87	23.77	21.10
	I65-04	54.4	7.6	1157.0	907.0	759.0	535.0	478.0	400.0	32.22	29.17	27.75	25.74	24.90	22.92
	Average	54.4	7.6	1146.7	894.3	746.3	520.3	463.7	387.7	31.53	29.41	28.35	26.34	25.43	22.93
	STDV	54.4	0.1	15.4	17.8	21.1	15.6	14.0	10.7	0.86	0.40	1.12	1.84	1.98	1.83
	CV, %	54.4	0.8	1.3	2.0	2.8	3.0	3.0	2.8	2.7	1.4	4.0	7.0	7.8	8.0

Mix	Sample ID	Temp. °C	V _a %	Confined Dynamic (Complex) Modulus E* (MPa)						Phase Angle φ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
SR15 (Mix 1)	SR15-05	40	7.2	3185.0	2610.0	2097.0	1350.0	1157.0	889.0	31.01	32.21	31.46	27.79	26.04	21.72
	SR15-06	40	7.5	2308.0	1741.0	1394.0	921.0	814.0	670.0	32.70	32.00	30.22	25.94	23.94	19.73
	SR15-09	40	7.6	2465.0	1884.0	1548.0	1058.0	938.0	780.0	32.16	32.03	30.50	25.49	23.54	19.43
	Average	40	7.4	2652.7	2078.3	1679.7	1109.7	969.7	779.7	31.96	32.08	30.73	26.41	24.51	20.29
	STDV	40	0.2	467.6	466.0	369.5	219.1	173.7	109.5	0.9	0.1	0.7	1.2	1.3	1.2
	CV, %	40	2.8	17.6	22.4	22.0	19.7	17.9	14.0	2.7	0.4	2.1	4.6	5.5	6.1
US24 (Mix 2)	US24-03	40	7.9	2320.0	1763.0	1489.0	1044.0	919.0	735.0	28.04	28.42	27.62	24.68	22.88	19.40
	US24-05	40	7.7	3503.0	2693.0	2192.0	1489.0	1295.0	1018.0	29.47	29.96	29.30	26.55	25.00	21.98
	US24-07	40	7.7	2150.0	1632.0	1331.0	923.0	816.0	650.0	27.05	27.38	26.69	23.71	22.00	18.54
	Average	40	7.8	2657.7	2029.3	1670.7	1152.0	1010.0	801.0	28.19	28.59	27.87	24.98	23.29	19.97
	STDV	40	0.1	737.0	578.5	458.3	298.1	252.1	192.7	1.2	1.3	1.3	1.4	1.5	1.8
	CV, %	40	1.5	27.7	28.5	27.4	25.9	25.0	24.1	4.3	4.5	4.7	5.8	6.6	9.0
SR161 (Mix 4)	SR161-02	40	7.9	3522.0	2695.0	2244.0	1529.0	1352.0	1105.0	29.91	29.43	28.41	24.88	23.19	19.83
	SR161-04	40	7.8	2837.0	2094.0	1672.0	1069.0	893.0	658.0	29.29	30.19	30.39	28.56	26.97	23.16
	SR161-06	40	7.5	4039.0	3242.0	2586.0	1619.0	1412.0	1124.0	26.90	27.55	27.12	25.87	24.38	21.10
	Average	40	7.7	3466.0	2677.0	2167.3	1405.7	1219.0	962.3	28.70	29.06	28.64	26.44	24.85	21.36
	STDV	40	0.2	603.0	574.2	461.8	295.0	283.9	263.7	1.6	1.4	1.6	1.9	1.9	1.7
	CV, %	40	2.7	17.4	21.4	21.3	21.0	23.3	27.4	5.5	4.7	5.8	7.2	7.8	7.9
SR56 (Mix 5)	SR56-04	40	7.2	3944.0	3040.0	2486.0	1587.0	1376.0	1047.0	28.52	28.53	28.40	28.28	26.92	23.57
	SR56-04t	40	7.3	2944.0	2277.0	1861.0	1220.0	1042.0	797.0	28.31	29.93	29.69	28.75	27.61	24.56
	SR56-08	40	7.8	4319.0	3264.0	2701.0	1798.0	1559.0	1203.0	24.59	27.21	27.22	26.37	25.29	22.81
	Average	40	7.4	3735.7	2860.3	2349.3	1535.0	1325.7	1015.7	27.14	28.56	28.44	27.80	26.61	23.65
	STDV	40	0.3	710.8	517.4	436.4	292.5	262.1	204.8	2.2	1.4	1.2	1.3	1.2	0.9
	CV, %	40	4.3	19.0	18.1	18.6	19.1	19.8	20.2	8.1	4.8	4.3	4.5	4.5	3.7
US30 (Mix 9)	US30-01t	40	7.1	2155.0	1660.0	1258.9	960.0	856.0	704.0	28.74	28.49	27.62	25.56	24.31	21.53
	US30-02	40	7.5	2716.0	2108.0	1750.0	1217.0	1076.0	875.0	30.38	30.17	29.29	27.34	26.34	23.82
	US30-06	40	7.3	2362.0	1832.0	1528.0	1044.0	922.0	740.0	28.38	28.30	27.46	25.33	24.08	21.26
	Average	40	7.3	2411.0	1866.7	1512.3	1073.7	951.3	773.0	29.17	28.99	28.12	26.08	24.91	22.20
	STDV	40	0.2	283.7	226.0	245.9	131.0	112.9	90.1	1.1	1.0	1.0	1.1	1.2	1.4
	CV, %	40	2.7	11.8	12.1	16.3	12.2	11.9	11.7	3.7	3.6	3.6	4.2	5.0	6.3

Mix	Sample ID	Temp. °C	V _a %	Confined Dynamic (Complex) Modulus E* (MPa)						Phase Angle φ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
SR66 (Mix 11)	SR66-02	40	7.4	3112.0	2445.0	1991.0	1282.0	1089.0	769.0	27.89	29.19	29.77	29.39	28.21	27.91
	SR66-02t	40	7.4	3713.0	2911.0	2405.0	1527.0	1266.0	870.0	26.43	28.39	29.22	30.48	30.43	27.21
	SR66-08	40	7.7	4050.0	3151.0	2590.0	1604.0	1354.0	954.0	33.65	35.29	35.09	34.36	33.17	27.33
	Average	40	7.5	3625.0	2835.7	2328.7	1471.0	1236.3	864.3	29.32	30.96	31.36	31.41	30.60	27.48
	STDV	40	0.2	475.2	359.0	306.7	168.1	135.0	92.6	3.8	3.8	3.2	2.6	2.5	0.4
	CV, %	40	2.3	13.1	12.7	13.2	11.4	10.9	10.7	13.0	12.2	10.3	8.3	8.1	1.4
SR135 (Mix 12)	SR135-03	40	7.3	3161.0	2399.0	1945.0	1268.0	1094.0	850.0	27.75	28.49	28.23	26.98	25.78	22.72
	SR135-06	40	7.4	3132.0	2355.0	1901.0	1259.0	1092.0	836.0	28.78	29.79	29.39	27.60	26.47	23.40
	SR135-08	40	7.0	4807.0	3702.0	3155.0	2043.0	1744.0	1323.0	27.27	28.48	28.67	27.08	25.94	23.31
	Average	40	7.2	3700.0	2818.7	2333.7	1523.3	1310.0	1003.0	27.93	28.92	28.76	27.22	26.06	23.14
	STDV	40	0.2	958.8	765.3	711.6	450.1	375.9	277.2	0.8	0.8	0.6	0.3	0.4	0.4
	CV, %	40	2.9	25.9	27.2	30.5	29.5	28.7	27.6	2.8	2.6	2.0	1.2	1.4	1.6
US31 (Mix 8S)	US31-02	40	7.5	1894.0	1449.0	1200.0	814.0	717.0	571.0	30.26	29.00	27.63	25.16	24.09	21.78
	US31-07	40	7.0	2693.0	2010.0	1630.0	1080.0	925.0	706.0	31.50	30.97	29.95	28.00	26.97	24.63
	US31-09	40	7.0	2741.0	2143.0	1799.0	1225.0	1075.0	878.0	28.60	27.50	26.35	25.23	24.56	22.60
	Average	40	7.2	2442.7	1867.3	1543.0	1039.7	905.7	718.3	30.12	29.16	27.98	26.13	25.21	23.00
	STDV	40	0.3	475.8	368.3	308.8	208.4	179.8	153.9	1.5	1.7	1.8	1.6	1.5	1.5
	CV, %	40	4.0	19.5	19.7	20.0	20.0	19.9	21.4	4.8	6.0	6.5	6.2	6.1	6.4
I74 (Mix 9S)	I74-04	40	7.5	3892.0	2981.0	2511.0	1725.0	1481.0	1094.0	27.16	27.45	27.25	26.55	25.79	24.02
	I74-06	40	7.4	4957.0	3748.0	3038.0	1940.0	1620.0	1180.0	26.83	26.51	27.63	29.72	29.42	28.17
	I74-07	40	7.0	5181.0	4006.0	3145.0	2121.0	1785.0	1303.0	30.36	29.67	29.17	30.70	29.88	28.34
	Average	40	7.3	4676.7	3578.3	2898.0	1928.7	1628.7	1192.3	28.12	27.88	28.02	28.99	28.36	26.84
	STDV	40	0.3	688.7	533.1	339.4	198.2	152.2	105.0	1.9	1.6	1.0	2.2	2.2	2.4
	CV, %	40	3.6	14.7	14.9	11.7	10.3	9.3	8.8	6.9	5.8	3.6	7.5	7.9	9.1
SR64 (Mix 11S)	SR64-10	40	7.2	3516.0	2837.0	2415.0	1511.0	1275.0	907.0	26.19	27.76	29.89	29.78	29.10	27.29
	SR64-17	40	7.3	4678.0	3621.0	2944.0	1863.0	1531.0	1057.0	27.59	28.59	28.71	29.25	28.78	27.27
	SR64-18	40	7.7	4574.0	3571.0	2924.0	1865.0	1577.0	1112.0	25.98	27.70	28.04	29.21	28.71	27.50
	Average	40	7.4	4256.0	3343.0	2761.0	1746.3	1461.0	1025.3	26.59	28.02	28.88	29.41	28.86	27.35
	STDV	40	0.3	643.0	438.9	299.8	203.8	162.7	106.1	0.9	0.5	0.9	0.3	0.2	0.1
	CV, %	40	3.6	15.1	13.1	10.9	11.7	11.1	10.3	3.3	1.8	3.2	1.1	0.7	0.5

Mix	Sample ID	Temp. °C	V _a %	Confined Dynamic (Complex) Modulus [E*] (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
I65 (Mix 12S)	I65-02	40	8.0	3154.0	2470.0	2020.0	1309.0	1122.0	820.0	27.58	28.41	28.55	27.56	26.65	24.78
	I65-05	40	7.4	3334.0	2577.0	2073.0	1334.0	1132.0	824.0	30.12	30.78	30.47	29.47	28.60	26.35
	I65-06	40	7.9	4372.0	3381.0	2715.0	1708.0	1414.0	984.0	27.42	28.76	29.15	29.05	28.73	28.33
	Average	40	7.8	3620.0	2809.3	2269.3	1450.3	1222.7	876.0	28.37	29.32	29.39	28.69	27.99	26.49
	STDV	40	0.3	657.4	498.0	386.9	223.5	165.8	93.6	1.5	1.3	1.0	1.0	1.2	1.8
	CV, %	40	4.1	18.2	17.7	17.0	15.4	13.6	10.7	5.3	4.4	3.3	3.5	4.2	6.7
SR15 (Mix 1)	SR15-05	54.4	7.2	1019.0	859.0	773.0	661.0	634.0	611.0	24.15	21.68	19.43	15.45	14.28	12.04
	SR15-06	54.4	7.5	1034.0	869.0	788.0	682.0	670.0	654.0	31.38	27.90	24.95	20.68	20.07	18.96
	SR15-09	54.4	7.6	2080.0	1788.0	1667.0	1510.0	1467.0	1438.0	20.49	19.40	17.67	14.32	13.62	12.86
	Average	54.4	7.4	1377.7	1172.0	1076.0	951.0	923.7	901.0	25.34	22.99	20.68	16.82	15.99	14.62
	STDV	54.4	0.2	608.3	533.5	511.9	484.2	470.9	465.6	5.5	4.4	3.8	3.4	3.5	3.8
	CV, %	54.4	2.8	44.2	45.5	47.6	50.9	51.0	51.7	21.9	19.1	18.4	20.2	22.2	25.9
US24 (Mix 2)	US24-03	54.4	7.9	1042.0	859.0	786.0	670.0	646.0	624.0	23.73	21.22	19.19	14.71	13.50	11.66
	US24-05	54.4	7.7	1391.0	1156.0	1037.0	887.0	852.0	815.0	23.74	21.24	19.22	15.23	14.16	12.46
	US24-07	54.4	7.7	973.0	814.0	741.0	640.0	617.0	590.0	23.68	21.22	19.09	14.84	13.80	12.05
	Average	54.4	7.8	1135.3	943.0	854.7	732.3	705.0	676.3	23.72	21.23	19.17	14.93	13.82	12.06
	STDV	54.4	0.1	224.1	185.8	159.5	134.8	128.1	121.3	0.0	0.0	0.1	0.3	0.3	0.4
	CV, %	54.4	1.5	19.7	19.7	18.7	18.4	18.2	17.9	0.1	0.1	0.4	1.8	2.4	3.3
SR161 (Mix 4)	SR161-02	54.4	7.9												
	SR161-04	54.4	7.8	1203.0	982.0	841.0	671.0	631.0	588.0	31.75	29.75	27.08	20.88	19.16	16.12
	SR161-06	54.4	7.5	1248.0	993.0	853.0	676.0	636.0	593.0	29.03	26.87	24.72	19.92	18.58	15.86
	Average	54.4	7.7	1225.5	987.5	847.0	673.5	633.5	590.5	30.39	28.31	25.90	20.40	18.87	15.99
	STDV	54.4	0.2	31.8	7.8	8.5	3.5	3.5	3.5	1.9	2.0	1.7	0.7	0.4	0.2
	CV, %	54.4	2.7	2.6	0.8	1.0	0.5	0.6	0.6	6.3	7.2	6.4	3.3	2.2	1.1
SR56 (Mix 5)	SR56-04	54.4	7.2	1695.0	1394.0	1215.0	978.0	910.0	842.0	26.40	25.06	23.37	19.75	18.72	16.87
	SR56-04t	54.4	7.3	1505.0	1221.0	1075.0	880.0	826.0	759.0	33.02	31.99	29.30	24.48	23.35	21.23
	SR56-08	54.4	7.8	1973.0	1605.0	1392.0	1136.0	1076.0	1018.0	27.24	25.50	23.56	20.15	19.43	17.34
	Average	54.4	7.4	1724.3	1406.7	1227.3	998.0	937.3	873.0	28.89	27.52	25.41	21.46	20.50	18.48
	STDV	54.4	0.3	235.4	192.3	158.9	129.2	127.2	132.3	3.6	3.9	3.4	2.6	2.5	2.4
	CV, %	54.4	4.3	13.7	13.7	12.9	12.9	13.6	15.1	12.5	14.1	13.3	12.2	12.2	12.9

Mix	Sample ID	Temp. °C	V _a %	Confined Dynamic (Complex) Modulus E* (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
US30 (Mix 9)	US30-01t	54.4	7.1	1111.0	961.0	871.0	1043.0	706.0	665.0	22.26	20.25	18.74	15.72	16.18	14.42
	US30-02	54.4	7.5	1934.0	1654.0	1435.0	1161.0	1100.0	1006.0	27.57	25.76	24.09	20.56	20.09	18.16
	US30-06	54.4	7.3	1333.0	1139.0	1047.0	877.0	843.0	793.0	27.59	25.23	23.27	20.69	20.30	18.84
	Average	54.4	7.3	1459.3	1251.3	1117.7	1027.0	883.0	821.3	25.81	23.75	22.03	18.99	18.86	17.14
	STDV	54.4	0.2	425.8	359.9	288.6	142.7	200.0	172.3	3.1	3.0	2.9	2.8	2.3	2.4
	CV, %	54.4	2.7	29.2	28.8	25.8	13.9	22.7	21.0	11.9	12.8	13.1	14.9	12.3	13.9
SR66 (Mix 11)	SR66-02	54.4	7.4	1318.0	1042.0	905.0	712.0	665.0	608.0	27.65	25.36	23.46	19.92	18.67	16.06
	SR66-02t	54.4	7.4	1476.0	1221.0	1063.0	829.0	767.0	686.0	29.92	28.18	26.68	23.36	22.34	20.04
	SR66-08	54.4	7.7	1545.0	1212.0	1032.0	819.0	766.0	698.0	27.39	25.82	23.42	19.35	18.07	15.68
	Average	54.4	7.5	1446.3	1158.3	1000.0	786.7	732.7	664.0	28.32	26.45	24.52	20.88	19.69	17.26
	STDV	54.4	0.2	116.4	100.8	83.7	64.9	58.6	48.9	1.4	1.5	1.9	2.2	2.3	2.4
	CV, %	54.4	2.3	8.0	8.7	8.4	8.2	8.0	7.4	4.9	5.7	7.6	10.4	11.7	14.0
SR135 (Mix 12)	SR135-03	54.4	7.3	1313.0	1074.0	934.0	748.0	701.0	637.0	25.17	23.01	21.36	18.07	16.87	14.93
	SR135-06	54.4	7.4	1583.0	1307.0	1123.0	855.0	795.0	704.0	27.72	25.98	24.73	21.50	20.17	17.88
	SR135-08	54.4	7.0	2066.0	1663.0	1475.0	1183.0	1103.0	1011.0	29.65	27.16	25.03	21.87	20.88	19.03
	Average	54.4	7.2	1654.0	1348.0	1177.3	928.7	866.3	784.0	27.51	25.38	23.71	20.48	19.31	17.28
	STDV	54.4	0.2	381.5	296.6	274.6	226.7	210.3	199.4	2.2	2.1	2.0	2.1	2.1	2.1
	CV, %	54.4	2.9	23.1	22.0	23.3	24.4	24.3	25.4	8.2	8.4	8.6	10.2	11.1	12.2
US31 (Mix 8S)	US31-02	54.4	7.5	970.0	831.0	755.0	623.0	587.0	544.0	24.54	21.69	20.23	18.27	17.56	16.26
	US31-07	54.4	7.0	1282.0	1083.0	950.0	769.0	724.0	660.0	26.12	24.00	22.14	19.67	19.06	17.39
	US31-09	54.4	7.0	1435.0	1210.0	1102.0	902.0	855.0	804.0	28.36	26.22	23.35	21.71	21.36	20.51
	Average	54.4	7.2	1229.0	1041.3	935.7	764.7	722.0	669.3	26.3	24.0	21.9	19.9	19.3	18.1
	STDV	54.4	0.3	237.0	192.9	173.9	139.6	134.0	130.3	1.9	2.3	1.6	1.7	1.9	2.2
	CV, %	54.4	4.0	19.3	18.5	18.6	18.2	18.6	19.5	7.3	9.4	7.2	8.7	9.9	12.2
I74 (Mix 9S)	I74-04	54.4	7.5	1620.0	1304.0	1102.0	824.0	738.0	597.0	28.62	27.54	25.84	23.02	22.11	21.77
	I74-06	54.4	7.4	1687.0	1343.0	1165.0	878.0	783.0	651.0	28.08	26.50	25.01	23.03	22.38	20.96
	I74-07	54.4	7.0	2130.0	1804.0	1545.0	1125.0	983.0	746.0	28.00	26.05	25.19	23.81	23.15	22.17
	Average	54.4	7.3	1812.3	1483.7	1270.7	942.3	834.7	664.7	28.23	26.70	25.35	23.29	22.55	21.63
	STDV	54.4	0.3	277.1	278.1	239.7	160.5	130.4	75.4	0.3	0.8	0.4	0.5	0.5	0.6
	CV, %	54.4	3.6	15.3	18.7	18.9	17.0	15.6	11.3	1.2	2.9	1.7	1.9	2.4	2.8

Mix	Sample ID	Temp. °C	V _a %	Confined Dynamic (Complex) Modulus E* (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
SR64 (Mix 11S)	SR64-10	54.4	7.2	1569.0	1281.0	1129.0	867.0	790.0	669.0	25.32	25.36	24.21	21.92	20.72	18.85
	SR64-17	54.4	7.3	1719.0	1404.0	1224.0	917.0	829.0	689.0	25.15	25.58	24.66	22.71	21.76	20.03
	SR64-18	54.4	7.7	2039.0	1669.0	1437.0	1100.0	991.0	834.0	25.96	26.52	25.59	23.48	22.34	20.19
	Average	54.4	7.4	1775.7	1451.3	1263.3	961.3	870.0	730.7	25.48	25.82	24.82	22.70	21.61	19.69
	STDV	54.4	0.3	240.1	198.3	157.7	122.7	106.6	90.0	0.4	0.6	0.7	0.8	0.8	0.7
	CV, %	54.4	3.6	13.5	13.7	12.5	12.8	12.3	12.3	1.7	2.4	2.8	3.4	3.8	3.7
I65 (Mix 12S)	I65-02	54.4	8.0	1399.0	1128.0	972.0	724.0	658.0	561.0	28.04	26.49	25.40	22.79	21.99	20.50
	I65-05	54.4	7.4	1429.0	1165.0	994.0	749.0	684.0	587.0	27.49	26.41	24.92	21.96	20.96	18.70
	I65-06	54.4	7.9	1818.0	1381.0	1135.0	781.0	686.0	528.0	27.64	28.72	28.14	26.83	26.93	26.63
	Average	54.4	7.8	1548.7	1224.7	1033.7	751.3	676.0	558.7	27.72	27.21	26.15	23.86	23.29	21.94
	STDV	54.4	0.3	233.7	136.6	88.4	28.6	15.6	29.6	0.3	1.3	1.7	2.6	3.2	4.2
	CV, %	54.4	4.1	15.1	11.2	8.6	3.8	2.3	5.3	1.0	4.8	6.6	10.9	13.7	18.9

Mix	Sample ID	Temp. (°C)	V _a (%)	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR15 (Mix 1)	SR15-01-02	40	7.3	301.7	213.6	123.2	79.6	50.8	27.9	15.7	10.3	7.0	6.5
	SR15-02-02	40	7.8	251.0	174.9	100.8	64.8	42.3	22.7	24.5	9.8	6.7	6.5
	SR15-03-02	40	7.9	214.0	140.1	78.8	50.4	32.2	19.1	12.2	5.0	0.7	2.6
	Average	40	7.7	255.5	176.2	100.9	65.0	41.8	23.3	17.5	8.4	4.8	5.2
	STDV	40	0.3	44.0	36.8	22.2	14.6	9.3	4.4	6.3	2.9	3.5	2.2
	CV, %	40	4.2	17.2	20.9	22.0	22.4	22.2	19.0	36.2	35.0	73.7	43.6
US24 (Mix 2)	US24-14-02	40	7.7	267.6	187.2	107.1	68.9	44.4	24.5	13.1	8.0	5.0	5.8
	US24-15-01	40	8.0	227.4	152.1	87.6	54.8	35.7	20.9	14.3	9.5	6.0	5.6
	US24-16-01	40	7.3	300.2	209.5	126.4	82.7	54.7	30.3	19.3	14.6	7.2	5.2
	Average	40	7.7	265.1	182.9	107.0	68.8	44.9	25.2	15.5	10.7	6.1	5.5
	STDV	40	0.4	36.5	29.0	19.4	13.9	9.5	4.7	3.3	3.4	1.1	0.3
	CV, %	40	4.6	13.8	15.8	18.1	20.3	21.2	18.8	21.1	32.2	18.6	5.7
SR161 (Mix 4)	SR161-15-01	40	7.9	493.6	357.1	217.7	142.9	95.1	53.1	34.0	24.7	13.4	5.4
	SR161-16-01	40	7.4	404.6	276.7	161.3	107.0	68.8	37.3	27.4	15.2	10.6	8.8
	SR161-17-02	40	7.5	483.1	341.5	205.6	136.1	91.6	51.8	37.6	23.0	13.3	12.3
	Average	40	7.6	460.5	325.1	194.9	128.6	85.2	47.4	33.0	21.0	12.4	8.8
	STDV	40	0.3	48.6	42.6	29.7	19.1	14.3	8.8	5.1	5.1	1.6	3.5
	CV, %	40	3.5	10.6	13.1	15.2	14.8	16.8	18.5	15.6	24.1	13.2	39.1
SR56 (Mix 5)	SR56-03-01	40	7.0	563.6	429.6	275.0	191.5	133.2	83.5	59.2	38.4	25.2	19.4
	SR56-04-01	40	7.4	574.9	411.8	259.4	176.2	120.0	70.0	48.6	33.3	18.2	13.7
	SR56-05-02	40	7.4	549.1	402.5	258.0	180.4	123.0	74.4	51.9	31.4	20.2	17.3
	Average	40	7.3	562.5	414.6	264.1	182.7	125.4	76.0	53.2	34.4	21.2	16.8
	STDV	40	0.2	13.0	13.8	9.4	7.9	6.9	6.9	5.4	3.6	3.6	2.9
	CV, %	40	3.2	2.3	3.3	3.6	4.3	5.5	9.0	10.2	10.5	16.9	17.1
US30 (Mix 9)	US30-01-01	40	7.4	347.5	246.0	147.4	101.1	69.5	40.7	25.8	21.4	18.7	12.2
	US30-02-01	40	7.5	347.0	237.3	144.7	99.0	67.2	40.9	28.8	15.8	12.2	12.7
	US30-03-02	40	7.6	360.9	255.8	161.4	110.0	75.7	45.3	33.2	25.5	15.4	10.4
	Average	40	7.5	351.8	246.3	151.2	103.4	70.8	42.3	29.3	20.9	15.5	11.8
	STDV	40	0.1	7.9	9.3	9.0	5.8	4.4	2.6	3.7	4.9	3.3	1.2
	CV, %	40	1.3	2.2	3.8	5.9	5.6	6.2	6.2	12.7	23.3	21.0	10.5
SR66 (Mix 11)	SR66-11-02	40	7.7	662.2	497.1	331.3	239.3	170.4	107.5	77.7	56.3	34.5	30.4
	SR66-12-02	40	7.9	404.4	311.8	200.6	142.2	100.5	62.5	44.1	31.6	16.8	15.2
	SR66-13-02	40	8.0	458.8	335.7	213.5	149.3	101.6	61.3	44.0	26.2	20.6	13.3
	Average	40	7.9	508.5	381.5	248.5	176.9	124.2	77.1	55.3	38.0	24.0	19.7
	STDV	40	0.2	135.9	100.8	72.0	54.2	40.1	26.4	19.4	16.1	9.3	9.4
	CV, %	40	1.9	26.7	26.4	29.0	30.6	32.3	34.2	35.2	42.3	39.0	47.8
SR135 (Mix 12)	SR135-16-01	40	7.2	597.0	427.3	268.8	189.0	131.8	80.3	57.0	39.5	25.8	15.9
	SR135-17-02	40	7.7	489.3	366.7	227.6	155.9	105.0	59.7	40.2	24.7	18.3	10.5
	SR135-19-02	40	7.4	503.8	365.2	227.8	154.9	105.9	63.6	44.6	28.8	18.5	14.9
	Average	40	7.4	530.0	386.4	241.4	166.6	114.2	67.9	47.3	31.0	20.9	13.8
	STDV	40	0.3	58.4	35.4	23.8	19.4	15.2	10.9	8.7	7.6	4.3	2.9
	CV, %	40	3.4	11.0	9.2	9.8	11.6	13.3	16.1	18.5	24.6	20.6	21.0

Mix	Sample ID	Temp. (°C)	V _a (%)	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
US31 (Mix 8S)	US31-15-01	40	6.8	344.6	257.3	173.3	125.3	93.6	65.5	50.5	40.5	32.5	26.3
	US31-17-01	40	7.0	382.6	285.6	187.9	137.3	103.0	71.0	53.3	42.0	32.7	25.6
	US31-17-02	40	8.1	323.7	241.5	159.0	115.4	83.0	56.9	44.4	29.6	21.6	16.4
	Average	40	7.3	350.3	261.5	173.4	126.0	93.2	64.4	49.4	37.3	28.9	22.8
	STDV	40	0.7	29.9	22.3	14.5	11.0	10.0	7.1	4.6	6.7	6.3	5.5
	CV, %	40	9.6	8.5	8.5	8.3	8.7	10.7	11.0	9.2	18.0	21.8	24.2
I74 (Mix 9S)	I74-12-01	40	7.1	775.8	559.6	383.9	284.9	202.0	136.4	101.3	75.9	49.1	42.4
	I74-12-02	40	7.1	639.9	506.0	351.3	258.3	191.8	129.3	98.1	75.4	53.0	37.4
	I74-13-02	40	6.9	647.2	473.2	326.1	242.1	173.2	115.7	85.8	62.1	41.8	30.4
	Average	40	7.0	687.6	512.9	353.8	261.8	189.0	127.1	95.1	71.1	48.0	36.7
	STDV	40	0.1	76.5	43.6	29.0	21.6	14.6	10.5	8.2	7.8	5.7	6.0
	CV, %	40	1.6	11.1	8.5	8.2	8.3	7.7	8.3	8.6	11.0	11.8	16.3
SR64 (Mix 11S)	SR64-13-01	40	6.8	663.0	515.3	391.5	321.3	267.1	212.1	177.8	150.2	118.3	102.5
	SR64-13-02	40	8.0	511.7	394.4	274.8	203.4	148.4	98.9	74.3	52.6	36.8	26.4
	SR64-15-01	40	7.1	839.7	638.0	433.2	318.3	228.3	151.1	112.6	82.5	58.1	46.2
	Average	40	7.3	671.5	515.9	366.5	281.0	214.6	154.0	121.5	95.1	71.1	58.4
	STDV	40	0.6	164.2	121.8	82.1	67.2	60.5	56.6	52.4	50.0	42.3	39.5
	CV, %	40	8.6	24.4	23.6	22.4	23.9	28.2	36.8	43.1	52.6	59.5	67.6
I65 (Mix 12S)	I65-15-01	40	7.1	585.3	461.2	336.7	254.5	200.0	151.1	120.2	99.9	75.2	68.6
	I65-16-02	40	7.5	586.8	420.0	299.9	225.3	174.1	128.3	102.5	85.7	65.5	57.4
	I65-17-01	40	7.5	635.6	499.7	363.1	285.9	217.9	164.2	133.7	108.6	87.1	73.9
	Average	40	7.4	602.6	460.3	333.2	255.2	197.3	147.9	118.8	98.1	75.9	66.6
	STDV	40	0.2	28.6	39.9	31.7	30.3	22.0	18.2	15.6	11.6	10.8	8.4
	CV, %	40	3.1	4.7	8.7	9.5	11.9	11.1	12.3	13.1	11.8	14.2	12.6
SR15 (Mix 1)	SR15-01-02	54.4	7.3	74.2	45.7	27.2	18.8	12.9	7.7	6.3	6.6	5.5	4.2
	SR15-02-02	54.4	7.8	64.0	36.5	17.9	11.9	7.4	7.4	6.9	5.2	3.5	3.2
	SR15-03-02	54.4	7.9	40.7	28.9	14.9	10.2	6.7	5.5	4.9	3.7	2.1	1.4
	Average	54.4	7.7	59.7	37.1	20.0	13.6	9.0	6.9	6.0	5.2	3.7	2.9
	STDV	54.4	0.3	17.2	8.4	6.4	4.6	3.4	1.2	1.0	1.4	1.7	1.4
	CV, %	54.4	4.2	28.8	22.7	32.2	33.5	37.6	16.9	17.2	27.5	46.6	46.9
US24 (Mix 2)	US24-14-02	54.4	7.7	57.2	34.9	20.0	13.8	9.3	3.2	3.3	4.5	0.7	2.5
	US24-15-01	54.4	8.0	52.1	35.5	21.8	15.3	11.1	7.7	5.1	6.3	2.6	7.3
	US24-16-01	54.4	7.3	75.9	50.1	27.7	17.8	13.1	5.5	4.8	3.9	2.4	2.0
	Average	54.4	7.7	61.7	40.2	23.2	15.6	11.2	5.4	4.4	4.9	1.9	3.9
	STDV	54.4	0.4	12.5	8.6	4.0	2.1	1.9	2.2	1.0	1.3	1.1	3.0
	CV, %	54.4	4.6	20.3	21.4	17.3	13.2	16.8	41.1	22.4	26.3	55.4	75.1
SR161 (Mix 4)	SR161-15-01	54.4	7.9	98.6	63.8	34.1	22.4	13.6	7.7	4.8	2.8	5.3	3.9
	SR161-16-01	54.4	7.4	89.1	56.5	32.4	20.9	13.1	6.4	8.5	2.9	2.5	0.8
	SR161-17-02	54.4	7.5	69.8	45.0	25.2	16.5	10.8	9.6	3.4	6.1	2.8	3.3
	Average	54.4	7.6	85.8	55.1	30.5	19.9	12.5	7.9	5.6	3.9	3.6	2.7
	STDV	54.4	0.3	14.7	9.5	4.7	3.1	1.5	1.6	2.6	1.9	1.5	1.7
	CV, %	54.4	3.5	17.1	17.2	15.5	15.5	11.8	20.7	46.5	48.0	42.9	62.9

Mix	Sample ID	Temp. (°C)	V _a (%)	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR56 (Mix 5)	SR56-03-01	54.4	7.0	170.1	116.3	68.4	44.4	30.8	19.4	13.5	7.9	3.4	5.0
	SR56-04-01	54.4	7.4	143.2	94.5	55.1	36.5	24.5	13.0	7.0	4.8	2.6	2.3
	SR56-05-02	54.4	7.4	133.3	88.0	51.8	34.9	22.0	13.3	6.6	5.4	1.8	3.7
	Average	54.4	7.3	148.9	99.6	58.4	38.6	25.8	15.3	9.1	6.0	2.6	3.7
	STDV	54.4	0.2	19.1	14.8	8.8	5.1	4.5	3.6	3.9	1.6	0.8	1.4
	CV, %	54.4	3.2	12.8	14.9	15.1	13.2	17.4	23.7	42.8	27.0	29.3	37.7
US30 (Mix 9)	US30-01-01	54.4	7.4	113.8	84.7	47.5	34.3	24.3	13.4	13.3	10.3	14.2	16.8
	US30-02-01	54.4	7.5	78.5	53.6	31.5	21.3	15.2	13.9	10.7	6.1	3.0	3.5
	US30-03-02	54.4	7.6	81.7	59.9	31.8	21.4	17.4	11.4	7.9	7.8	5.7	8.1
	Average	54.4	7.5	91.4	66.1	36.9	25.7	19.0	12.9	10.6	8.1	7.6	9.5
	STDV	54.4	0.1	19.5	16.4	9.2	7.4	4.8	1.4	2.7	2.1	5.8	6.8
	CV, %	54.4	1.3	21.4	24.9	24.8	29.0	25.1	10.5	25.3	26.3	76.6	71.9
SR66 (Mix 11)	SR66-11-02	54.4	7.7	202.1	148.2	90.8	64.6	43.1	29.6	23.4	14.4	12.1	11.1
	SR66-12-02	54.4	7.9	125.8	84.6	50.5	32.4	21.6	15.4	9.8	6.7	8.2	2.1
	SR66-13-02	54.4	8.0	99.9	71.4	43.6	28.2	19.3	12.0	12.2	9.5	5.9	6.0
	Average	54.4	7.9	142.6	101.4	61.7	41.8	28.0	19.0	15.1	10.2	8.7	6.4
	STDV	54.4	0.2	53.1	41.1	25.5	19.9	13.1	9.3	7.3	3.9	3.1	4.5
	CV, %	54.4	1.9	37.3	40.5	41.4	47.7	46.9	49.2	48.1	38.1	35.9	70.2
SR135 (Mix 12)	SR135-16-01	54.4	7.2	209.8	152.0	92.8	62.2	41.3	29.0	21.0	19.1	11.2	12.5
	SR135-17-02	54.4	7.7	179.8	125.6	75.6	51.1	30.4	23.8	22.3	13.3	12.4	15.1
	SR135-19-02	54.4	7.4	137.2	99.0	57.6	39.7	25.4	17.8	16.9	8.2	2.9	11.3
	Average	54.4	7.4	175.6	125.5	75.3	51.0	32.4	23.5	20.1	13.5	8.8	13.0
	STDV	54.4	0.3	36.5	26.5	17.6	11.3	8.1	5.6	2.8	5.5	5.1	2.0
	CV, %	54.4	3.4	20.8	21.1	23.3	22.1	25.1	23.9	13.9	40.5	58.1	15.3
US31 (Mix 8S)	US31-15-01	54.4	6.8	105.6	76.0	51.5	39.4	30.2	24.5	12.6	12.4	12.3	9.5
	US31-17-01	54.4	7.0	82.9	62.4	42.2	32.2	25.4	19.4	17.7	14.7	11.9	7.9
	US31-17-02	54.4	8.1	79.5	59.4	38.0	27.9	20.8	12.4	12.9	7.8	8.2	4.4
	Average	54.4	7.3	89.3	65.9	43.9	33.1	25.5	18.8	14.4	11.6	10.8	7.3
	STDV	54.4	0.7	14.2	8.8	6.9	5.8	4.7	6.1	2.8	3.5	2.3	2.6
	CV, %	54.4	9.6	15.9	13.4	15.8	17.5	18.3	32.3	19.6	30.2	21.0	36.4
I74 (Mix 9S)	I74-12-01	54.4	7.1	196.2	150.1	101.7	76.0	55.5	38.0	25.6	18.9	12.1	10.3
	I74-12-02	54.4	7.1	180.3	130.9	82.2	59.2	41.8	26.7	20.4	16.4	11.9	10.0
	I74-13-02	54.4	6.9	198.5	146.8	95.0	69.3	52.1	35.3	29.5	21.7	13.4	11.9
	Average	54.4	7.0	191.7	142.6	93.0	68.2	49.8	33.3	25.2	19.0	12.5	10.8
	STDV	54.4	0.1	9.9	10.3	9.9	8.5	7.1	5.9	4.6	2.6	0.8	1.0
	CV, %	54.4	1.6	5.2	7.2	10.7	12.4	14.3	17.8	18.2	13.9	6.5	9.2
SR64 (Mix 11S)	SR64-13-01	54.4	6.8	259.3	201.8	148.1	108.0	87.6	65.0	53.3	46.7	34.7	34.9
	SR64-13-02	54.4	8.0	140.2	107.6	67.1	48.4	35.4	22.6	20.8	13.2	9.2	8.7
	SR64-15-01	54.4	7.1	200.7	152.9	99.4	70.5	52.7	34.0	26.4	22.9	15.0	11.4
	Average	54.4	7.3	200.1	154.1	104.9	75.6	58.6	40.5	33.5	27.6	19.6	18.3
	STDV	54.4	0.6	59.6	47.1	40.8	30.1	26.6	21.9	17.4	17.2	13.4	14.4
	CV, %	54.4	8.6	29.8	30.6	38.9	39.9	45.4	54.1	51.9	62.4	68.2	78.7
I65 (Mix 12S)	I65-15-01	54.4	7.1	174.4	130.3	89.7	70.6	56.7	42.7	37.4	30.5	24.2	21.2
	I65-16-02	54.4	7.5	163.9	126.4	88.1	70.7	57.0	42.8	37.3	32.3	23.3	20.1
	I65-17-01	54.4	7.5	234.1	181.3	130.2	104.3	85.4	68.1	55.1	48.6	42.0	36.7
	Average	54.4	7.4	190.8	146.0	102.7	81.9	66.3	51.2	43.3	37.1	29.8	26.0
	STDV	54.4	0.2	37.8	30.6	23.9	19.4	16.5	14.6	10.3	10.0	10.6	9.3
	CV, %	54.4	3.1	19.8	21.0	23.2	23.7	24.8	28.6	23.7	26.9	35.4	35.8

Mix	Sample ID	Temp. (°C)	V _a (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR15 (Mix 1)	SR15-01-02	40	7.3	57.46	59.01	60.59	60.29	61.61	62.79	58.71	49.10	52.30	69.85
	SR15-02-02	40	7.8	57.20	56.43	58.76	58.28	59.46	55.62	48.86	48.88	47.10	9.01
	SR15-03-02	40	7.9	59.08	60.99	59.85	59.42	58.36	53.58	33.16	63.61	60.50	20.86
	Average	40	7.7	57.91	58.81	59.73	59.33	59.81	57.33	46.91	53.86	53.30	33.24
	STDV	40	0.3	1.0	2.3	0.9	1.0	1.7	4.8	12.9	8.4	6.8	32.3
	CV, %	40	4.2	1.8	3.9	1.5	1.7	2.8	8.4	27.5	15.7	12.7	97.0
US24 (Mix 2)	US24-14-02	40	7.7	56.77	57.37	59.30	60.48	60.41	60.94	68.85	58.27	65.97	29.85
	US24-15-01	40	8.0	57.68	59.00	57.87	59.41	59.26	61.05	53.81	53.17	44.59	11.92
	US24-16-01	40	7.3	53.64	54.30	55.00	56.86	56.83	58.09	51.01	49.55	60.24	9.37
	Average	40	7.7	56.03	56.89	57.39	58.92	58.83	60.03	57.89	53.66	56.93	17.05
	STDV	40	0.4	2.1	2.4	2.2	1.9	1.8	1.7	9.6	4.4	11.1	11.2
	CV, %	40	4.6	3.8	4.2	3.8	3.2	3.1	2.8	16.6	8.2	19.4	65.5
SR161 (Mix 4)	SR161-15-01	40	7.9	48.73	50.04	53.34	56.80	57.12	57.90	52.76	59.07	37.79	46.26
	SR161-16-01	40	7.4	55.01	56.16	57.86	58.30	58.57	59.16	50.39	52.11	34.44	74.25
	SR161-17-02	40	7.5	51.77	52.35	54.18	55.62	55.69	54.96	53.20	51.70	61.33	39.32
	Average	40	7.6	51.84	52.85	55.13	56.91	57.13	57.34	52.12	54.29	44.52	53.28
	STDV	40	0.3	3.1	3.1	2.4	1.3	1.4	2.2	1.5	4.1	14.7	18.5
	CV, %	40	3.5	6.1	5.8	4.4	2.4	2.5	3.8	2.9	7.6	32.9	34.7
SR56 (Mix 5)	SR56-03-01	40	7.0	44.15	45.42	47.73	49.62	50.41	50.58	52.98	45.47	47.40	45.60
	SR56-04-01	40	7.4	45.69	47.73	50.94	52.68	54.05	55.04	55.97	54.36	61.26	58.00
	SR56-05-02	40	7.4	46.33	47.99	50.33	52.10	53.38	53.57	54.35	54.30	49.67	49.28
	Average	40	7.3	45.39	47.05	49.67	51.47	52.61	53.06	54.43	51.38	52.78	50.96
	STDV	40	0.2	1.1	1.4	1.7	1.6	1.9	2.3	1.5	5.1	7.4	6.4
	CV, %	40	3.2	2.5	3.0	3.4	3.2	3.7	4.3	2.7	10.0	14.1	12.5
US30 (Mix 9)	US30-01-01	40	7.4	49.88	50.34	51.35	51.78	51.54	50.07	43.57	49.80	46.53	57.05
	US30-02-01	40	7.5	52.92	54.11	55.03	53.79	51.81	51.37	49.70	40.40	39.01	52.64
	US30-03-02	40	7.6	49.88	50.34	51.35	51.78	51.54	50.07	43.57	49.80	46.53	57.05
	Average	40	7.5	50.89	51.60	52.58	52.45	51.63	50.50	45.61	46.67	44.02	55.58
	STDV	40	0.1	1.8	2.2	2.1	1.2	0.2	0.8	3.5	5.4	4.3	2.5
	CV, %	40	1.3	3.4	4.2	4.0	2.2	0.3	1.5	7.8	11.6	9.9	4.6
SR66 (Mix 11)	SR66-11-02	40	7.7	42.92	43.15	45.06	45.71	46.45	46.45	45.88	45.38	46.15	41.17
	SR66-12-02	40	7.9	41.67	43.27	46.67	47.85	48.81	49.71	49.16	51.03	40.00	48.22
	SR66-13-02	40	8.0	46.49	46.84	49.65	50.59	51.99	52.13	50.43	56.51	53.74	49.62
	Average	40	7.9	43.69	44.42	47.13	48.05	49.08	49.43	48.49	50.97	46.63	46.34
	STDV	40	0.2	2.5	2.1	2.3	2.4	2.8	2.9	2.3	5.6	6.9	4.5
	CV, %	40	1.9	5.7	4.7	4.9	5.1	5.7	5.8	4.8	10.9	14.8	9.8
SR135 (Mix 12)	SR135-16-01	40	7.2	43.71	46.14	49.02	50.15	50.55	50.44	49.41	46.47	46.87	63.30
	SR135-17-02	40	7.7	47.76	48.51	51.92	53.18	54.48	54.45	57.33	58.64	47.14	52.55
	SR135-19-02	40	7.4	50.29	51.02	51.93	53.06	53.08	52.74	53.03	52.43	52.31	36.08
	Average	40	7.4	47.25	48.56	50.96	52.13	52.70	52.54	53.26	52.51	48.77	50.64
	STDV	40	0.3	3.3	2.4	1.7	1.7	2.0	2.0	4.0	6.1	3.1	13.7
	CV, %	40	3.4	7.0	5.0	3.3	3.3	3.8	3.8	7.4	11.6	6.3	27.1

Mix	Sample ID	Temp. (°C)	V _a (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
US31 (Mix 8S)	US31-15-01	40	6.8	49.18	47.23	45.39	44.72	42.17	39.64	38.31	39.13	33.72	29.11
	US31-17-01	40	7.0	46.52	45.28	45.84	43.28	41.39	38.17	37.92	35.58	35.91	39.54
	US31-17-02	40	8.1	45.88	46.12	45.91	45.08	43.83	43.61	39.40	37.78	35.48	40.36
	Average	40	7.3	47.19	46.21	45.71	44.36	42.46	40.47	38.54	37.50	35.04	36.34
	STDV	40	0.7	1.8	1.0	0.3	1.0	1.2	2.8	0.8	1.8	1.2	6.3
	CV, %	40	9.6	3.7	2.1	0.6	2.1	2.9	7.0	2.0	4.8	3.3	17.3
I74 (Mix 9S)	I74-12-01	40	7.1	42.20	43.12	44.31	45.43	46.01	45.26	44.72	43.35	48.31	48.60
	I74-12-02	40	7.1	41.18	41.21	42.98	44.04	44.22	43.77	43.42	46.31	40.60	44.95
	I74-13-02	40	6.9	40.99	41.20	42.68	43.20	44.25	44.05	43.87	40.35	43.98	45.81
	Average	40	7.0	41.46	41.84	43.32	44.22	44.83	44.36	44.00	43.34	44.30	46.45
	STDV	40	0.1	0.7	1.1	0.9	1.1	1.0	0.8	0.7	3.0	3.9	1.9
	CV, %	40	1.6	1.6	2.6	2.0	2.5	2.3	1.8	1.5	6.9	8.7	4.1
SR64 (Mix 11S)	SR64-13-01	40	6.8	28.88	32.12	29.62	29.07	27.90	27.90	28.68	28.30	28.25	29.01
	SR64-13-02	40	8.0	41.58	41.11	42.11	42.69	43.08	43.27	39.88	44.68	42.25	54.61
	SR64-15-01	40	7.1	42.65	42.71	43.29	43.93	44.40	43.76	43.51	43.53	46.04	41.26
	Average	40	7.3	37.70	38.65	38.34	38.56	38.46	38.31	37.36	38.84	38.85	41.63
	STDV	40	0.6	7.7	5.7	7.6	8.2	9.2	9.0	7.7	9.1	9.4	12.8
	CV, %	40	8.6	20.3	14.8	19.8	21.4	23.8	23.5	20.7	23.5	24.1	30.8
I65 (Mix 12S)	I65-15-01	40	7.1	38.26	37.22	36.88	36.91	35.20	32.88	31.37	29.29	28.52	29.99
	I65-16-02	40	7.5	39.92	40.29	39.03	39.23	37.30	34.25	32.79	32.07	29.70	29.55
	I65-17-01	40	7.5	39.47	38.95	37.11	35.99	35.71	32.85	30.52	27.13	25.66	26.24
	Average	40	7.4	39.22	38.82	37.67	37.38	36.07	33.33	31.56	29.50	27.96	28.59
	STDV	40	0.2	0.9	1.5	1.2	1.7	1.1	0.8	1.1	2.5	2.1	2.0
	CV, %	40	3.1	2.2	4.0	3.1	4.5	3.0	2.4	3.6	8.4	7.4	7.2
SR15 (Mix 1)	SR15-01-02	54.4	7.3	65.48	65.56	59.00	58.72	52.29	70.12	51.72	40.93	23.07	33.29
	SR15-02-02	54.4	7.8	71.80	61.15	68.57	62.60	63.34	55.55	43.48	56.46	85.31	6.62
	SR15-03-02	54.4	7.9	70.95	73.15	66.44	62.80	57.54	54.00	39.72	38.07	20.71	43.45
	Average	54.4	7.7	69.41	66.62	64.67	61.37	57.72	59.89	44.97	45.15	43.03	27.79
	STDV	54.4	0.3	3.4	6.1	5.0	2.3	5.5	8.9	6.1	9.9	36.6	19.0
	CV, %	54.4	4.2	4.9	9.1	7.8	3.7	9.6	14.8	13.6	21.9	85.1	68.5
US24 (Mix 2)	US24-14-02	54.4	7.7	68.67	65.05	59.60	57.86	56.48	77.60	84.64	62.21	77.73	25.72
	US24-15-01	54.4	8.0	67.29	62.09	59.89	52.85	51.07	34.18	34.19	14.21	78.23	13.54
	US24-16-01	54.4	7.3	66.37	63.30	61.79	56.92	53.12	60.31	31.41	86.31	46.05	18.36
	Average	54.4	7.7	67.44	63.48	60.43	55.88	53.56	57.36	50.08	54.24	67.34	19.21
	STDV	54.4	0.4	1.2	1.5	1.2	2.7	2.7	21.9	30.0	36.7	18.4	6.1
	CV, %	54.4	4.6	1.7	2.3	2.0	4.8	5.1	38.1	59.8	67.7	27.4	31.9
SR161 (Mix 4)	SR161-15-01	54.4	7.9	66.23	64.77	65.23	66.02	61.41	42.25	71.97	49.59	41.69	9.31
	SR161-16-01	54.4	7.4	68.61	64.24	63.85	60.47	59.02	39.30	37.09	1.30	89.22	38.11
	SR161-17-02	54.4	7.5	69.63	66.12	65.38	62.36	58.39	81.77	88.00	48.81	17.81	48.04
	Average	54.4	7.6	68.16	65.04	64.82	62.95	59.61	54.44	65.69	33.23	49.57	31.82
	STDV	54.4	0.3	1.7	1.0	0.8	2.8	1.6	23.7	26.0	27.7	36.4	20.1
	CV, %	54.4	3.5	2.6	1.5	1.3	4.5	2.7	43.6	39.6	83.2	73.3	63.2

Mix	Sample ID	Temp. (°C)	V _a (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR56 (Mix 5)	SR56-03-01	54.4	7.0	59.09	58.84	57.71	58.88	57.38	54.80	44.73	48.16	35.71	46.67
	SR56-04-01	54.4	7.4	60.73	61.14	57.62	57.66	56.19	58.92	38.52	66.71	32.16	33.17
	SR56-05-02	54.4	7.4	60.70	62.38	60.58	60.78	59.29	57.91	58.47	44.46	36.66	24.31
	Average	54.4	7.3	60.17	60.79	58.64	59.11	57.62	57.21	47.24	53.11	34.84	34.72
	STDV	54.4	0.2	0.9	1.8	1.7	1.6	1.6	2.1	10.2	11.9	2.4	11.3
	CV, %	54.4	3.2	1.6	3.0	2.9	2.7	2.7	3.8	21.6	22.4	6.8	32.4
US30 (Mix 9)	US30-01-01	54.4	7.4	65.52	63.84	56.24	58.23	53.25	46.97	43.28	45.24	19.37	71.22
	US30-02-01	54.4	7.5	63.14	61.81	58.33	54.56	50.37	59.51	60.02	50.73	12.20	40.00
	US30-03-02	54.4	7.6	64.35	59.10	56.73	53.29	51.37	48.26	34.92	35.93	17.61	9.93
	Average	54.4	7.5	64.34	61.58	57.10	55.36	51.66	51.58	46.07	43.97	16.39	40.38
	STDV	54.4	0.1	1.2	2.4	1.1	2.6	1.5	6.9	12.8	7.5	3.7	30.6
	CV, %	54.4	1.3	1.8	3.9	1.9	4.6	2.8	13.4	27.7	17.0	22.8	75.9
SR66 (Mix 11)	SR66-11-02	54.4	7.7	61.37	62.06	63.48	61.66	60.17	53.87	62.85	55.13	74.46	61.19
	SR66-12-02	54.4	7.9	64.19	65.97	60.90	57.30	59.13	57.43	55.24	25.36	55.96	89.82
	SR66-13-02	54.4	8.0	62.17	61.01	59.33	58.55	54.53	50.94	49.06	48.97	74.02	30.01
	Average	54.4	7.9	62.58	63.01	61.24	59.17	57.94	54.08	55.72	43.15	68.15	60.34
	STDV	54.4	0.2	1.5	2.6	2.1	2.2	3.0	3.3	6.9	15.7	10.6	29.9
	CV, %	54.4	1.9	2.3	4.1	3.4	3.8	5.2	6.0	12.4	36.4	15.5	49.6
SR135 (Mix 12)	SR135-16-01	54.4	7.2	63.28	63.55	61.52	62.30	62.01	59.38	45.47	55.11	52.75	73.56
	SR135-17-02	54.4	7.7	63.87	63.00	64.82	65.73	59.94	59.23	68.54	72.84	59.42	35.14
	SR135-19-02	54.4	7.4	67.17	60.34	66.74	65.71	65.44	61.46	48.78	61.77	17.52	34.32
	Average	54.4	7.4	64.77	62.30	64.36	64.58	62.46	60.02	54.26	63.24	43.23	47.67
	STDV	54.4	0.3	2.1	1.7	2.6	2.0	2.8	1.2	12.5	9.0	22.5	22.4
	CV, %	54.4	3.4	3.2	2.8	4.1	3.1	4.4	2.1	23.0	14.2	52.1	47.0
US31 (Mix 8S)	US31-15-01	54.4	6.8	54.18	48.91	44.42	41.08	39.23	33.54	43.67	31.89	36.82	30.34
	US31-17-01	54.4	7.0	53.37	51.47	47.45	45.13	39.31	41.55	37.76	38.10	39.23	43.97
	US31-17-02	54.4	8.1	54.67	51.80	47.96	43.34	42.78	28.51	51.27	35.64	36.00	29.28
	Average	54.4	7.3	54.07	50.73	46.61	43.18	40.44	34.53	44.23	35.21	37.35	34.53
	STDV	54.4	0.7	0.7	1.6	1.9	2.0	2.0	6.6	6.8	3.1	1.7	8.2
	CV, %	54.4	9.6	1.2	3.1	4.1	4.7	5.0	19.0	15.3	8.9	4.5	23.7
I74 (Mix 9S)	I74-12-01	54.4	7.1	49.75	48.01	47.79	46.50	46.06	44.44	40.98	54.33	62.44	50.07
	I74-12-02	54.4	7.1	52.60	52.34	51.49	50.18	51.26	49.35	44.64	51.58	56.86	59.59
	I74-13-02	54.4	6.9	52.55	50.83	49.89	48.18	46.34	46.50	45.50	42.41	35.24	35.75
	Average	54.4	7.0	51.63	50.39	49.72	48.29	47.89	46.76	43.71	49.44	51.51	48.47
	STDV	54.4	0.1	1.6	2.2	1.9	1.8	2.9	2.5	2.4	6.2	14.4	12.0
	CV, %	54.4	1.6	3.2	4.4	3.7	3.8	6.1	5.3	5.5	12.6	27.9	24.8
SR64 (Mix 11S)	SR64-13-01	54.4	6.8	57.13	50.48	49.06	46.27	43.82	39.23	33.57	32.19	30.37	26.30
	SR64-13-02	54.4	8.0	54.63	54.11	53.56	52.13	53.27	48.50	48.46	41.00	70.49	42.09
	SR64-15-01	54.4	7.1	52.11	49.31	48.35	48.24	46.64	42.85	43.14	48.41	34.77	39.95
	Average	54.4	7.3	54.62	51.30	50.32	48.88	47.91	43.53	41.72	40.53	45.21	36.11
	STDV	54.4	0.6	2.5	2.5	2.8	3.0	4.9	4.7	7.5	8.1	22.0	8.6
	CV, %	54.4	8.6	4.6	4.9	5.6	6.1	10.1	10.7	18.1	20.0	48.7	23.7
I65 (Mix 12S)	I65-15-01	54.4	7.1	50.13	47.42	42.51	39.06	36.09	32.52	28.94	27.78	22.90	18.93
	I65-16-02	54.4	7.5	48.50	45.27	41.75	38.22	35.27	35.74	31.61	25.48	26.60	24.07
	I65-17-01	54.4	7.5	46.56	42.77	38.43	35.09	32.93	30.07	27.19	25.38	27.05	23.33
	Average	54.4	7.4	48.40	45.15	40.90	37.46	34.76	32.78	29.25	26.21	25.52	22.11
	STDV	54.4	0.2	1.8	2.3	2.2	2.1	1.6	2.8	2.2	1.4	2.3	2.8
	CV, %	54.4	3.1	3.7	5.2	5.3	5.6	4.7	8.7	7.6	5.2	8.9	12.6

Road No.	Sample ID	Air Voids (%)	Temperature (°C)	Confining Pressure (kPa)	Max. Deviatoric Stress σ_d (kPa)	Max. Normal Stress σ_1 (kPa)	Strain at Failure (%)
SR15	SR15-13	7.8	54.4	0	281.41	281.4	0.74
SR15	SR15-14	7.6	54.4	138.247	1196.484	1334.7	3.17
SR15	SR15-15	7.6	54.4	276.512	1831.914	2108.4	5.46
SR15			54.4				
US24	US24-23	7.2	54.4	0	243.241	243.2	0.69
US24	US24-24	7.4	54.4	138.247	1034.192	1172.4	3.09
US24	US24-25	7.4	54.4	276.567	1643.424	1920.0	5.11
US24	US24-26	7.6	54.4	414.96	2180.242	2595.2	7.57
SR161	SR161-22	7.9	54.4	0	393.857	393.9	1.28
SR161	SR161-23	7.6	54.4	138.265	1237.891	1376.2	3.81
SR161	SR161-24	7.5	54.4	276.53	1887.548	2164.1	6.17
SR161	SR161-25	7.6	54.4	414.942	2381.095	2796.0	7.76
SR56	SR56-09	7.7	54.4	0	563.998	564.0	1.63
SR56	SR56-10	7.6	54.4	138.228	1437.665	1575.9	3.92
SR56	SR56-11	7.9	54.4	276.603	2017.46	2294.1	6.66
SR56	SR56-12	7.5	54.4	414.96	2546.919	2961.9	8.68
US30	US30-07	7.5	54.4	0	608.25	608.3	1.78
US30	US30-08	7.4	54.4	138.302	1399.692	1538.0	3.66
US30	US30-09	7.3	54.4	276.603	1962.218	2238.8	6.54
US30	US30-10	7.3	54.4	415.015	2569.193	2984.2	8.03
SR66	SR66-17	7.3	54.4	0	546.63	546.6	1.82
SR66	SR66-18	7.3	54.4	138.283	1396.258	1534.5	4.00
SR66	SR66-19	7.3	54.4	276.585	2007.746	2284.3	6.78
SR66	SR66-20	7.8	54.4	414.978	2417.596	2832.6	12.58
SR135	SR135-25	7.6	54.4	0	523.67	523.7	1.41
SR135	SR135-26	7.7	54.4	138.247	1310.794	1449.0	4.89
SR135	SR135-27	7.4	54.4	276.548	2075.744	2352.3	6.41
SR135	SR135-28	7.6	54.4	414.978	2629.733	3044.7	8.77
US31	US31-21	7.0	54.4	0	712.847	712.8	2.19
US31	US31-22	7.0	54.4	138.228	1347.982	1486.2	5.25
US31	US31-23	7.0	54.4	276.548	1825.83	2102.4	10.21
US31	US31-24	7.0	54.4	414.978	2184.854	2599.8	7.86
I74	I74-21	7.6	54.4	0	567.628	567.6	1.60
I74	I74-22	7.5	54.4	138.283	1001.126	1139.4	2.71
I74	I74-23	7.1	54.4	276.585	1690.325	1966.9	12.95
I74	I74-24	7.3	54.4	414.997	1961.237	2376.2	28.38
SR64	SR64-23	7.8	54.4	0	520.53	520.5	1.82
SR64	SR64-24	7.6	54.4	138.247	897.51	1035.8	4.47
SR64	SR64-25	7	54.4	276.512	1596.816	1873.3	11.33
SR64	SR64-26	7.7	54.4	414.978	1817.588	2232.6	12.68
I65	I65-15	7.9	54.4	0	847.174	847.2	1.54
I65	I65-16	7.8	54.4	138.265	1457.779	1596.0	3.22
I65	I65-17	7.5	54.4	276.585	1955.938	2232.5	7.19
I65	I65-18	7.7	54.4				

Road No.	Sample ID	Air Voids (%)	Temperature (°C)	Confining Pressure (kPa)	Max. Deviatoric Stress σ_d (kPa)	Max. Normal Stress σ_1 (kPa)	Strain at Failure (%)
SR15	SR15-10	7.2	54.4	0	429.474	429.5	1.45
SR15	SR15-11	7.6	54.4	138.247	1148.503	1286.8	2.93
SR15	SR15-12	8.0	54.4	276.512	1730.261	2006.8	4.93
SR15	SR15-13	7.9	54.4	414.905	2264.724	2679.6	6.59
US24	US24-08	7.8	54.4	0	289.456	289.5	1.21
US24	US24-09	8.2	54.4	137.093	1024.478	1161.6	1.77
US24	US24-10	7.8	54.4	274.791	1535.982	1810.8	4.37
US24	US24-11	7.7	54.4	413.202	2104.297	2517.5	5.99
SR161	SR161-07	7.8	54.4	0	568.904	568.9	1.72
SR161	SR161-08	7.8	54.4	138.228	1250.254	1388.5	3.28
SR161	SR161-09	7.7	54.4	276.567	1678.551	1955.1	5.59
SR161	SR161-10	8.2	54.4	414.887	2153.946	2568.8	7.65
SR56	SR56-09	7.4	54.4	0	992.491	992.5	2.09
SR56	SR56-10	7.0	54.4	138.32	1307.458	1445.8	2.69
SR56	SR56-11	7.5	54.4	276.548	2068.188	2344.7	6.42
SR56	SR56-12	8.0	54.4	415.015	2548.98	2964.0	7.37
US30	US30-08	7.5	54.4	0	875.335	875.3	1.83
US30	US30-09	7.6	54.4	138.375	1500.069	1638.4	3.31
US30	US30-10	7.7	54.4	276.695	2063.478	2340.2	5.43
US30	US30-11	7.4	54.4	415.106	2651.418	3066.5	7.20
SR66	SR66-04	7.5	54.4	0	824.705	824.7	1.88
SR66	SR66-05	7.5	54.4	138.302	1448.948	1587.3	3.03
SR66	SR66-07	7.3	54.4	276.622	2018.049	2294.7	7.08
SR66	SR66-09	7.2	54.4	415.033	2450.074	2865.1	13.13
SR135	SR135-09	7.1	54.4	0	872.98	873.0	2.06
SR135	SR135-10	7.5	54.4	138.247	1563.848	1702.1	3.52
SR135	SR135-11	7.4	54.4	276.603	2191.133	2467.7	2.62
SR135	SR135-12	7.8	54.4	415.033	2678.499	3093.5	7.81
US31	US31-04	7.6	54.4	0	1079.916	1079.9	3.61
US31	US31-06	7.4	54.4	138.192	1575.23	1713.4	4.40
US31	US31-10	7.3	54.4	276.567	2080.061	2356.6	9.73
US31	US31-12	7.1	54.4	414.942	2431.431	2846.4	12.86
I74	I74-14	6.9	54.4	0	894.37	894.4	1.43
I74	I74-16	7.0	54.4	138.283	1366.723	1505.0	2.54
I74	I74-17	8.0	54.4	276.585	1751.062	2027.6	10.57
I74	I74-20	7.8	54.4	414.997	2325.56	2740.6	8.51
SR64	SR64-16	7.1	54.4	0	886.913	886.9	1.60
SR64	SR64-17	7.0	54.4	138.283	1320.607	1458.9	3.37
SR64	SR64-18	7.1	54.4	276.548	1723.392	1999.9	6.21
SR64	SR64-22	6.9	54.4	414.978	2291.805	2706.8	14.93
I65	I65-07	7.8	54.4	0	1427.068	1427.1	2.30
I65	I65-08	7.7	54.4	138.21	1795.609	1933.8	2.90
I65	I65-09	7.7	54.4	276.475	2222.532	2499.0	5.43
I65	I65-10	7.7	54.4	414.887	2548.097	2963.0	9.57

Road No.	Sample ID	Diameter (mm)	Thickness (mm)	Air Voids (%)	Temp. (°C)	Loading Rate (mm/min)	Max. Compressive Force (kN)	Tensile Strength (kPa)	Strain at Failure (%)
SR15	SR15-01-01	149.91	49.58	7.9	35	0.06	0.283	24.24	1.26
SR15	SR15-02-01	150.12	51.18	7.2	35	0.06	0.381	31.57	1.44
SR15	SR15-03-01	150.51	51.85	7.9	35	0.39	1.056	86.14	1.17
US24	US24-14-01	150.19	51.41	7.4	35	0.06	0.455	37.51	1.44
US24	US24-17-01	149.84	49.21	8.0	35	0.06	0.436	37.64	0.90
US24	US24-17-02	150.11	49.58	7.6	35	0.39	0.586	50.13	1.61
SR161	SR161-14-02	150.03	48.95	7.8	35	0.06	0.401	34.76	1.64
SR161	SR161-15-02	150.08	51.51	7.5	35	0.06	0.541	44.55	1.95
SR161	SR161-13-01	150.14	50.29	7.7	35	0.39	0.916	77.23	1.95
SR56	SR56-03-02	149.77	51.14	7.7	35	0.06	0.551	45.80	0.73
SR56	SR56-04-02	149.81	50.18	7.0	35	0.06	0.72	60.97	2.01
SR56	SR56-05-01	149.97	51.67	7.2	35	0.39	1.727	141.88	1.66
US30	US30-01-02	149.84	48.29	7.3	35	0.06	0.703	61.85	2.29
US30	US30-03-01	150.06	49.9	7.7	35	0.06	0.703	59.77	2.29
US30	US30-02-02	149.87	51.02	7.5	35	0.39	1.336	111.23	1.96
SR66	SR66-11-01	149.95	48.88	7.4	35	0.06	0.953	82.77	2.19
SR66	SR66-12-01	149.71	52.57	7.7	35	0.06	0.812	65.68	1.83
SR66	SR66-13-01	149.83	49.95	7.6	35	0.39	1.395	118.66	2.20
SR135	SR135-15-02	149.76	48.74	7.2	35	0.06	0.764	66.63	1.63
SR135	SR135-19-01	149.89	47.91	7.7	35	0.06	0.705	62.50	1.43
SR135	SR135-18-01	149.82	49.12	7.6	35	0.39	1.276	110.38	1.56
US31	US31-15-02	149.66	48.71	7.5	35	0.06	1.006	87.85	2.67
US31	US31-16-01	150.12	50.87	7.4	35	0.06	1.200	100.04	3.11
US31	US31-16-02	149.73	47.75	7.4	35	0.39	1.792	159.56	3.08
I74	I74-11-01	149.87	50.44	7.6	35	0.06	1.054	88.76	2.02
I74	I74-13-01	150.06	51.39	6.8	35	0.06	1.051	86.76	2.60
I74	I74-11-02	149.84	49.47	6.9	35	0.39	1.747	150.04	1.25
SR64	SR64-14-01	149.86	51.13	7.4	35	0.06	1.168	97.04	2.40
SR64	SR64-14-02	149.79	51.17	7.3	35	0.06	1.107	91.95	1.99
SR64	SR64-15-02	149.79	52.04	7.4	35	0.39	2.042	166.77	2.59
I65	I65-15-02	150.18	53.92	7.1	35	0.06	1.958	153.93	1.82
I65	I65-17-02	149.72	48.78	7.7	35	0.06	1.552	135.29	1.81
I65	I65-16-01	149.76	50.1	7.3	35	0.39	2.465	209.15	1.98

Road No.	Sample ID	Air Voids (%)	Temp. (°C)	Applied Cycles	Intercept	Slope	μ	Resilient Strain (ϵ_p 200)	Resilient Strain 10 ⁴ Cycles	ϵ_p at 10 ⁴ Cycles (%)	ϵ_p/ϵ_r at 10 ⁴ Cycles	Resilient Modulus at 10 ⁴ Cycles	ϵ_p Ratio at 10 ⁴ Cycles	Axial Flow Number	Radial Flow Number	ϵ_p at Flow (%)	ϵ_p/ϵ_r at Flow	Resilient Modulus at Flow (MPa)	Plastic Strain Ratio at Flow	Failed
SR15	SR15-05	7.9	54.4	10,000	0.066	0.39	0.44	0.059	0.061	2.45	40	1335	0.92	9887	9871	2.44	41	1382	0.60	N
	SR15-06	7.9	54.4	10,000	0.119	0.33	0.71	0.056	0.055	2.58	47	1464	1.15	9567	9871	2.54	45	1456	0.94	N
	SR15-07	7.7	54.4	10,000	0.107	0.34	0.71	0.051	0.057	2.45	43	1440	1.83	8767	9887	2.34	46	1595	0.46	N
US24	US24-18	7.4	54.4	10,000	0.094	0.37	0.79	0.044	0.038	2.86	75	2160	1.86	9375	9887	2.78	63	1873	1.84	N
	US24-19	7.1	54.4	10,000	0.160	0.33	0.69	0.076	0.083	3.31	40	987	0.71	9215	463	3.22	42	1071	0.72	N
	US24-22	7.9	54.4	10,000	0.116	0.40	0.69	0.067	0.028	4.32	154	2912	1.87	8463	9887	4.17	62	1199	1.89	N
SR161	SR161-19	8.0	54.4	10,000	0.120	0.31	0.65	0.057	0.064	2.09	33	1280	2.81	9887	9599	2.08	37	1426	0.69	N
	SR161-20	8.0	54.4	10,000	0.180	0.26	0.83	0.057	0.062	2.03	33	1310	0.68	8607	9423	1.95	34	1429	0.90	N
	SR161-21	8.0	54.4	10,000	0.161	0.30	0.73	0.066	0.059	2.52	43	1378	0.96	9839	8895	2.51	38	1230	0.48	N
SR56	SR56-06	7.6	54.4	10,000	0.175	0.24	0.95	0.045	0.045	1.66	37	1819	1.86	9871	9375	1.65	37	1823	0.96	N
	SR56-06-1	7.5	54.4	10,000	0.211	0.22	1.03	0.045	0.047	1.60	34	1736	0.61	9791	463	1.59	35	1828	0.62	N
	SR56-08	7.3	54.4	10,000	0.561	0.17	1.66	0.059	0.061	2.82	46	1327	1.86	9727	1119	2.81	48	1385	0.46	N
US30	US30-04	7.5	54.4	10,000	0.162	0.23	0.57	0.065	0.067	1.34	20	1207	0.92	9871	6399	1.34	21	1266	0.62	N
	US30-05	7.5	54.4	10,000	0.140	0.24	0.58	0.059	0.064	1.33	21	1278	0.61	9887	8751	1.33	22	1380	0.46	N
SR66	SR66-14	7.6	54.4	10,000	0.141	0.30	0.66	0.063	0.063	2.14	34	1293	1.37	9599	2255	2.12	34	1293	0.91	N
	SR66-16	7.5	54.4	10,000	0.154	0.30	0.69	0.067	0.082	2.39	29	986	0.61	9695	1983	2.37	35	1206	0.30	N
SR135	SR135-22	7.8	54.4	10,000	0.244	0.27	1.20	0.055	0.056	2.95	53	1454	0.73	9887	8095	2.94	53	1474	0.73	N
	SR135-23	7.8	54.4	10,000	0.169	0.28	0.98	0.049	0.057	2.32	41	1445	0.57	9439	9183	2.28	46	1648	0.55	N
	SR135-N1	7.5	54.4	10,000	0.024	0.39	0.21	0.043	0.041	0.82	20	1954	0.62	9887	9183	0.81	19	1883	0.61	N
US31	US31-08	7.5	54.4	10,000	0.187	0.26	0.81	0.059	0.056	1.96	35	1455	0.52	9887	3583	1.95	33	1384	0.52	N
	US31-18	7.2	54.4	12,447	0.385	0.21	1.32	0.061	0.037	2.65	72	2184	1.84	12079	12175	2.75	45	1323	0.92	N
	US31-N1	7.5	54.4	10,000	0.412	0.18	1.23	0.062	0.050	2.24	45	1637	0.84	8511	8159	2.18	35	1319	0.75	N
I74	I74-15	7.7	54.4	10,000	0.182	0.23	0.94	0.045	0.045	1.55	34	1823	0.29	9951	3727	1.54	34	1823	0.64	N
	I74-18	7.6	54.4	10,000	0.434	0.20	2.29	0.038	0.031	2.74	88	2629	0.61	9087	719	2.69	71	2146	0.92	N
	I74-19	7.3	54.4	10,000	0.095	0.31	0.56	0.052	0.055	1.61	29	1473	0.93	9631	9887	1.59	31	1560	0.62	N
SR64	SR64-19	7.2	54.4	10,000	0.241	0.30	1.44	0.051	0.038	3.89	102	2176	2.81	8383	447	3.71	73	1601	0.46	N
	SR64-21	7.1	54.4	2,099	0.047	0.61	0.74	0.039	0.037	5.00	135	2209	0.71	2099	2099	1.45	37	2099	0.20	Y
I65	I65-11	7.6	54.4	15,000	0.075	0.28	0.56	0.038	0.038	1.00	26	2160	0.61	12863	13631	1.08	28	13631	0.46	N
	I65-13	7.4	54.4	8,811	0.074	0.40	0.45	0.067	0.031	5.01	162	2646	0.88	2959	3807	1.88	28	3807	0.91	Y
	I65-14	7.9	54.4	3,623	0.082	0.40	0.64	0.051	0.040	4.28	107	2056		3623	1903	2.18	43	1903	4.18	Y

Core No.	Road No.																							
	SR15						US24						SR161						SR56					
	1st			2nd			1st			2nd			1st			2nd			1st			2nd		
		V _a (%)	Test		V _a (%)	Test		V _a (%)	Test		V _a (%)	Test		V _a (%)	Test		V _a (%)	Test		V _a (%)	Test		V _a (%)	Test
1	2.221	11.2	G*	2.278	9.4	G*	2.283	8.3	E*	2.35	4.7	G*	2.206	11.2	G*	2.224	10.6	G*	2.435	9.5	E*	2.442	8.7	G*
2	2.228	10.9	G*	2.263	10.0	G*	2.266	9.0	E*	2.35	4.8	G*	2.227	10.3	G*	2.221	10.7	G*	2.450	8.9	E*	2.471	7.6	G*
3	2.214	11.5	G*	2.273	9.6	G*	2.251	9.6	E*	2.34	5.2	G*	2.215	10.8	G*	2.218	10.8	G*	2.421	10.0	G*	2.510	6.1	G*
4	2.233	10.7	E*	2.273	9.6	E*	2.266	9.0	E*	2.346	4.9	IDT	2.113	14.9	E*	2.149	13.6	E*	2.420	10.0	E*	2.501	6.5	E*
5	2.228	10.9	E*	2.268	9.8	IDT	2.284	8.2	E*	2.337	5.3	IDT	2.135	14.0	E*	2.144	13.8	IDT	2.445	9.1	E*	2.488	7.0	IDT
6	2.235	10.6	E*	2.261	10.1	E*	2.269	8.8	E*	2.333	5.4	E*	2.183	12.1	E*	2.148	13.6	E*	2.469	8.2	E*	2.510	6.1	E*
7	2.207	11.8	E*	2.261	10.0	E*	2.250	9.6	G*	2.331	5.5	E*	2.158	13.1	E*	2.131	14.3	E*	2.452	8.8	E*	2.514	6.0	IDT
8	2.227	11.0	E*	2.270	9.7	E*	2.232	10.3	G*	2.353	4.6	E*	2.134	14.1	E*	2.132	14.3	E*	2.476	8.0	E*	2.540	5.0	IDT
9	2.224	11.1	E*	2.261	10.1	IDT	2.277	8.5	G*	2.343	5.0	E*			G*	2.134	14.2	E*	2.408	10.5	E*	2.556	4.4	E*
10	2.215	11.4	E*	2.256	10.2	IDT			G*	2.343	5.0	E*	2.132	14.1	E*	2.148	13.6	E*	2.438	9.4	E*	2.568	4.0	E*
11	2.214	11.5	E*	2.263	10.0	E*			G*	2.340	5.1	IDT	2.153	13.3	E*	2.145	13.8	E*	2.396	9.9	G*	2.532	5.3	E*
12	2.210	11.6	E*	2.261	10.0	E*	2.283	8.3	E*	2.350	4.7	E*	2.163	12.9	E*	2.153	13.4	IDT	2.425	8.8	G*	2.549	4.7	E*
13	2.210	11.6	IDT	2.273	9.6	E*	2.257	9.3	IDT	2.359	4.4	E*	2.169	12.6	IDT	2.177	12.5	E*	2.413	10.3	IDT	2.593	3.0	E*
14	2.218	11.3	IDT	2.267	9.8	E*	2.251	9.6	IDT	2.342	5.0	E*	2.169	12.6	IDT	2.199	11.6	E*	2.405	10.6	IDT	2.592	3.1	E*
15	2.215	11.4	IDT	2.273	9.6	E*	2.268	8.9	IDT	2.350	4.8	E*	2.184	12.0	IDT	2.193	11.8	IDT	2.448	9.0	IDT	2.599	2.8	E*
Ave.	2.220	11.2		2.267	9.8		2.264	9.0		2.344	5.0		2.167	12.7		2.168	12.8		2.433	9.4		2.531	5.3	
Coring Location	Center			Center			Center			Wheel Path			Center			Center			Center			Wheel Path		

Core No.	Road No.																							
	US30						SR66						SR135						US31					
	1st			2nd			1st			2nd			1st			2nd			1st			2nd		
		V _a (%)	Test		V _a (%)	Test		V _a (%)	Test		V _a (%)	Test		V _a (%)	Test		V _a (%)	Test		V _a (%)	Test		V _a (%)	Test
1	2.313	6.7	G*	2.384	3.4	G*	2.120	13.5	G*	2.265	7.9	G*	2.243	8.7	G*	2.348	3.3	G*	2.777	7.8	G*	2.724	9.3	G*
2	2.317	6.5	G*	2.387	3.3	G*	2.143	12.5	G*	2.244	8.7	G*	2.251	8.4	G*	2.341	3.6	G*	2.777	7.8	G*	2.721	9.4	G*
3	2.324	6.3	G*	2.370	4.0	G*	2.160	11.8	G*	2.238	9.0	G*	2.249	8.5	G*	2.339	3.7	G*	2.737	9.2	G*	2.738	8.9	G*
4	2.289	7.7	E*	2.370	4.0	E*	2.179	11.1	E*	2.228	9.4	E*	2.290	6.8	E*	2.318	4.5	E*	2.788	7.5	E*	2.795	7.0	E*
5	2.304	7.1	E*	2.349	4.8	E*	2.153	12.1	E*	2.226	9.4	E*	2.290	6.8	E*	2.318	4.5	E*	2.760	8.4	E*	2.802	6.7	E*
6	2.285	7.8	E*	2.365	4.2	E*	2.162	11.8	E*	2.230	9.3	IDT	2.293	6.7	E*	2.310	4.9	E*	2.789	7.4	E*	2.804	6.7	IDT
7	2.297	7.3	E*	2.359	4.4	IDT	2.178	11.1	E*	2.249	8.5	E*	2.268	7.7	E*	2.317	4.6	E*	2.772	8.0	E*	2.800	6.8	E*
8	2.296	7.4	E*	2.359	4.4	IDT	2.180	11.0	E*	2.261	8.0	IDT	2.276	7.4	E*	2.318	4.5	IDT	2.760	8.4	E*	2.828	5.9	E*
9	2.292	7.5	E*	2.366	4.2	E*	2.169	11.5	E*	2.279	7.3	E*	2.297	6.6	E*	2.325	4.2	E*	2.756	8.5	E*	2.826	5.9	E*
10	2.300	7.2	E*	2.356	4.6	E*	2.167	11.6	E*	2.293	6.7	E*	2.289	6.9	E*	2.331	4.0	E*	2.750	8.7	E*	2.802	6.7	IDT
11	2.294	7.5	E*	2.360	4.4	E*	2.154	12.1	E*	2.284	7.1	IDT	2.303	6.3	E*	2.334	3.9	E*	2.765	8.2	E*	2.780	7.5	E*
12	2.302	7.1	E*	2.354	4.6	IDT	2.188	10.7	E*	2.291	6.8	E*	2.265	7.9	E*	2.332	4.0	E*	2.772	8.0	E*	2.811	6.4	IDT
13	2.269	8.5	IDT	2.348	4.9	E*	2.109	13.9	IDT	2.277	7.4	E*	2.282	7.2	IDT	2.333	3.9	E*	2.773	8.0	IDT	2.789	7.1	E*
14	2.307	6.9	IDT				2.162	11.8	IDT	2.288	6.9	E*	2.266	7.8	IDT	2.316	4.6	IDT	2.758	8.5	IDT	2.803	6.7	E*
15	2.312	6.7	IDT	2.356	4.6	E*	2.161	11.8	IDT	2.265	7.9	E*	2.300	6.4	IDT	2.303	5.2	IDT	2.757	8.5	IDT	2.826	5.9	E*
Ave.	2.300	7.2		2.363	4.3		2.159	11.9		2.261	8.0		2.277	7.3		2.325	4.2		2.766	8.2		2.790	7.1	
Coring Location	Center			Center			Center			Wheel Path			Center			Wheel Path			Center			Center		

[illegible]

Road No.	Specimen ID	Top			Middle			Bottom			Averaged Area (mm ²)	Converted Diameter (mm)
		Width (mm)	Length (mm)	Area (mm) ²	Width (mm)	Length (mm)	Area (mm) ²	Width (mm)	Length (mm)	Area (mm) ²		
SR15	SR15C-01	76.39	74.89	5674.3	76.17	74.12	5660.5	76.08	73.82	5624.5	5653.1	84.84
		76.36	73.70		76.92	73.78		77.02	73.13			
	SR15C-02	79.41	69.25	5524.7	78.46	67.64	5406.2	78.10	67.04	5358.9	5429.9	83.15
		78.28	70.89		78.22	70.38		78.49	69.85			
	SR15C-03	78.36	69.20	5344.5	77.39	67.62	5146.5	76.82	66.29	5003.4	5164.8	81.09
		77.58	67.89		76.65	66.02		76.33	64.39			
US24	US24C-01	76.32	82.82	6415.1	76.53	82.66	6336.9	77.36	82.09	6326.2	6359.4	89.98
		77.75	83.73		76.85	82.60		76.75	82.11			
	US24C-02	77.35	82.56	6371.6	76.99	81.44	6319.7	77.27	83.05	6365.5	6352.3	89.93
		76.60	82.99		76.83	82.90		77.41	81.56			
	US24C-03	76.40	87.55	6731.6	76.17	87.26	6639.2	76.48	87.82	6670.4	6680.4	92.23
		77.87	86.99		76.21	87.02		75.89	87.29			
SR161	SR161C-01	75.75	83.72	6389.9	76.05	83.93	6348.9	76.18	83.75	6357.1	6365.3	90.03
		76.60	84.05		76.01	83.08		76.26	83.06			
	SR161C-02	74.00	87.26	6469.1	74.20	83.08	6336.8	74.44	86.68	6423.0	6409.6	90.34
		74.11	87.45		74.91	86.91		74.00	86.40			
SR56	SR56C-01	74.72	74.89	5530.8	74.52	73.73	5466.0	74.93	73.20	5453.8	5483.5	83.56
		73.32	74.55		73.67	73.81		74.56	72.73			
	SR56C-02	75.43	77.58	5813.1	75.10	77.56	5832.0	74.93	77.57	5874.6	5839.9	86.23
		74.43	77.58		75.22	77.63		75.43	78.71			
	SR56C-03	74.96	79.48	5956.1	73.66	79.54	5912.6	73.09	80.32	5988.5	5952.4	87.06
		75.22	79.16		75.01	79.54		75.73	80.64			
US30	US30C-01	76.39	74.89	5674.3	76.17	74.12	5660.5	76.08	73.82	5624.5	5653.1	84.84
		76.36	73.70		76.92	73.78		77.02	73.13			
	US30C-02	79.41	69.25	5524.7	78.46	67.64	5406.2	78.10	67.04	5358.9	5429.9	83.15
		78.28	70.89		78.22	70.38		78.49	69.85			
	US30C-03	78.36	69.20	5344.5	77.39	67.62	5146.5	76.82	66.29	5003.4	5164.8	81.09
		77.58	67.89		76.65	66.02		76.33	64.39			
SR66	SR66C-01	76.60	76.87	5957.1	77.70	76.53	5973.3	76.27	77.60	5963.6	5964.7	87.15
		77.98	77.28		77.12	77.80		77.68	77.35			
	SR66C-02	72.48	77.27	5576.5	76.40	71.77	5481.9	70.48	76.70	5474.2	5510.8	83.77
		72.58	76.50		77.09	71.09		71.31	77.73			
	SR66C-03	69.89	73.31	5172.2	74.57	70.45	5218.3	70.62	73.95	5247.9	5212.8	81.47
		69.40	75.22		73.95	70.09		70.89	74.39			

Road No.	Specimen ID	Top			Middle			Bottom			Averaged Area (mm ²)	Converted Diameter (mm)
		Width (mm)	Length (mm)	Area (mm) ²	Width (mm)	Length (mm)	Area (mm) ²	Width (mm)	Length (mm)	Area (mm) ²		
SR135	SR135C-01	76.43	78.45	5970.2	77.08	79.47	6073.4	78.10	80.19	6198.0	6080.5	87.99
		75.55	78.68		75.70	79.54		75.84	80.86			
	SR135C-02	75.64	76.06	5761.9	76.60	75.76	5750.3	78.08	75.47	5822.9	5778.4	85.77
		78.70	73.27		77.47	73.53		77.28	74.45			
	SR135C-03	77.53	72.46	5700.4	77.34	71.75	5627.9	78.05	72.24	5645.1	5657.8	84.87
		78.09	74.06		78.19	72.99		77.59	72.84			
	SR135C-04	78.27	85.94	6663.1	77.92	84.95	6527.1	79.06	84.56	6566.9	6585.7	91.57
		78.98	83.55		78.24	82.24		79.16	81.46			
US31	US31C-01	76.50	73.77	5672.2	76.95	73.48	5684.7	78.32	72.88	5734.2	5697.0	85.17
		76.06	74.95		76.65	74.56		77.85	73.99			
	US31C-02	78.06	74.57	5811.1	76.95	73.48	5684.7	78.32	72.88	5734.2	5743.3	85.51
		76.83	75.50		76.65	74.56		77.85	73.99			
	US31C-03	76.61	74.32	5699.0	78.42	74.07	5796.4	78.83	74.33	5836.2	5777.2	85.77
		76.67	74.40		76.98	75.13		77.72	74.79			
I74	I74C-01	75.46	75.72	5720.3	76.62	74.72	5629.0	73.01	78.43	5662.0	5670.4	84.97
		74.07	77.30		75.32	73.47		74.40	75.21			
	I74C-02	83.61	74.38	6343.8	74.16	85.54	6280.4	84.21	73.48	6233.0	6285.7	89.46
		87.37	74.03		73.91	84.12		85.65	73.30			
SR64	SR64C-01	77.84	89.95	6825.0	78.20	89.30	6847.8	78.32	88.49	6779.5	6817.4	93.17
		77.08	86.27		77.68	86.42		77.20	85.88			
	SR64C-02	74.73	67.51	5013.6	74.79	67.45	5013.2	74.19	67.59	4942.7	4989.9	79.71
		74.74	66.66		74.07	67.26		71.57	68.05			
	SR64C-03	78.67	65.51	5129.0	77.94	65.40	5097.2	77.90	65.36	5112.2	5112.8	80.68
		75.18	67.84		75.21	67.73		76.06	67.46			
I65	I65C-01	78.82	66.57	5287.5	79.62	66.83	5376.9	79.36	67.26	5312.1	5325.5	82.34
		81.25	65.56		80.18	67.76		79.97	66.10			
	I65C-02	78.41	65.75	5283.9	78.71	65.19	5260.2	79.58	65.19	5263.0	5269.0	81.91
		79.78	67.86		79.61	67.71		78.98	67.58			
	I65C-03	79.20	63.01	5118.0	77.71	64.06	5110.9	76.78	63.80	5086.8	5105.2	80.62
		78.35	66.93		77.86	67.35		77.87	67.77			

Road No.	Specimen ID	Top			Middle			Bottom			Averaged Area (mm ²)	Converted Diameter (mm)
		Width (mm)	Length (mm)	Area (mm) ²	Width (mm)	Length (mm)	Area (mm) ²	Width (mm)	Length (mm)	Area (mm) ²		
SR15	SR15C-2-01	91.40	76.98	7063.0	91.75	76.84	7058.7	91.53	76.52	7032.4	7051.4	94.75
		92.28	76.83		92.19	76.66		92.24	76.55			
	SR15C-2-02	92.56	76.47	7087.5	92.65	76.84	7118.0	92.65	76.84	7118.0	7107.9	95.13
		92.59	76.65		92.39	77.03		92.39	77.03			
	SR15C-2-03	83.36	76.95	6449.7	83.37	76.97	6438.8	83.26	77.19	6465.3	6451.3	90.63
		84.23	76.99		83.84	77.06		84.05	77.38			
US24	US24C-2-01	76.19	89.77	6841.9	89.48	76.36	6815.6	75.82	89.35	6760.4	6806.0	93.09
		76.71	89.22		89.15	76.26		75.98	88.79			
	US24C-2-02	76.10	90.83	6967.1	76.46	91.37	6991.5	91.16	75.94	6989.3	6982.6	94.29
		76.83	91.40		76.41	91.57		91.46	77.15			
	US24C-2-03	93.23	76.67	7145.4	93.55	76.45	7128.8	93.21	75.89	7067.4	7113.9	95.17
		92.97	76.83		93.03	76.38		92.80	76.09			
SR161	SR161C-2-01	77.60	85.81	6768.5	77.33	87.04	6817.4	76.95	87.85	6854.3	6813.4	93.14
		77.33	88.94		77.19	89.44		76.95	90.30			
	SR161C-2-02	77.55	84.25	6471.3	77.12	84.30	6458.4	76.93	84.61	6457.9	6462.5	90.71
		77.48	82.72		77.35	82.94		77.04	83.16			
	SR161C-2-03	77.58	84.99	6604.3	77.16	85.85	6653.5	76.91	86.49	6712.4	6656.7	92.06
		76.59	86.36		76.90	86.90		77.08	87.87			
SR56	SR56C-2-01	89.70	76.51	6870.5	89.34	76.11	6816.0	88.72	75.80	6739.1	6808.5	93.11
		89.71	76.67		89.51	76.33		89.01	75.87			
	SR56C-2-02	95.81	77.02	7361.7	96.22	76.69	7347.9	96.22	76.69	7347.9	7352.5	96.75
		95.44	76.95		95.87	76.32		95.87	76.32			
	SR56C-2-03	96.36	76.36	7359.8	96.10	76.12	7329.4	95.47	75.83	7299.8	7329.7	96.60
		96.76	76.08		96.16	76.37		96.10	76.59			
US30	US30C-2-01	76.22	76.43	5793.5	76.25	76.15	5800.3	75.33	76.71	5769.0	5787.6	85.84
		76.14	75.67		76.44	75.80		75.78	76.00			
	US30C-2-02	76.67	72.42	5614.6	74.19	76.45	5619.2	75.83	72.57	5592.4	5608.7	84.51
		76.42	74.28		72.91	76.35		76.51	74.27			
	US30C-2-03	78.55	76.03	5965.6	77.49	76.09	5907.1	75.73	77.23	5896.5	5923.1	86.84
		78.12	76.28		77.95	75.92		76.38	77.83			
SR66	SR66C-2-01	70.56	76.95	5455.9	70.92	76.67	5436.7	71.51	76.44	5470.4	5454.3	83.33
		71.07	77.14		71.03	76.53		71.60	76.46			
	SR66C-2-02	96.79	76.15	7394.8	97.16	76.63	7424.8	97.78	76.46	7461.8	7427.1	97.24
		95.97	77.30		96.75	76.53		97.35	76.50			
	SR66C-2-03	100.23	77.07	7689.6	100.77	76.83	7693.5	101.23	76.69	7708.5	7697.2	99.00
		99.46	76.96		100.04	76.42		100.47	76.18			

Road No.	Specimen ID	Top			Middle			Bottom			Averaged Area (mm ²)	Converted Diameter (mm)
		Width (mm)	Length (mm)	Area (mm) ²	Width (mm)	Length (mm)	Area (mm) ²	Width (mm)	Length (mm)	Area (mm) ²		
SR135	SR135C-2-01	77.05	79.64	6174.8	76.50	81.58	6183.5	76.51	81.88	6207.0	6188.4	88.77
		75.99	81.75		76.33	80.26		76.75	80.12			
	SR135C-2-02	76.86	83.62	6327.5	81.82	76.58	6314.0	76.83	81.03	6287.0	6309.5	89.63
		76.33	81.60		83.23	76.44		76.39	83.10			
	SR135C-2-03	78.95	76.93	6053.8	78.40	76.43	6009.6	77.34	77.88	6016.9	6026.8	87.60
		79.04	76.34		78.60	76.68		76.91	78.15			
US31	US31C-2-01	69.21	76.36	5291.8	68.82	75.81	5226.8	68.92	75.38	5214.3	5244.3	81.71
		68.84	76.97		68.81	76.10		69.07	75.77			
	US31C-2-02	76.03	71.01	5315.5	75.63	70.13	5250.5	69.22	75.91	5236.9	5267.6	81.90
		75.83	69.00		76.48	67.94		67.29	77.54			
	US31C-2-03	76.00	69.95	5396.6	76.49	70.77	5439.7	77.01	72.08	5493.4	5443.2	83.25
		76.49	71.61		76.01	71.91		76.90	70.69			
I74	I74C-2-01	77.59	88.05	6827.0	87.78	77.88	6852.7	78.31	88.88	6937.6	6872.4	93.54
		77.86	87.62		88.45	77.66		77.96	88.70			
	I74C-2-02	77.79	89.99	6971.2	89.29	77.61	6941.3	77.93	90.12	7024.9	6979.1	94.27
		77.47	89.61		89.77	77.45		77.79	90.33			
	I74C-2-03	76.88	86.15	6582.4	84.90	77.38	6626.4	78.08	86.92	6704.5	6637.8	91.93
		77.60	84.29		86.27	77.47		77.83	85.09			
SR64	SR64C-2-01	77.05	84.52	6623.2	77.87	84.43	6603.6	78.32	84.57	6604.9	6610.6	91.74
		79.01	85.24		78.05	84.98		77.65	84.82			
	SR64C-2-02	76.48	86.63	6719.7	76.00	87.02	6625.1	76.66	85.66	6607.3	6650.7	92.02
		78.13	87.22		76.89	86.31		77.07	86.26			
	SR64C-2-03	83.04	77.07	6410.2	77.02	83.36	6390.6	83.50	77.24	6443.6	6414.8	90.37
		83.62	76.78		76.86	82.76		83.52	77.08			
I65	I65C-2-01	76.94	74.80	5703.5	76.37	73.54	5592.8	76.39	73.04	5539.6	5612.0	84.53
		76.95	73.45		76.45	72.85		76.32	72.06			
	I65C-2-02	76.30	73.91	5662.4	76.40	73.50	5618.9	76.05	73.30	5558.5	5613.3	84.54
		76.84	73.99		76.33	73.66		75.74	73.18			
	I65C-2-03	70.22	77.37	5436.5	70.13	77.21	5460.9	69.65	76.02	5379.0	5425.5	83.11
		71.79	75.76		71.38	77.15		71.31	76.62			

Road No.	Composite Specimen ID	Core No.	V _a (%)	Average V _a (%)	Converted Diameter (mm)	Road No.	Composite Specimen ID	Core No.	V _a (%)	Average V _a (%)	Converted Diameter (mm)
SR15	SR15C-1-01	6	10.6	11.0	84.84	US24	US24C-1-01	2	9.0	9.0	89.98
		10	11.4					4	9.0		
	SR15C-1-02	8	11.0	11.1	83.15		US24C-1-02	1	8.3	8.3	89.93
		9	11.1					5	8.2		
	SR15C-1-03	5	10.9	11.2	81.09		US24C-1-03	3	9.6	9.0	92.23
		11	11.5					12	8.3		
SR161	SR161C-1-01	4	14.9	14.4	90.03	SR56	SR56C-1-01	7	8.8	8.4	83.56
		8	14.1					8	8.0		
		10	14.1				SR56C-1-02	6	8.2	8.8	86.23
	SR161C-1-02	7	13.1	10	9.4						
		11	13.3	SR56C-1-03	2		8.9	9.0	87.06		
		12	12.9		5		9.1				
US30	US30C-1-01	8	7.4	7.5		SR66	SR66C-1-01	4	11.1	11.6	87.15
		9	7.5					5	12.1		
		11	7.5								
	US30C-1-02	4	7.7	7.5			SR66C-1-02	8	11.0	11.3	83.77
		5	7.1					10	11.6		
		6	7.8								
	US30C-1-03	7	7.3	7.2			SR66C-1-03	6	11.8	11.5	81.47
		10	7.2					7	11.1		
		12	7.1								
SR135	SR135C-1-01	10	6.9	6.6	87.99	US31	US31C-1-01	7	8.0	8.1	85.17
		11	6.3					11	8.2		
	SR135C-1-02	4	6.8	7.3	85.77		US31C-1-02	5	8.4	8.5	85.51
		7	7.7					9	8.5		
	SR135C-1-03	6	6.7	7.1	84.87		US31C-1-03			8.4	85.77
		8	7.4					10	8.7		
	SR135C-1-04	5	6.8	7.1	91.57			12	8.0		
		9	6.6								
		12	7.9								

Road No.	Composite Specimen ID	Core No.	V _a (%)	Average V _a (%)	Converted Diameter (mm)		Road No.	Composite Specimen ID	Core No.	V _a (%)	Average V _a (%)	Converted Diameter (mm)	
I74	I74C-1-01	7	8.9	8.1	84.97		SR64	SR64C-1-01	7	3.9	4.3	93.17	
		9	7.2						10	3.5			
									11	5.6			
	I74C-1-02	5	7.9	7.7	89.46			SR64C-1-02	5	4.3	4.2	79.71	
		11	6.3						12	3.5			
		12	8.9						16	4.8			
								SR64C-1-03	4	5.5	5.5	80.68	
									6	5.0			
									8	6.1			
I65	I65C-1-01	2	8.8	7.5	82.34								
		9	6.7										
		11	7.1										
	I65C-1-02	5	7.1	7.4	81.91								
		6	7.8										
		12	7.2										
	I65C-1-03	7	7.6	7.4	80.62								
		8	7.1										
		10	7.4										

Road No.	Composite Specimen ID	Core No.	V _a (%)	Average V _a (%)	Converted Diameter (mm)	Road No.	Composite Specimen ID	Core No.	V _a (%)	Average V _a (%)	Converted Diameter (mm)
SR15	SR15C-2-01	7	10.0	9.9	94.75	US24	US24C-2-01	6	5.4	5.2	93.09
		11	10.0					9	5.0		
		13	9.6								
	SR15C-2-02	4	9.6	9.8	95.13		US24C-2-02	7	5.5	5.2	94.29
		6	10.1					15	4.8		
		8	9.7								
	SR15C-2-03	12	10.0	9.7	90.63		US24C-2-03	10	5.0	5.0	95.17
		14	9.8					14	5.0		
		15	9.6								
SR161	SR161C-2-01	8	14.3	12.8	93.14	SR56	SR56C-2-01	4	6.5	4.8	93.11
		13	12.5					14	3.1		
		14	11.6								
	SR161C-2-02	6	13.6	14.0	90.71		SR56C-2-02	11	5.3	4.1	96.75
		7	14.3					15	2.8		
		9	14.2								
	SR161C-2-03	4	13.6	13.7	92.06		SR56C-2-03	6	6.1	4.6	96.6
		10	13.6					13	3.0		
		11	13.8								
US30	US30C-2-01	10	4.6	4.6	85.84	SR66	SR66C-2-01	14	6.9	7.4	83.33
		15	4.6					15	7.9		
	US30C-2-02	5	4.8	4.6	84.51		SR66C-2-02	4	9.4	9.4	97.24
		11	4.4					5	9.4		
US30C-2-03	6	4.2	4.2	86.84	SR66C-2-03	9	7.3	7.1	99.00		
	9	4.2				12	6.8				
SR135	SR135C-2-01	9	4.2	4.1	88.77	US31	US31C-2-01	13	7.1	6.9	81.71
		10	4.0					14	6.7		
	SR135C-2-02	12	4.0	4.0	89.63		US31C-2-02	7	6.8	6.4	81.90
		13	3.9					9	5.9		
	SR135C-2-03	4	4.5	4.7	87.60		US31C-2-03	8	5.9	5.9	83.25
		6	4.9					15	5.9		

Road No.	Composite Specimen ID	Core No.	V _a (%)	Average V _a (%)	Converted Diameter (mm)		Road No.	Composite Specimen ID	Core No.	V _a (%)	Average V _a (%)	Converted Diameter (mm)								
I74	I74C-2-01	4	5.7	5.7	93.54		SR64	SR64C-2-01	6	3.6	2.5	91.74								
		7	5.7						11	2.1										
									13	1.9										
	I74C-2-02	5	4.0	4.1	94.27			SR64C-2-02	7	3.4	3.7	92.02								
		8	4.2						9	3.9										
									15	3.8										
	I74C-2-03	9	1.5	2.6	91.93			SR64C-2-03	10	3.5	2.9	90.37								
		10	3.6						12	2.5										
									14	2.7										
I65	I65C-2-01	4	10.6	10.6	84.53															
		10	10.6																	
	I65C-2-02	5	9.7	10.2	84.54															
		14	10.7																	
	I65C-2-03	9	11.2	10.7	83.11															
		13	10.1																	

Road No.	Test Method	Specimen ID	V _a (%)	Average V _a (%)	Standard Deviation (%)	Coefficient of Variation (%)
SR15	Unconfined Dynamic Modulus	SR15C-1-01	11.0	11.1	0.1	0.9
		SR15C-1-02	11.1			
		SR15C-1-03	11.2			
US24	Unconfined Dynamic Modulus	US24C-1-01	9.0	8.7	0.4	4.8
		US24C-1-02	8.3			
		US24C-1-03	9.0			
SR161	Unconfined Dynamic Modulus	SR161C-1-01	14.4	13.7	0.9	6.5
		SR161C-1-02	13.1			
SR56	Unconfined Dynamic Modulus	SR56C-1-01	8.4	8.7	0.3	3.5
		SR56C-1-02	8.8			
		SR56C-1-03	9.0			
US30	Unconfined Dynamic Modulus	US30C-1-01	7.5	7.4	0.2	2.4
		US30C-1-02	7.5			
		US30C-1-03	7.2			
SR66	Unconfined Dynamic Modulus	SR66C-1-01	11.6	11.5	0.2	1.3
		SR66C-1-02	11.3			
		SR66C-1-03	11.5			
SR135	Unconfined Dynamic Modulus	SR135C-1-01	6.6	7.0	0.3	4.0
		SR135C-1-02	7.3			
		SR135C-1-03	7.1			
		SR135C-1-04	7.1			
US31	Unconfined Dynamic Modulus	US31C-1-01	8.1	8.3	0.2	2.2
		US31C-1-02	8.5			
		US31C-1-03	8.4			
I74	Unconfined Dynamic Modulus	I74C-1-01	8.1	7.9	0.2	3.1
		I74C-1-02	7.7			
SR64	Unconfined Dynamic Modulus	SR64C-1-01	4.3	4.7	0.7	15.7
		SR64C-1-02	4.2			
		SR64C-1-03	5.5			
I65	Unconfined Dynamic Modulus	I65C-1-01	7.5	7.4	0.1	1.1
		I65C-1-02	7.4			
		I65C-1-03	7.4			

Road No.	Test Method	Specimen ID	V _a (%)	Average V _a (%)	Standard Deviation (%)	Coefficient of Variation (%)
SR15	Unconfined Dynamic Modulus	SR15C-2-01	9.9	9.8	0.1	1.0
		SR15C-2-02	9.8			
		SR15C-2-03	9.7			
US24	Unconfined Dynamic Modulus	US24C-2-01	5.2	5.1	0.1	2.2
		US24C-2-02	5.2			
		US24C-2-03	5.0			
SR161	Unconfined Dynamic Modulus	SR161C-2-01	12.8	13.5	0.6	4.6
		SR161C-2-02	14.0			
		SR161C-2-03	13.7			
SR56	Unconfined Dynamic Modulus	SR56C-2-01	4.8	4.5	0.4	8.0
		SR56C-2-02	4.1			
		SR56C-2-03	4.6			
US30	Unconfined Dynamic Modulus	US30C-2-01	4.6	4.5	0.2	5.2
		US30C-2-02	4.6			
		US30C-2-03	4.2			
SR66	Unconfined Dynamic Modulus	SR66C-2-01	7.4	8.0	1.3	15.7
		SR66C-2-02	9.4			
		SR66C-2-03	7.1			
SR135	Unconfined Dynamic Modulus	SR135C-2-01	4.1	4.3	0.4	8.9
		SR135C-2-02	4.0			
		SR135C-2-03	4.7			
US31	Unconfined Dynamic Modulus	US31C-2-01	6.9	6.4	0.5	7.8
		US31C-2-02	6.4			
		US31C-2-03	5.9			
I74	Unconfined Dynamic Modulus	I74C-2-01	5.7	4.1	1.6	37.5
		I74C-2-02	4.1			
		I74C-2-03	2.6			
SR64	Unconfined Dynamic Modulus	SR64C-2-01	2.5	3.0	0.6	20.1
		SR64C-2-02	3.7			
		SR64C-2-03	2.9			
I65	Unconfined Dynamic Modulus	I65C-2-01	10.6	10.5	0.3	2.5
		I65C-2-02	10.2			
		I65C-2-03	10.7			

1st Set of Cores

Road No.	Measured G_{mm}					JFM G_{mm}	Difference
	Sample 1	Sample 2	Average	StDev.	CV%		
SR15	2.501	2.501	2.501	0.000	0.00	2.488	0.013
US24	2.490	2.488	2.489	0.001	0.06	2.417	0.072
SR161	2.483	2.483	2.483	0.000	0.00	2.457	0.026
SR56	2.688	2.692	2.690	0.003	0.11	2.659	0.031
US30	2.481	2.476	2.479	0.004	0.14	2.455	0.023
SR66	2.445	2.455	2.450	0.007	0.29	2.457	0.007
SR135	2.448	2.468	2.458	0.014	0.58	2.431	0.027
US31	3.007	3.018	3.013	0.008	0.26	2.980	0.033
I74	3.175	3.167	3.171	0.006	0.18	3.154	0.017
SR64	2.971	2.972	2.972	0.001	0.02	2.966	0.005
I65	2.938	2.948	2.943	0.007	0.24	3.017	0.074

2nd Set of Cores

Road No.	Measured G_{mm}					JFM G_{mm}	Difference
	Sample 1	Sample 2	Average	StDev.	CV%		
SR15	2.513	2.514	2.514	0.001	0.03	2.488	0.025
US24	2.468	2.466	2.467	0.001	0.06	2.417	0.050
SR161	2.484	2.490	2.487	0.004	0.17	2.457	0.030
SR56	2.679	2.669	2.674	0.007	0.26	2.659	0.015
US30	2.470	2.467	2.469	0.002	0.09	2.455	0.014
SR66	2.459	2.457	2.458	0.001	0.06	2.457	0.001
SR135	2.426	2.430	2.428	0.003	0.12	2.431	0.003
US31	3.001	3.007	3.004	0.004	0.14	2.980	0.024
I74	3.117	3.096	3.107	0.015	0.48	3.154	0.047
SR64	2.931	2.918	2.925	0.009	0.31	2.966	0.042
I65	3.055	3.044	3.050	0.008	0.26	3.017	0.033

Mix	Sample ID	Temp. (°C)	Va (%)	Dynamic (Complex) Modulus E* (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
SR15 (Mix 1)	SR15C-01	40	11.0	1114.0	802.0	676.0	497.0	498.0	485.0	33.39	31.13	28.13	21.78	19.75	26.87
	SR15C-02	40	11.1	1091.0	808.0	669.0	505.0	468.0	416.0	32.13	30.20	27.97	22.85	22.66	27.83
	SR15C-03	40	11.2	1246.0	919.0	738.0	576.0	530.0	612.0	39.11	35.85	33.20	26.47	25.69	30.70
	Average	40	11.1	1150.3	843.0	694.3	526.0	498.7	504.3	34.88	32.39	29.77	23.70	22.70	28.47
	STDV	40	0.1	83.6	65.9	38.0	43.5	31.0	99.4	3.7	3.0	3.0	2.5	3.0	2.0
	CV, (%)	40	0.9	7.3	7.8	5.5	8.3	6.2	19.7	10.7	9.4	10.0	10.4	13.1	7.0
US24 (Mix 2)	US24C-01	40	9.0	2759.0	1833.0	1377.0	839.0	719.0	551.0	32.42	32.25	31.59	25.05	22.26	17.34
	US24C-02	40	8.3	2655.0	1766.0	1284.0	769.0	657.0	546.0	40.62	40.23	38.00	32.69	30.55	28.39
	US24C-03	40	9.0	4946.0	2367.0	1653.0	1039.0	923.0	749.0	37.94	34.09	30.74	25.31	23.43	22.79
	Average	40	8.7	3453.3	1988.7	1438.0	882.3	766.3	615.3	36.99	35.52	33.44	27.68	25.41	22.84
	STDV	40	0.4	1293.7	329.4	191.9	140.1	139.2	115.8	4.2	4.2	4.0	4.3	4.5	5.5
	CV, (%)	40	4.8	37.5	16.6	13.3	15.9	18.2	18.8	11.3	11.8	11.9	15.7	17.7	24.2
SR161 (Mix 4)	SR161C-01	40	14.4	2632.0	1942.0	1554.0	957.0	850.0	668.0	35.15	34.66	33.81	31.04	29.73	27.48
	SR161C-02	40	13.1	3517.0	2153.0	1659.0	1007.0	850.0	704.0	30.62	31.03	30.50	27.94	25.58	24.76
	Average	40	13.8	3074.5	2047.5	1606.5	982.0	850.0	686.0	32.89	32.85	32.16	29.49	27.66	26.12
	STDV	40	0.9	625.8	149.2	74.2	35.4	0.0	25.5	3.2	2.6	2.3	2.2	2.9	1.9
	CV, (%)	40	6.7	20.4	7.3	4.6	3.6	0.0	3.7	9.7	7.8	7.3	7.4	10.6	7.4
SR56 (Mix 5)	SR56C-01	40	8.4	3685.0	2448.0	1766.0	1044.0	867.0	580.0	35.70	36.33	36.07	33.97	33.04	33.86
	SR56C-02	40	8.8	4715.0	2748.0	1907.0	1037.0	815.0	599.0	42.14	40.36	38.63	34.65	34.21	35.17
	SR56C-03	40	9.0	4598.0	3408.0	2730.0	1831.0	1606.0	1251.0	22.61	21.77	22.30	25.98	25.28	23.46
	Average	40	8.7	4332.7	2868.0	2134.3	1304.0	1096.0	810.0	33.48	32.82	32.33	31.53	30.84	30.83
	STDV	40	0.3	563.9	491.1	520.7	456.4	442.4	382.0	10.0	9.8	8.8	4.8	4.9	6.4
	CV, (%)	40	3.6	13.0	17.1	24.4	35.0	40.4	47.2	29.7	29.8	27.2	15.3	15.7	20.8
US30 (Mix 9)	US30C-01	40	7.5	3332.0	2292.0	1827.0	1174.0	1015.0	863.0	35.42	33.56	32.07	28.70	26.50	22.07
	US30C-02	40	7.5	1631.0	1219.0	1036.0	691.0	621.0	513.0	33.28	32.80	31.27	27.86	25.80	23.23
	US30C-03	40	7.2	2704.0	1887.0	1567.0	1074.0	972.0	831.0	34.56	32.64	29.99	26.56	24.34	22.07
	Average	40	7.4	2555.7	1799.3	1476.7	979.7	869.3	735.7	34.42	33.00	31.11	27.71	25.55	22.46
	STDV	40	0.1	860.1	541.8	403.2	254.9	216.1	193.5	1.1	0.5	1.0	1.1	1.1	0.7
	CV, (%)	40	2.0	33.7	30.1	27.3	26.0	24.9	26.3	3.1	1.5	3.4	3.9	4.3	3.0
SR66 (Mix 11)	SR66C-01	40	11.6	2930.0	2000.0	1671.0	1124.0	975.0	744.0	33.97	31.19	29.01	24.99	24.47	29.73
	SR66C-02	40	11.3	2997.0	2069.0	1664.0	937.0	798.0	435.0	34.83	34.70	34.04	34.94	36.77	52.42
	SR66C-03	40	11.5	1476.0	1106.0	1299.0	619.0	600.0	444.0	36.53	30.92	36.31	30.02	30.03	42.21
	Average	40	11.5	2467.7	1725.0	1544.7	893.3	791.0	541.0	35.11	32.27	33.12	29.98	30.42	41.45
	STDV	40	0.2	859.5	537.2	212.8	255.3	187.6	175.9	1.3	2.1	3.7	5.0	6.2	11.4
	CV, (%)	40	1.4	34.8	31.1	13.8	28.6	23.7	32.5	3.7	6.5	11.3	16.6	20.2	27.4

Mix	Sample ID	Temp. (°C)	Va (%)	Dynamic (Complex) Modulus E* (MPa)						Phase Angle φ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
SR135 (Mix 12)	SR135C-01	40	6.6	8241.0	4789.0	3486.0	2214.0	1875.0	1502.0	33.63	33.19	31.42	26.42	24.32	20.20
	SR135C-02	40	7.3	5678.0	3079.0	2247.0	1470.0	1291.0	1147.0	37.63	33.21	30.57	24.69	22.30	18.55
	SR135C-03	40	7.1	3066.0	2187.0	1631.0	1059.0	926.0	770.0	30.64	30.37	29.33	24.72	22.49	18.09
	SR135C-04	40	7.1	3632.0	2574.0	1977.0	1173.0	980.0	777.0	34.85	35.71	35.16	33.72	32.96	31.02
	Average	40	7.0	5154.3	3157.3	2335.3	1479.0	1268.0	1049.0	34.19	33.12	31.62	27.39	25.52	21.97
	STDV	40	0.3	2343.8	1147.5	807.5	519.7	435.5	349.6	2.9	2.2	2.5	4.3	5.0	6.1
	CV, (%)	40	4.2	45.5	36.3	34.6	35.1	34.3	33.3	8.5	6.6	7.9	15.7	19.8	27.8
US31 (Mix 8S)	US31C-01	40	8.1	3130.0	1864.0	1412.0	879.0	770.0	629.0	44.50	38.74	35.03	29.87	27.89	24.75
	US31C-02	40	8.5	3181.0	1938.0	1454.0	824.0	692.0	493.0	48.26	43.19	39.02	32.66	29.35	24.67
	US31C-03	40	8.4	2901.0	1635.0	1203.0	713.0	625.0	440.0	43.74	39.41	36.18	32.08	30.05	27.64
	Average	40	8.3	3070.7	1812.3	1356.3	805.3	695.7	520.7	45.50	40.45	36.74	31.54	29.10	25.69
	STDV	40	0.2	149.1	158.0	134.4	84.6	72.6	97.5	2.4	2.4	2.1	1.5	1.1	1.7
	CV, (%)	40	2.2	4.9	8.7	9.9	10.5	10.4	18.7	5.3	5.9	5.6	4.7	3.8	6.6
I74 (Mix 9S)	I74C-02	40	8.1	2897.0	2043.0	1680.0	1060.0	886.0	631.0	31.20	31.47	31.30	31.75	31.88	33.48
	I74C-03	40	7.7	4353.0	2748.0	2012.0	1159.0	922.0	629.0	31.57	31.98	32.42	33.05	32.33	30.97
	Average	40	7.9	3625.0	2395.5	1846.0	1109.5	904.0	630.0	31.39	31.73	31.86	32.40	32.11	32.23
	STDV	40	0.3	1029.5	498.5	234.8	70.0	25.5	1.4	0.3	0.4	0.8	0.9	0.3	1.8
	CV, (%)	40	3.4	28.4	20.8	12.7	6.3	2.8	0.2	0.8	1.1	2.5	2.8	1.0	5.5
SR64 (Mix 11S)	SR64C-01	40	4.4	7232.0	4643.0	3541.0	2059.0	1715.0	1240.0	32.15	32.06	31.37	31.23	29.84	27.49
	SR64C-02	40	4.2	5239.0	3820.0	3075.0	1842.0	1614.0	1287.0	31.73	32.52	31.64	28.55	26.12	22.32
	SR64C-03	40	5.5	2723.0	2051.0	1639.0	1082.0	898.0	662.0	29.91	29.75	28.83	28.24	27.13	25.71
	Average	40	4.7	5064.7	3504.7	2751.7	1661.0	1409.0	1063.0	31.26	31.44	30.61	29.34	27.70	25.17
	STDV	40	0.7	2259.5	1324.5	991.4	513.0	445.4	348.1	1.2	1.5	1.6	1.6	1.9	2.6
	CV, (%)	40	15.7	44.6	37.8	36.0	30.9	31.6	32.7	3.8	4.7	5.1	5.6	6.9	10.4
I65 (Mix 12S)	I65C-01	40	7.5	6151.0	4089.0	3090.0	1849.0	1510.0	1117.0	31.32	32.60	32.79	32.37	30.87	28.32
	I65C-02	40	7.4	1486.0	1175.0	1005.0	667.0	587.0	453.0	26.88	27.69	27.88	27.38	26.44	24.10
	I65C-03	40	7.4	3623.0	2637.0	2031.0	1142.0	948.0	679.0	34.75	35.35	35.89	34.46	33.38	30.15
	Average	40	7.4	3753.3	2633.7	2042.0	1219.3	1015.0	749.7	30.98	31.88	32.19	31.40	30.23	27.52
	STDV	40	0.1	2335.2	1457.0	1042.5	594.8	465.1	337.6	3.9	3.9	4.0	3.6	3.5	3.1
	CV, (%)	40	1.1	62.2	55.3	51.1	48.8	45.8	45.0	12.7	12.2	12.5	11.6	11.6	11.3
SR15 (Mix 1)	SR15C-01	54.4	11.6												
	SR15C-02	54.4	10.8												
	SR15C-03	54.4	11.2												
	Average	54.4	11.2												
	STDV	54.4	0.4												
	CV, (%)	40	3.6												

Mix	Sample ID	Temp. (°C)	Va (%)	Dynamic (Complex) Modulus E* (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
US24 (Mix 2)	US24C-01	54.4	9.0	1190.0	1009.0	885.0	698.0	668.0	643.0	20.86	13.47	13.00	16.29	15.09	12.03
	US24C-02	54.4	8.3	1301.0	1020.0	1048.0	828.0	750.0	786.0	24.76	20.70	17.02	14.07	13.09	16.89
	US24C-03	54.4	8.9	1005.0	835.0	759.0	648.0	596.0	385.0	23.02	20.16	18.75	17.70	18.81	37.61
	Average	54.4	8.7	1165.3	954.7	897.3	724.7	671.3	604.7	22.88	18.11	16.26	16.02	15.66	22.18
	STDV	54.4	0.4	149.5	103.8	144.9	92.9	77.1	203.2	2.0	4.0	3.0	1.8	2.9	13.6
	CV, (%)	40	4.5	12.8	10.9	16.1	12.8	11.5	33.6	8.5	22.2	18.1	11.4	18.5	61.3
SR161 (Mix 4)	SR161C-01	54.4	14.4	1119.0	890.0	740.0	527.0	422.0	187.0	25.4	24.1	24.1	25.2	28.9	33.3
	SR161C-02	54.4	13.1	809.0	676.0	649.0	518.0	433.0	172.0	28.08	24.39	24.04	25.21	28.93	18.44
	Average	54.4	13.8	964.0	783.0	694.5	522.5	427.5	179.5	26.72	24.24	24.06	25.22	28.93	25.87
	STDV	54.4	0.9	219.2	151.3	64.3	6.4	7.8	10.6	1.9	0.2	0.0	0.0	0.0	10.5
	CV, (%)	40	6.7	22.7	19.3	9.3	1.2	1.8	5.9	7.2	0.9	0.1	0.0	0.0	40.6
SR56 (Mix 5)	SR56C-01	54.4	8.4	1101.0	822.0	743.0	616.0	593.0	581.0	30.32	26.93	24.26	20.36	20.65	24.92
	SR56C-02	54.4	8.8	983.0	780.0	675.0	553.0	508.0	467.0	29.62	25.84	23.75	20.24	19.86	24.14
	SR56C-03	54.4	9.0	950.0	697.0	598.0	509.0	517.0	517.0	34.32	29.79	27.01	21.52	20.33	17.72
	Average	54.4	8.7	1011.3	766.3	672.0	559.3	539.3	521.7	31.42	27.52	25.01	20.71	20.28	22.26
	STDV	54.4	0.3	79.4	63.6	72.5	53.8	46.7	57.1	2.5	2.0	1.8	0.7	0.4	4.0
	CV, (%)	40	3.6	7.8	8.3	10.8	9.6	8.7	11.0	8.1	7.4	7.0	3.4	2.0	17.7
US30 (Mix 9)	US30C-01	54.4	7.5	839.0	715.0	634.0	566.0	552.0	572.0	26.52	22.49	19.60	15.57	14.44	13.25
	US30C-02	54.4	7.5	484.0	398.0	358.0	307.0	314.0	305.0	29.21	25.88	22.92	18.06	16.67	14.65
	US30C-03	54.4	7.2												
	Average	54.4	7.4	661.5	556.5	496.0	436.5	433.0	438.5	27.87	24.19	21.26	16.82	15.56	13.95
	STDV	54.4	0.1	251.0	224.2	195.2	183.1	168.3	188.8	1.9	2.4	2.3	1.8	1.6	1.0
	CV, (%)	40	2.0	37.9	40.3	39.3	42.0	38.9	43.1	6.8	9.9	11.0	10.5	10.1	7.1
SR66 (Mix 11)	SR66C-01	54.4	11.6												
	SR66C-02	54.4	11.3												
	SR66C-03	54.4	11.4												
	Average	54.4	11.4												
	STDV	54.4	0.2												
	CV, (%)	40	1.3												
SR135 (Mix 12)	SR135C-01	54.4	6.6	1799.0	1449.0	1322.0	1192.0	1158.0	1127.0	22.36	18.81	16.30	11.99	11.10	11.31
	SR135C-02	54.4	7.3	1437.0	1225.0	1136.0	1093.0	1070.0	1047.0	20.68	16.60	14.53	11.46	11.33	14.16
	SR135C-03	54.4	7.1	1027.0	882.0	838.0	834.0	854.0	872.0	21.70	17.49	14.54	10.77	10.47	10.80
	SR135C-04	54.4	7.1	1323.0	1094.0	1032.0	1043.0	1058.0	992.0	32.61	28.81	25.45	22.63	21.50	24.41
	Average	54.4	7.0	1396.5	1162.5	1082.0	1040.5	1035.0	1009.5	24.34	20.43	17.71	14.21	13.60	15.17
	STDV	54.4	0.3	319.2	237.6	202.1	150.9	128.6	107.1	5.6	5.7	5.2	5.6	5.3	6.3
	CV, (%)	40	4.2	22.9	20.4	18.7	14.5	12.4	10.6	22.8	27.7	29.5	39.6	38.8	41.8

Mix	Sample ID	Temp. (°C)	Va (%)	Dynamic (Complex) Modulus E* (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
US31 (Mix 8S)	US31C-01	54.4	8.1	970.0	825.0	756.0	658.0	628.0	579.0	23.96	21.01	19.37	16.71	16.11	15.91
	US31C-02	54.4	8.5	767.0	625.0	537.0	467.0	435.0	420.0	29.36	25.72	23.73	20.10	19.04	17.65
	US31C-03	54.4	8.4	719.0	591.0	500.0	425.0	403.0	380.0	26.45	23.77	22.33	20.01	19.54	18.99
	Average	54.4	8.3	818.7	680.3	597.7	516.7	488.7	459.7	26.6	23.5	21.8	18.9	18.2	17.5
	STDV	54.4	0.2	133.2	126.4	138.4	124.2	121.7	105.3	2.7	2.4	2.2	1.9	1.9	1.5
	CV, (%)	40	2.2	16.3	18.6	23.2	24.0	24.9	22.9	10.2	10.1	10.2	10.2	10.2	8.8
I74 (Mix 9S)	I74C-02	54.4	8.1	1440.0	1178.0	968.0	693.0	632.0	563.0	27.05	26.13	25.45	25.25	24.73	26.50
	I74C-03	54.4	7.7	1348.0	1053.0	914.0	742.0	677.0	594.0	25.31	23.35	21.13	17.53	16.56	18.41
	Average	54.4	7.9	1394.0	1115.5	941.0	717.5	654.5	578.5	26.18	24.74	23.29	21.39	20.65	22.46
	STDV	54.4	0.3	65.1	88.4	38.2	34.6	31.8	21.9	1.2	2.0	3.1	5.5	5.8	5.7
	CV, (%)	40	3.4	4.7	7.9	4.1	4.8	4.9	3.8	4.7	7.9	13.1	25.5	28.0	25.5
SR64 (Mix 11S)	SR64C-01	54.4	4.4	1610.0	1232.0	1055.0	836.0	774.0	669.0	27.13	24.32	22.05	19.82	19.13	19.27
	SR64C-02	54.4	4.2	965.0	758.0	639.0	486.0	455.0	441.0	28.94	26.15	23.20	18.01	15.52	10.95
	SR64C-03	54.4	5.5	1201.0	956.0	822.0	596.0	542.0	453.0	29.84	27.20	25.59	22.33	21.23	20.45
	Average	54.4	4.7	1258.7	982.0	838.7	639.3	590.3	521.0	28.64	25.89	23.61	20.05	18.63	16.89
	STDV	54.4	0.7	326.3	238.1	208.5	179.0	164.9	128.3	1.4	1.5	1.8	2.2	2.9	5.2
	CV, (%)	40	15.7	25.9	24.2	24.9	28.0	27.9	24.6	4.8	5.6	7.6	10.8	15.5	30.7
I65 (Mix 12S)	I65C-01	54.4	7.5	1755.0	1460.0	1267.0	968.0	900.0	803.0	25.18	24.45	23.48	21.83	20.34	19.01
	I65C-02	54.4	7.4	697.0	578.0	495.0	384.0	364.0	325.0	28.58	28.33	27.38	25.36	23.79	21.66
	I65C-03	54.4	7.4	853.0	732.0	616.0	467.0	428.0	393.0	27.29	25.35	24.24	21.67	20.50	17.06
	Average	54.4	7.4	1101.7	923.3	792.7	606.3	564.0	507.0	27.02	26.04	25.03	22.95	21.54	19.24
	STDV	54.4	0.1	571.2	471.1	415.2	315.9	292.7	258.6	1.7	2.0	2.1	2.1	1.9	2.3
	CV, (%)	40	1.1	51.8	51.0	52.4	52.1	51.9	51.0	6.4	7.8	8.3	9.1	9.0	12.0

Mix	Sample ID	Temp. (°C)	Va (%)	Dynamic (Complex) Modulus E* (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
SR15 (Mix 1)	SR15C2-01	40	9.9	3016.0	2292.0	1821.0	1117.0	951.0	829.0	29.43	30.73	32.23	30.11	27.73	21.43
	SR15C2-02	40	9.8	2316.0	1833.0	1436.0	822.0	679.0	474.0	25.19	27.00	28.28	30.80	30.06	27.23
	SR15C2-03	40	9.7	6833.0	4198.0	2829.0	1266.0	910.0	580.0	34.20	38.06	39.03	40.33	37.86	32.87
	Average	40	9.8	4055.0	2774.3	2028.7	1068.3	846.7	627.7	29.61	31.93	33.18	33.75	31.88	27.18
	STDV	40	0.1	2431.1	1254.1	719.3	226.0	146.6	182.2	4.5	5.6	5.4	5.7	5.3	5.7
	CV, (%)	40	1.0	60.0	45.2	35.5	21.2	17.3	29.0	15.2	17.6	16.4	16.9	16.6	21.0
US24 (Mix 2)	US24C2-01	40	5.2	4053.0	3065.0	2385.0	1338.0	1091.0	799.0	30.05	31.58	32.56	29.34	26.77	21.23
	US24C2-02	40	5.2	6074.0	4526.0	3422.0	1897.0	1551.0	1037.0	32.08	33.50	33.11	30.84	29.39	26.34
	US24C2-03	40	5.0	3268.0	2493.0	1949.0	1109.0	892.0	598.0	29.83	32.14	33.38	32.62	31.26	27.17
	Average	40	5.1	4465.0	3361.3	2585.3	1448.0	1178.0	811.3	30.65	32.41	33.02	30.93	29.14	24.91
	STDV	40	0.1	1447.7	1048.4	756.7	405.4	338.0	219.8	1.2	1.0	0.4	1.6	2.3	3.2
	CV, (%)	40	2.2	32.4	31.2	29.3	28.0	28.7	27.1	4.0	3.0	1.3	5.3	7.7	12.9
SR161 (Mix 4)	SR161C2-01	40	12.8	2721.0	718.0	1725.0	1067.0	899.0	662.0	26.70	22.01	28.30	27.66	26.56	23.09
	SR161C2-02	40	14.0	2132.0	1719.0	1446.0	902.0	753.0	547.0	24.59	26.97	28.16	28.08	27.62	25.07
	SR161C2-03	40	13.7	2686.0	2102.0	1789.0	1119.0	953.0	725.0	28.54	30.34	30.16	28.73	27.76	25.68
	Average	40	13.5	2513.0	1513.0	1653.3	1029.3	868.3	644.7	26.61	26.44	28.87	28.16	27.31	24.61
	STDV	40	0.6	330.4	714.6	182.4	113.3	103.5	90.3	2.0	4.2	1.1	0.5	0.7	1.4
	CV, (%)	40	4.6	13.1	47.2	11.0	11.0	11.9	14.0	7.4	15.8	3.9	1.9	2.4	5.5
SR56 (Mix 5)	SR56C2-01	40	4.8	3308.0	2458.0	1880.0	1027.0	835.0	577.0	31.52	33.17	33.66	32.46	30.76	27.44
	SR56C2-02	40	4.1	4299.0	3010.0	2212.0	1179.0	949.0	655.0	40.01	39.03	38.63	34.87	32.57	28.43
	SR56C2-03	40	4.6	3810.0	2891.0	2180.0	1168.0	928.0	620.0	32.25	34.91	36.00	35.59	33.79	29.27
	Average	40	4.5	3805.7	2786.3	2090.7	1124.7	904.0	617.3	34.59	35.70	36.10	34.31	32.37	28.38
	STDV	40	0.4	495.5	290.5	183.1	84.8	60.7	39.1	4.7	3.0	2.5	1.6	1.5	0.9
	CV, (%)	40	8.0	13.0	10.4	8.8	7.5	6.7	6.3	13.6	8.4	6.9	4.8	4.7	3.2
US30 (Mix 9)	US30C2-01	40	4.6	4316.0	3242.0	2624.0	1558.0	1317.0	983.0	32.01	33.24	33.69	31.26	29.57	25.68
	US30C2-02	40	4.6	2599.0	2037.0	1636.0	1019.0	869.0	654.0	29.17	30.97	31.00	29.07	27.64	23.85
	US30C2-03	40	4.2	3521.0	2566.0	1998.0	1183.0	988.0	712.0	30.76	32.20	32.23	30.51	28.90	25.58
	Average	40	4.5	3478.7	2615.0	2086.0	1253.3	1058.0	783.0	30.65	32.14	32.31	30.28	28.70	25.04
	STDV	40	0.2	859.3	604.0	499.8	276.3	232.1	175.6	1.4	1.1	1.3	1.1	1.0	1.0
	CV, (%)	40	5.2	24.7	23.1	24.0	22.0	21.9	22.4	4.6	3.5	4.2	3.7	3.4	4.1
SR66 (Mix 11)	SR66C2-01	40	7.4	1977.0	1643.0	1384.0	945.0	805.0	603.0	23.15	23.95	24.48	24.49	24.04	23.13
	SR66C2-02	40	9.4	2891.0	2296.0	1865.0	1121.0	922.0	649.0	27.96	29.67	30.53	30.41	29.51	26.05
	SR66C2-03	40	7.1	2760.0	2217.0	1810.0	1127.0	964.0	752.0	29.94	31.03	31.49	30.17	29.07	26.45
	Average	40	8.0	2542.7	2052.0	1686.3	1064.3	897.0	668.0	27.02	28.22	28.83	28.36	27.54	25.21
	STDV	40	1.3	494.2	356.4	263.3	103.4	82.4	76.3	3.5	3.8	3.8	3.4	3.0	1.8
	CV, (%)	40	15.7	19.4	17.4	15.6	9.7	9.2	11.4	12.9	13.3	13.2	11.8	11.0	7.2

Mix	Sample ID	Temp. (°C)	Va (%)	Dynamic (Complex) Modulus E* (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
SR135 (Mix 12)	SR135C2-01	40	4.1	3658.0	2733.0	2105.0	1207.0	958.0	662.0	29.68	31.98	32.65	31.52	29.86	25.60
	SR135C2-02	40	4.0	2697.0	2076.0	1642.0	976.0	804.0	541.0	29.09	31.59	32.50	31.74	30.27	26.05
	SR135C2-03	40	4.7	4354.0	3340.0	2599.0	1486.0	1220.0	842.0	29.22	31.67	32.70	33.23	31.94	27.54
	Average	40	4.3	3569.7	2716.3	2115.3	1223.0	994.0	681.7	29.33	31.75	32.62	32.16	30.69	26.40
	STDV	40	0.4	832.0	632.2	478.6	255.4	210.3	151.5	0.3	0.2	0.1	0.9	1.1	1.0
	CV, (%)	40	8.9	23.3	23.3	22.6	20.9	21.2	22.2	1.1	0.6	0.3	2.9	3.6	3.8
US31 (Mix 8S)	US31C2-01	40	6.9	1764.0	1354.0	1093.0	677.0	579.0	433.0	31.62	31.57	31.01	27.82	26.36	23.28
	US31C2-02	40	6.4	1720.0	1269.0	969.0	599.0	512.0	376.0	38.64	36.83	35.59	32.70	30.84	27.85
	US31C2-03	40	5.9	1494.0	1134.0	894.0	568.0	493.0	379.0	34.18	33.42	32.65	29.96	28.88	27.00
	Average	40	6.4	1659.3	1252.3	985.3	614.7	528.0	396.0	34.81	33.94	33.08	30.16	28.69	26.04
	STDV	40	0.5	144.9	110.9	100.5	56.2	45.2	32.1	3.6	2.7	2.3	2.4	2.2	2.4
	CV, (%)	40	7.8	8.7	8.9	10.2	9.1	8.6	8.1	10.2	7.9	7.0	8.1	7.8	9.3
I74 (Mix 9S)	I74C2-01	40	5.7	4079.0	3118.0	2511.0	1579.0	1343.0	1035.0	29.1	30.4	30.5	28.7	27.4	25.4
	I74C2-02	40	4.1	3664.0	2774.0	2188.0	1372.0	1179.0	876.0	28.92	31.92	31.72	28.94	27.06	24.08
	I74C2-03	40	2.6	2169.0	1706.0	1375.0	859.0	719.0	556.0	27.76	30.25	30.64	30.27	29.57	27.73
	Average	40	4.1	3304.0	2532.7	2024.7	1270.0	1080.3	822.3	28.59	30.87	30.94	29.32	28.01	25.73
	STDV	40	1.6	1004.6	736.3	585.3	370.7	323.5	244.0	0.7	0.9	0.7	0.8	1.4	1.9
	CV, (%)	40	37.5	30.4	29.1	28.9	29.2	29.9	29.7	2.5	3.0	2.2	2.8	4.9	7.2
SR64 (Mix 11S)	SR64C2-01	40	2.5	4021.0	3206.0	2530.0	1620.0	1365.0	993.0	27.39	29.79	30.21	30.57	30.15	28.88
	SR64C2-02	40	3.7	5507.0	4633.0	3890.0	2383.0	1941.0	1245.0	27.00	19.44	32.40	34.56	30.96	29.52
	SR64C2-03	40	2.9	6586.0	5176.0	4254.0	2562.0	2069.0	1287.0	25.92	27.76	28.90	30.65	30.61	29.50
	Average	40	3.0	5371.3	4338.3	3558.0	2188.3	1791.7	1175.0	26.77	25.66	30.50	31.93	30.57	29.30
	STDV	40	0.6	1287.9	1017.5	908.7	500.3	375.0	159.0	0.8	5.5	1.8	2.3	0.4	0.4
	CV, (%)	40	20.1	24.0	23.5	25.5	22.9	20.9	13.5	2.8	21.4	5.8	7.1	1.3	1.2
I65 (Mix 12S)	I65C2-01	40	10.6	2960.0	2342.0	1907.0	1123.0	939.0	709.0	27.55	28.31	29.21	28.90	27.94	25.68
	I65C2-02	40	10.2	2843.0	2042.0	1573.0	926.0	778.0	566.0	29.10	30.72	31.33	29.89	28.65	25.41
	I65C2-03	40	10.7	2005.0	1629.0	1351.0	878.0	766.0	599.0	26.17	27.27	27.98	27.39	26.53	23.91
	Average	40	10.5	2602.7	2004.3	1610.3	975.7	827.7	624.7	27.61	28.77	29.51	28.73	27.71	25.00
	STDV	40	0.3	520.9	358.0	279.9	129.8	96.6	74.9	1.5	1.8	1.7	1.3	1.1	1.0
	CV, (%)	40	2.5	20.0	17.9	17.4	13.3	11.7	12.0	5.3	6.2	5.7	4.4	3.9	3.8
SR15 (Mix 12S)	SR15C2-01	54.4	9.9	1099.0	900.0	765.0	753.0	839.0	863.0	32.50	27.32	23.13	13.74	10.66	10.66
	SR15C2-02	54.4	9.8	738.0	567.0	490.0	395.0	384.0	411.0	32.27	29.17	26.67	21.00	19.10	19.64
	SR15C2-03	54.4	9.7	1103.0	792.0	629.0	446.0	422.0	438.0	37.27	33.41	30.95	25.32	23.63	22.68
	Average	54.4	9.8	980.0	753.0	628.0	531.3	548.3	570.7	34.01	29.97	26.92	20.02	17.80	17.66
	STDV	54.4	0.1	209.6	169.9	137.5	193.7	252.4	253.5	2.8	3.1	3.9	5.9	6.6	6.2
	CV, (%)	54.4	1.0	21.4	22.6	21.9	36.4	46.0	44.4	8.3	10.4	14.5	29.2	37.0	35.4

Mix	Sample ID	Temp. (°C)	Va (%)	Dynamic (Complex) Modulus E* (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
US24 (Mix 2)	US24C2-01	54.4	5.2	1040.0	842.0	764.0	628.0	620.0	655.0	28.56	25.69	21.44	15.97	14.49	13.27
	US24C2-02	54.4	5.2	2698.0	1906.0	1526.0	943.0	813.0	708.0	39.24	36.05	30.18	25.32	22.83	18.35
	US24C2-03	54.4	5.0	1096.0	786.0	684.0	418.0	373.0	324.0	33.27	32.07	29.14	24.47	22.09	18.22
	Average	54.4	5.1	1611.3	1178.0	991.3	663.0	602.0	562.3	33.69	31.27	26.92	21.92	19.80	16.61
	STDV	54.4	0.1	941.5	631.1	464.8	264.2	220.6	208.1	5.4	5.2	4.8	5.2	4.6	2.9
	CV, (%)	54.4	2.2	58.4	53.6	46.9	39.9	36.6	37.0	15.9	16.7	17.7	23.6	23.3	17.4
SR161 (Mix 4)	SR161C2-01	54.4	12.8	891.0	746.0	633.0	475.0	435.0	431.0	28.2	27.4	26.3	21.6	19.9	17.9
	SR161C2-02	54.4	14.0	950.0	770.0	634.0	467.0	429.0	393.0	29.2	27.5	26.0	21.8	20.2	19.9
	SR161C2-03	54.4	13.7	1149.0	862.0	704.0	504.0	459.0	406.0	30.05	28.75	27.42	24.59	23.72	24.78
	Average	54.4	13.5	996.7	792.7	657.0	482.0	441.0	410.0	29.14	27.87	26.58	22.65	21.28	20.86
	STDV	54.4	0.6	135.2	61.2	40.7	19.5	15.9	19.3	0.9	0.8	0.7	1.7	2.1	3.5
	CV, (%)	54.4	4.6	13.6	7.7	6.2	4.0	3.6	4.7	3.1	2.7	2.8	7.4	9.9	16.9
SR56 (Mix 5)	SR56C2-01	54.4	4.8	965.0	762.0	646.0	511.0	482.0	468.0	28.41	25.68	23.11	16.84	15.08	13.06
	SR56C2-02	54.4	4.1	1411.0	1020.0	835.0	576.0	532.0	534.0	38.56	33.84	30.25	24.38	22.46	21.28
	SR56C2-03	54.4	4.6	1219.0	910.0	719.0	521.0	474.0	470.0	35.91	32.84	30.19	24.16	22.65	19.84
	Average	54.4	4.5	1198.3	897.3	733.3	536.0	496.0	490.7	34.29	30.79	27.85	21.79	20.06	18.06
	STDV	54.4	0.4	223.7	129.5	95.3	35.0	31.4	37.5	5.3	4.5	4.1	4.3	4.3	4.4
	CV, (%)	54.4	8.0	18.7	14.4	13.0	6.5	6.3	7.7	15.4	14.5	14.7	19.7	21.5	24.3
US30 (Mix 9)	US30C2-01	54.4	4.6	1316.0	993.0	828.0	653.0	622.0	593.0	33.02	30.22	28.01	22.62	21.52	19.29
	US30C2-02	54.4	4.6	960.0	760.0	624.0	490.0	465.0	441.0	30.12	27.39	25.58	21.36	20.06	17.97
	US30C2-03	54.4	4.2	1136.0	887.0	737.0	551.0	514.0	486.0	30.93	28.69	27.64	24.49	23.60	20.39
	Average	54.4	4.5	1137.3	880.0	729.7	564.7	533.7	506.7	31.36	28.77	27.08	22.82	21.73	19.22
	STDV	54.4	0.2	178.0	116.7	102.2	82.4	80.3	78.1	1.5	1.4	1.3	1.6	1.8	1.2
	CV, (%)	54.4	5.2	15.7	13.3	14.0	14.6	15.1	15.4	4.8	4.9	4.8	6.9	8.2	6.3
SR66 (Mix 11)	SR66C2-01	54.4	7.4	1144.0	936.0	781.0	578.0	519.0	430.0	26.52	26.23	25.61	22.68	22.07	23.70
	SR66C2-02	54.4	9.4	1101.0	840.0	693.0	489.0	440.0	372.0	28.11	28.59	27.37	23.65	22.93	25.27
	SR66C2-03	54.4	7.1	1000.0	874.0	780.0	636.0	606.0	572.0	28.15	26.77	25.19	20.41	19.11	16.83
	Average	54.4	8.0	1081.7	883.3	751.3	567.7	521.7	458.0	27.59	27.20	26.06	22.25	21.37	21.93
	STDV	54.4	1.3	73.9	48.7	50.5	74.0	83.0	102.9	0.9	1.2	1.2	1.7	2.0	4.5
	CV, (%)	54.4	15.7	6.8	5.5	6.7	13.0	15.9	22.5	3.4	4.5	4.4	7.5	9.4	20.5
SR135 (Mix 12)	SR135C2-01	54.4	4.1	1308.0	978.0	823.0	620.0	570.0	516.0	29.89	27.67	25.29	20.48	18.73	17.73
	SR135C2-02	54.4	4.0	923.0	693.0	582.0	423.0	383.0	337.0	29.04	27.65	25.84	21.67	20.36	18.02
	SR135C2-03	54.4	4.7	1357.0	981.0	803.0	588.0	536.0	501.0	34.36	32.51	30.47	26.80	26.11	25.08
	Average	54.4	4.3	1196.0	884.0	736.0	543.7	496.3	451.3	31.10	29.28	27.20	22.98	21.73	20.28
	STDV	54.4	0.4	237.7	165.4	133.7	105.7	99.6	99.3	2.9	2.8	2.8	3.4	3.9	4.2
	CV, (%)	54.4	8.9	19.9	18.7	18.2	19.4	20.1	22.0	9.2	9.6	10.5	14.6	17.8	20.5

Mix	Sample ID	Temp. (°C)	Va (%)	Dynamic (Complex) Modulus [E*] (MPa)						Phase Angle ϕ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
US31 (Mix 8S)	US31C2-01	54.4	6.9	862.0	713.0	613.0	453.0	420.0	382.0	28.00	25.29	23.70	20.75	19.80	18.95
	US31C2-02	54.4	6.4	591.0	493.0	426.0	310.0	288.0	248.0	28.82	26.22	24.36	21.55	20.60	19.84
	US31C2-03	54.4	5.9	697.0	582.0	513.0	409.0	386.0	343.0	28.95	25.93	24.68	22.56	22.30	23.81
	Average	54.4	6.4	716.7	596.0	517.3	390.7	364.7	324.3	28.59	25.81	24.25	21.62	20.90	20.87
	STDV	54.4	0.5	136.6	110.7	93.6	73.2	68.5	68.9	0.5	0.5	0.5	0.9	1.3	2.6
	CV, (%)	54.4	7.8	19.1	18.6	18.1	18.7	18.8	21.3	1.8	1.8	2.1	4.2	6.1	12.4
I74 (Mix 9S)	I74C2-01	54.4	5.7	1801.0	1436.0	1230.0	957.0	896.0	802.0	29.17	26.59	24.19	21.07	19.19	20.06
	I74C2-02	54.4	4.1	1700.0	1391.0	1194.0	909.0	834.0	718.0	29.72	27.71	25.58	23.07	21.66	21.39
	I74C2-03	54.4	2.6	816.0	752.0	674.0	550.0	514.0	475.0	26.29	23.82	22.21	21.01	19.77	20.09
	Average	54.4	4.1	1439.0	1193.0	1032.7	805.3	748.0	665.0	28.39	26.04	23.99	21.72	20.21	20.51
	STDV	54.4	1.6	541.9	382.6	311.1	222.4	205.0	169.8	1.8	2.0	1.7	1.2	1.3	0.8
	CV, (%)	54.4	37.5	37.7	32.1	30.1	27.6	27.4	25.5	6.5	7.7	7.1	5.4	6.4	3.7
SR64 (Mix 11S)	SR64C2-01	54.4	2.5	1898.0	1517.0	1266.0	873.0	780.0	632.0	30.35	28.79	27.86	25.99	24.91	23.58
	SR64C2-02	54.4	3.7	3276.0	2515.0	1912.0	423.0	950.0	711.0	36.13	35.40	33.81	37.96	29.40	27.12
	SR64C2-03	54.4	2.9	2141.0	1643.0	1364.0	929.0	822.0	664.0	27.99	28.22	27.11	25.41	24.62	23.72
	Average	54.4	3.0	2438.3	1891.7	1514.0	741.7	850.7	669.0	31.49	30.80	29.59	29.79	26.31	24.81
	STDV	54.4	0.6	735.5	543.5	348.1	277.4	88.6	39.7	4.2	4.0	3.7	7.1	2.7	2.0
	CV, (%)	54.4	20.1	30.2	28.7	23.0	37.4	10.4	5.9	13.3	13.0	12.4	23.8	10.2	8.1
I65 (Mix 12S)	I65C2-01	54.4	10.6	1146.0	926.0	775.0	566.0	552.0	458.0	28.57	27.19	25.89	22.99	19.71	20.07
	I65C2-02	54.4	10.2	1375.0	1049.0	780.0	598.0	547.0	470.0	31.90	30.27	28.86	24.62	23.21	21.09
	I65C2-03	54.4	10.7	966.0	782.0	669.0	493.0	450.0	402.0	28.13	26.52	25.38	22.45	21.34	18.98
	Average	54.4	10.5	1162.3	919.0	741.3	552.3	516.3	443.3	29.53	27.99	26.71	23.35	21.42	20.05
	STDV	54.4	0.3	205.0	133.6	62.7	53.8	57.5	36.3	2.1	2.0	1.9	1.1	1.8	1.1
	CV, (%)	54.4	2.5	17.6	14.5	8.5	9.7	11.1	8.2	7.0	7.1	7.0	4.8	8.2	5.3

Mix	Sample ID	Temp. (°C)	Va (%)	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR15 (Mix 1)	SR15-1	40	11.2	126.3	91.6	56.4	38.2	27.4	17.9	14.6	8.8	9.2	9.5
	SR15-2	40	10.9	139.8	95.1	55.3	35.5	23.8	14.8	12.0	10.4	7.4	4.9
	SR15-3	40	11.5	134.1	93.3	52.4	34.8	23.1	14.6	10.5	8.4	6.0	6.5
	Average	40	11.2	133.4	93.3	54.7	36.2	24.7	15.8	12.3	9.2	7.5	7.0
	STDV	40	0.3	6.8	1.7	2.1	1.8	2.3	1.9	2.1	1.0	1.6	2.3
	CV, (%)	40	2.4	5.1	1.9	3.8	5.0	9.2	12.0	16.7	11.3	20.8	33.3
US24 (Mix 2)	US24-7	40	9.6	174.8	119.7	67.2	42.0	29.9	21.3	14.8	12.6	14.5	15.5
	US24-9	40	10.3	232.7	166.9	101.4	69.2	48.9	32.2	23.0	18.0	14.3	11.8
	US24-10	40	8.5	150.2	106.3	68.1	43.5	31.1	23.4	19.2	18.2	12.4	14.8
	US24-11	40	9.5	153.0	108.6	62.4	43.2	29.0	19.2	16.4	11.0	9.3	9.7
	Average	40	9.5	177.7	125.4	74.8	49.5	34.7	24.0	18.4	14.9	12.6	12.9
	STDV	40	0.7	38.3	28.3	17.9	13.2	9.5	5.7	3.6	3.7	2.4	2.7
SR161 (Mix 4)	SR161-1	40	11.2	239.5	170.2	103.8	71.7	47.8	29.0	20.5	17.1	10.1	7.4
	SR161-2	40	10.3	263.8	187.4	122.4	82.6	58.3	36.8	25.6	19.2	13.7	11.1
	SR161-3	40	10.8	277.5	202.2	125.2	85.7	61.4	39.6	28.7	21.8	12.6	7.9
	Average	40	10.8	260.3	186.6	117.1	80.0	55.8	35.2	25.0	19.4	12.1	8.8
	STDV	40	0.4	19.2	16.0	11.6	7.3	7.1	5.5	4.2	2.3	1.8	2.0
	CV, (%)	40	4.0	7.4	8.6	9.9	9.2	12.7	15.7	16.6	12.0	15.2	22.8
SR56 (Mix 5)	SR56-1-C	40	10.0	144.6	101.4	61.0	42.0	27.4	16.4	12.3	7.4	5.5	5.0
	SR56-1-K	40	9.9	177.0	123.2	74.4	49.9	32.5	19.1	13.5	10.9	6.7	3.9
	SR56-1-L	40	8.8	173.0	118.8	70.8	46.2	29.6	18.0	12.1	8.3	7.3	4.7
	Average	40	9.6	164.9	114.5	68.7	46.0	29.9	17.8	12.6	8.9	6.5	4.6
	STDV	40	0.7	17.6	11.5	6.9	4.0	2.5	1.3	0.8	1.8	0.9	0.6
	CV, (%)	40	6.8	10.7	10.1	10.1	8.6	8.5	7.5	6.2	20.7	14.3	13.1
US30 (Mix 9)	US30-1	40	6.7	177.6	122.2	75.0	52.1	35.2	23.4	17.1	13.1	8.8	6.2
	US30-2	40	6.5	224.4	156.4	94.1	63.8	43.3	26.6	18.7	12.9	8.9	6.3
	US30-3	40	6.3	276.8	193.7	128.7	92.1	65.6	45.9	36.7	27.3	24.3	16.6
	Average	40	6.5	226.3	157.4	99.3	69.3	48.0	32.0	24.2	17.8	14.0	9.7
	STDV	40	0.2	49.6	35.7	27.2	20.6	15.7	12.2	10.9	8.3	8.9	5.9
	CV, (%)	40	3.3	21.9	22.7	27.4	29.7	32.8	38.0	44.9	46.7	63.4	61.4
SR66 (Mix 11)	SR66-01	40	13.5	179.5	123.3	72.9	48.8	32.9	19.2	12.3	8.6	6.5	5.5
	SR66-02	40	12.5	184.1	128.6	76.6	51.9	34.3	20.0	13.6	10.4	7.3	7.7
	SR66-03	40	11.8	186.8	129.0	74.3	48.6	31.4	17.5	11.7	6.1	4.7	2.2
	Average	40	12.6	183.4	126.9	74.6	49.8	32.9	18.9	12.5	8.4	6.2	5.2
	STDV	40	0.8	3.7	3.2	1.9	1.9	1.4	1.3	1.0	2.2	1.3	2.7
	CV, (%)	40	6.5	2.0	2.5	2.5	3.7	4.4	6.8	7.9	25.7	21.5	53.2
SR135 (Mix 12)	SR135-1	40	8.7	228.4	158.3	92.0	61.4	41.0	25.6	18.1	13.8	8.8	9.3
	SR135-2	40	8.4	219.6	149.7	96.2	66.8	48.0	31.8	24.3	21.3	17.1	13.6
	SR135-3	40	8.5	185.3	125.4	72.9	47.9	31.5	18.4	14.5	9.1	7.0	6.0
	Average	40	8.6	211.1	144.5	87.1	58.7	40.2	25.2	19.0	14.7	11.0	9.6
	STDV	40	0.2	22.8	17.1	12.4	9.7	8.3	6.7	5.0	6.2	5.4	3.8
	CV, (%)	40	2.0	10.8	11.8	14.2	16.6	20.6	26.5	26.3	42.0	49.6	39.8

Mix	Sample ID	Temp. (°C)	Va (%)	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
US31 (Mix 8S)	US31-01	40	7.8	278.0	216.1	156.3	122.4	91.8	70.9	56.5	50.4	40.2	35.0
	US31-02	40	7.8	247.5	189.9	130.1	96.8	76.5	57.2	46.5	40.0	32.8	28.8
	US31-03	40	9.2	209.1	169.9	112.5	85.1	64.7	48.3	38.6	31.7	20.4	20.6
	Average	40	8.3	244.9	192.0	132.9	101.4	77.7	58.8	47.2	40.7	31.1	28.1
	STDV	40	0.8	34.5	23.1	22.0	19.1	13.6	11.4	9.0	9.4	10.0	7.2
	CV, (%)	40	9.4	14.1	12.1	16.6	18.8	17.5	19.4	19.1	23.1	32.1	25.6
I74 (Mix 9S)	I74-1	40		316.7	238.7	164.9	123.5	93.9	66.8	50.6	41.9	30.7	24.3
	I74-2	40		329.6	250.2	175.6	130.4	100.2	71.6	56.6	44.8	32.9	27.3
	I74-3	40		249.4	181.3	121.6	87.2	64.2	42.7	32.2	26.7	19.0	17.6
	Average	40		298.5	223.4	154.0	113.7	86.1	60.4	46.5	37.8	27.6	23.1
	STDV	40		43.1	36.9	28.6	23.2	19.2	15.5	12.7	9.7	7.5	5.0
	CV, (%)	40		14.4	16.5	18.6	20.4	22.3	25.7	27.3	25.8	27.1	21.6
SR64 (Mix 11S)	SR64-01	40		307.9	233.3	157.6	117.2	87.5	61.7	47.5	38.5	29.0	22.0
	SR64-02	40		354.9	264.9	171.5	123.7	91.5	59.4	44.8	32.5	22.0	16.2
	SR64-03	40		341.1	253.0	165.5	118.2	84.1	53.8	38.9	28.8	18.6	12.4
	Average	40		334.7	250.4	164.9	119.7	87.7	58.3	43.7	33.3	23.2	16.9
	STDV	40		24.1	16.0	7.0	3.5	3.7	4.1	4.4	4.8	5.3	4.9
	CV, (%)	40		7.2	6.4	4.2	2.9	4.2	7.0	10.0	14.6	22.8	28.9
I65 (Mix 12S)	I65-01	40	8.2	447.1	368.1	259.3	200.5	156.0	114.5	93.6	78.0	61.2	53.2
	I65-03	40	9.3	496.4	388.7	276.2	210.0	161.2	119.7	97.4	79.6	64.9	54.8
	I65-04	40	9.3	481.6	371.9	259.5	207.0	163.5	121.2	98.6	81.3	64.7	52.2
	Average	40	8.9	475.0	376.2	265.0	205.8	160.2	118.5	96.5	79.6	63.6	53.4
	STDV	40	0.6	25.3	11.0	9.7	4.9	3.9	3.5	2.6	1.6	2.1	1.3
	CV, (%)	40	7.0	5.3	2.9	3.7	2.4	2.4	3.0	2.7	2.1	3.3	2.5
SR15 (Mix 1)	SR15-1	54.4	11.2	31.1	21.6	15.1	11.0	9.3	6.1	5.4	4.4	4.0	2.8
	SR15-2	54.4	10.9	42.3	35.6	26.1	19.4	16.8	13.8	12.9	12.7	11.8	10.4
	SR15-3	54.4	11.5	46.3	30.4	22.5	16.1	18.7	14.1	14.2	12.5	8.3	11.2
	Average	54.4	11.2	39.9	29.2	21.2	15.5	14.9	11.3	10.8	9.9	8.0	8.1
	STDV	54.4	0.3	7.9	7.1	5.6	4.2	4.9	4.5	4.8	4.7	3.9	4.6
	CV, (%)	40	2.4	19.8	24.3	26.5	27.2	33.0	40.0	44.0	47.9	48.3	56.8
US24 (Mix 2)	US24-7	54.4	9.6	40.7	32.4	21.1	12.9	9.7	8.6	7.4	7.1	5.2	7.8
	US24-9	54.4	10.3	65.7	44.7	35.4	21.5	22.8	19.6	15.9	16.9	16.7	13.9
	US24-10	54.4	8.5	59.3	42.7	26.6	19.4	14.2	14.0	10.5	8.0	9.1	6.1
	US24-11	54.4	9.5	58.3	39.1	23.7	17.7	13.9	11.5	9.7	9.5	7.9	7.1
	Average	54.4	9.5	56.0	39.7	26.7	17.9	15.2	13.4	10.9	10.4	9.7	8.7
	STDV	54.4	0.7	10.7	5.4	6.2	3.7	5.5	4.7	3.6	4.5	4.9	3.5
SR161 (Mix 4)	SR161-1	54.4	11.2	49.5	33.7	21.7	15.5	11.5	8.1	7.8	6.5	4.5	5.4
	SR161-2	54.4	10.3	51.7	39.6	25.2	16.8	13.4	9.1	8.8	6.8	5.3	5.4
	SR161-3	54.4	10.8	58.8	42.1	26.2	17.9	12.8	9.2	7.9	5.9	6.1	5.1
	Average	54.4	10.8	53.3	38.5	24.4	16.8	12.6	8.8	8.2	6.4	5.3	5.3
	STDV	54.4	0.4	4.9	4.3	2.3	1.2	1.0	0.6	0.6	0.4	0.8	0.1
	CV, (%)	40	4.0	9.2	11.2	9.6	7.1	7.7	7.2	7.1	6.6	14.6	2.5

Mix	Sample ID	Temp. (°C)	Va (%)	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR56 (Mix 5)	SR56-1-C	54.4	10.0	40.2	26.8	17.5	13.6	10.1	8.3	6.4	6.6	5.4	4.6
	SR56-1-K	54.4	9.9	38.3	28.8	20.0	14.6	11.2	7.9	6.7	6.9	5.6	5.5
	SR56-1-L	54.4	8.8	45.0	33.0	20.7	13.7	11.3	8.7	7.5	5.8	5.5	4.7
	Average	54.4	9.6	41.1	29.5	19.4	14.0	10.9	8.3	6.9	6.4	5.5	4.9
	STDV	54.4	0.7	3.4	3.1	1.7	0.6	0.7	0.4	0.6	0.6	0.1	0.5
	CV, (%)	40	6.8	8.4	10.6	8.8	4.0	6.4	4.7	8.6	9.2	2.3	9.9
US30 (Mix 9)	US30-1	54.4	6.7	37.0	27.7	18.7	14.4	10.9	8.2	7.2	5.4	4.0	3.7
	US30-2	54.4	6.5	50.9	37.7	26.6	19.2	15.0	10.5	8.5	6.1	5.6	4.9
	US30-3	54.4	6.3	52.3	40.0	27.7	19.0	17.5	13.4	11.0	8.1	6.2	6.1
	Average	54.4	6.5	46.7	35.1	24.4	17.5	14.5	10.7	8.9	6.5	5.3	4.9
	STDV	54.4	0.2	8.4	6.6	4.9	2.7	3.3	2.6	2.0	1.4	1.2	1.2
	CV, (%)	40	3.3	18.0	18.6	20.2	15.6	23.1	24.3	22.2	20.8	22.5	24.4
SR66 (Mix 11)	SR66-01	54.4	13.5	46.0	31.6	20.3	14.5	11.1	9.5	6.5	5.7	5.0	3.9
	SR66-02	54.4	12.5	51.2	34.1	20.2	14.3	10.1	8.1	6.2	5.8	4.5	3.6
	SR66-03	54.4	11.8	52.3	37.1	20.0	13.7	10.2	7.9	5.0	3.5	4.1	3.0
	Average	54.4	12.6	49.9	34.3	20.2	14.2	10.5	8.5	5.9	5.0	4.5	3.5
	STDV	54.4	0.8	3.4	2.7	0.2	0.4	0.5	0.9	0.8	1.3	0.5	0.5
	CV, (%)	40	6.5	6.7	7.9	0.8	3.1	5.2	10.4	13.5	26.3	10.6	13.2
SR135 (Mix 12)	SR135-1	54.4	8.7	50.1	34.6	21.1	16.3	12.8	9.8	7.7	8.2	6.0	4.5
	SR135-2	54.4	8.4	41.2	30.4	19.7	16.7	13.4	11.5	9.8	10.1	9.9	8.6
	SR135-3	54.4	8.5	43.3	33.2	18.5	14.1	10.6	8.1	7.4	5.5	4.5	4.9
	Average	54.4	8.6	44.9	32.7	19.8	15.7	12.3	9.8	8.3	8.0	6.8	6.0
	STDV	54.4	0.2	4.7	2.1	1.3	1.4	1.5	1.7	1.3	2.3	2.8	2.3
	CV, %	54.4	2.0	10.4	6.4	6.7	9.0	11.8	17.5	16.0	29.1	40.9	37.9
US31 (Mix 8S)	US31-01	54.4	7.8	70.9	61.0	45.0	39.9	32.9	31.0	29.3	28.5	27.2	33.7
	US31-02	54.4	7.8	95.3	72.1	52.3	41.0	34.3	27.9	23.8	20.6	17.4	16.0
	US31-03	54.4	9.2	84.7	63.9	45.8	37.5	30.4	24.3	21.7	18.3	15.2	13.2
	Average	54.4	8.3	83.6	65.7	47.7	39.5	32.5	27.7	25.0	22.4	19.9	21.0
	STDV	54.4	0.8	12.2	5.8	4.0	1.8	1.9	3.3	4.0	5.4	6.4	11.1
	CV, (%)	40	9.4	14.6	8.8	8.3	4.6	6.0	12.0	15.8	24.0	31.9	53.1
I74 (Mix 9S)	I74-1	54.4		108.7	84.0	55.1	42.9	33.0	25.3	20.9	16.8	16.1	14.0
	I74-2	54.4		103.2	81.8	56.3	46.1	37.4	30.7	27.4	24.7	22.5	20.2
	I74-3	54.4		83.5	60.1	40.4	30.7	22.3	15.9	13.0	10.6	6.7	8.1
	Average	54.4		98.5	75.3	50.6	39.9	30.9	24.0	20.4	17.3	15.1	14.1
	STDV	54.4		13.2	13.2	8.8	8.1	7.7	7.5	7.2	7.1	7.9	6.0
	CV, (%)	40		13.4	17.6	17.5	20.4	25.1	31.3	35.3	40.7	52.4	42.7
SR64 (Mix 11S)	SR64-01	54.4		91.3	70.6	48.3	36.4	28.1	20.4	17.0	14.2	10.9	8.1
	SR64-02	54.4		69.0	52.9	34.4	27.1	21.0	16.1	14.8	13.8	13.0	14.8
	SR64-03	54.4		95.4	67.7	40.9	29.3	21.0	16.2	12.9	7.3	6.4	6.8
	Average	54.4		85.2	63.7	41.2	30.9	23.4	17.6	14.9	11.8	10.1	9.9
	STDV	54.4		14.2	9.5	7.0	4.9	4.1	2.5	2.0	3.9	3.3	4.3
	CV, (%)	40		16.7	14.9	16.9	15.7	17.6	14.1	13.6	32.8	33.1	43.3
I65 (Mix 12S)	I65-01	54.4	8.2	139.5	107.6	76.6	59.3	47.1	37.1	30.3	26.9	23.7	22.1
	I65-03	54.4	9.3	151.9	118.7	86.0	67.7	53.9	42.2	34.5	29.1	23.9	22.9
	I65-04	54.4	9.3	163.3	122.1	85.1	66.8	52.7	40.2	33.8	29.6	24.8	22.1
	Average	54.4	8.9	151.5	116.1	82.6	64.6	51.2	39.9	32.9	28.5	24.2	22.4
	STDV	54.4	0.6	11.9	7.6	5.2	4.6	3.6	2.6	2.3	1.5	0.6	0.5
	CV, (%)	40	7.0	7.8	6.5	6.3	7.2	7.1	6.5	6.9	5.1	2.4	2.2

Mix	Sample ID	Temp. (°C)	Va (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR15 (Mix 1)	SR15-1	40	11.2	62.91	63.02	66.74	63.71	60.84	58.78	63.56	50.06	43.97	46.17
	SR15-2	40	10.9	60.80	61.69	61.02	58.07	55.25	47.28	53.68	36.35	46.49	23.81
	SR15-3	40	11.5	65.18	63.54	65.35	65.43	62.02	52.15	52.96	49.49	48.40	47.93
	Average	40	11.2	62.96	62.75	64.37	62.40	59.37	52.74	56.73	45.30	46.29	39.30
	STDV	40	0.3	2.2	1.0	3.0	3.9	3.6	5.8	5.9	7.8	2.2	13.4
	CV, (%)	40	2.4	3.5	1.5	4.6	6.2	6.1	10.9	10.4	17.1	4.8	34.2
US24 (Mix 2)	US24-7	40	9.6	65.7	66.5	67.7	68.2	68.3	68.3	70.15	71.97	67.65	66.07
	US24-9	40	10.3	60.8	60.3	66.2	64.4	62.5	60.1	56.43	51.56	53.28	59.43
	US24-10	40	8.5	68.1	68.1	67.7	63.3	64.0	64.4	67.11	54.58	58.86	73.11
	US24-11	40	9.5	68.8	68.4	69.4	72.4	62.5	62.8	73.44	57.49	61.59	56.58
	Average	40	9.5	65.87	65.83	67.72	67.06	64.30	63.91	66.78	58.90	60.35	63.80
	STDV	40	0.7	3.6	3.8	1.3	4.1	2.8	3.4	7.4	9.0	6.0	7.4
SR161 (Mix 4)	SR161-1	40	11.2	51.39	53.79	56.29	54.74	55.43	50.78	47.65	45.21	35.67	24.04
	SR161-2	40	10.3	50.23	51.38	52.90	54.45	53.86	50.87	47.37	45.87	35.94	35.68
	SR161-3	40	10.8	48.79	50.40	52.66	54.37	55.46	56.08	57.26	56.91	58.32	39.20
	Average	40	10.8	50.14	51.86	53.95	54.52	54.92	52.58	50.76	49.33	43.31	32.97
	STDV	40	0.4	1.3	1.7	2.0	0.2	0.9	3.0	5.6	6.6	13.0	7.9
	CV, (%)	40	4.0	2.6	3.4	3.8	0.4	1.7	5.8	11.1	13.3	30.0	24.1
SR56 (Mix 5)	SR56-1-C	40	10.0	57.53	57.06	56.90	55.17	53.68	54.41	41.40	55.12	47.25	49.40
	SR56-1-K	40	9.9	59.25	59.86	59.54	61.58	60.82	56.27	53.78	44.64	33.36	27.63
	SR56-1-L	40	8.8	60.53	62.93	63.66	64.75	61.05	55.61	51.37	52.27	50.12	39.54
	Average	40	9.6	59.10	59.95	60.03	60.50	58.52	55.43	48.85	50.68	43.58	38.86
	STDV	40	0.7	1.5	2.9	3.4	4.9	4.2	0.9	6.6	5.4	9.0	10.9
	CV, (%)	40	6.8	2.5	4.9	5.7	8.1	7.2	1.7	13.4	10.7	20.6	28.1
US30 (Mix 9)	US30-1	40	6.7	59.32	59.41	58.89	56.22	54.02	50.33	44.93	48.35	43.36	33.53
	US30-2	40	6.5	56.74	56.68	57.87	57.78	56.33	51.26	52.06	40.12	47.40	42.13
	US30-3	40	6.3	59.86	60.70	60.68	60.68	59.68	55.47	51.15	46.73	49.05	43.49
	Average	40	6.5	58.64	58.93	59.15	58.23	56.68	52.35	49.38	45.07	46.60	39.72
	STDV	40	0.2	1.7	2.1	1.4	2.3	2.8	2.7	3.9	4.4	2.9	5.4
	CV, (%)	40	3.3	2.8	3.5	2.4	3.9	5.0	5.2	7.9	9.7	6.3	13.6
SR66 (Mix 11)	SR66-01	40	13.5	56.43	56.19	58.41	57.78	57.03	54.05	59.69	37.97	38.89	37.21
	SR66-02	40	12.5	54.62	55.05	56.17	56.47	54.82	50.03	44.78	45.86	29.34	36.00
	SR66-03	40	11.8	57.26	58.86	61.77	62.27	60.89	61.73	61.28	53.76	61.46	47.61
	Average	40	12.6	56.10	56.70	58.78	58.84	57.58	55.27	55.25	45.86	43.23	40.27
	STDV	40	0.8	1.3	2.0	2.8	3.0	3.1	5.9	9.1	7.9	16.5	6.4
	CV, (%)	40	6.5	2.4	3.4	4.8	5.2	5.3	10.8	16.5	17.2	38.2	15.8
SR135 (Mix 12)	SR135-1	40	8.7	57.74	57.29	56.35	55.24	51.23	45.74	39.13	31.42	35.88	26.54
	SR135-2	40	8.4	54.87	53.37	52.95	52.56	49.49	42.10	34.99	26.66	24.07	20.41
	SR135-3	40	8.5	60.18	60.32	61.23	59.83	56.99	52.90	49.02	52.63	51.86	41.84
	Average	40	8.6	57.60	56.99	56.84	55.88	52.57	46.91	41.05	36.90	37.27	29.60
	STDV	40	0.2	2.7	3.5	4.2	3.7	3.9	5.5	7.2	13.8	13.9	11.0
	CV, (%)	40	2.0	4.6	6.1	7.3	6.6	7.5	11.7	17.6	37.5	37.4	37.3

Mix	Sample ID	Temp. (°C)	Va (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
US31 (Mix 8S)	US31-01	40	7.8	54.03	52.41	50.86	51.82	47.13	42.61	38.10	37.02	34.01	36.95
	US31-02	40	7.8	50.88	49.15	47.71	47.49	44.42	40.47	35.21	39.64	35.59	30.14
	US31-03	40	9.2	48.93	46.00	45.91	43.84	40.16	36.48	32.55	29.77	24.99	35.26
	Average	40	8.3	51.28	49.19	48.16	47.72	43.90	39.85	35.29	35.48	31.53	34.12
	STDV	40	0.8	2.6	3.2	2.5	4.0	3.5	3.1	2.8	5.1	5.7	3.5
	CV, (%)	40	9.4	5.0	6.5	5.2	8.4	8.0	7.8	7.9	14.4	18.1	10.4
I74 (Mix 9S)	I74-1	40		47.38	45.17	44.68	44.39	43.27	41.66	39.15	38.78	37.70	38.62
	I74-2	40		44.27	43.59	43.00	43.16	41.20	39.15	38.81	35.06	34.72	35.09
	I74-3	40		48.80	48.02	48.11	45.98	45.20	43.37	42.08	39.68	39.67	38.01
	Average	40		46.82	45.59	45.26	44.51	43.22	41.39	40.01	37.84	37.36	37.24
	STDV	40		2.3	2.2	2.6	1.4	2.0	2.1	1.8	2.4	2.5	1.9
	CV, (%)	40		4.9	4.9	5.8	3.2	4.6	5.1	4.5	6.5	6.7	5.1
SR64 (Mix 11S)	SR64-01	40		45.70	44.47	44.95	44.70	43.91	41.83	39.39	40.60	36.74	33.70
	SR64-02	40		48.26	47.64	48.56	47.28	47.03	45.28	43.38	43.98	43.74	43.84
	SR64-03	40		46.86	47.23	47.43	48.86	47.88	46.82	45.80	48.88	49.02	48.77
	Average	40		46.94	46.45	46.98	46.95	46.27	44.64	42.86	44.49	43.17	42.10
	STDV	40		1.3	1.7	1.8	2.1	2.1	2.6	3.2	4.2	6.2	7.7
	CV, (%)	40		2.7	3.7	3.9	4.5	4.5	5.7	7.6	9.4	14.3	18.2
I65 (Mix 12S)	I65-01	40	8.2	45.27	43.52	43.84	42.18	39.76	37.26	33.76	32.01	30.91	30.60
	I65-03	40	9.3	42.00	40.33	39.99	40.10	38.44	35.98	33.26	30.97	28.95	27.69
	I65-04	40	9.3	39.54	39.89	38.49	37.37	36.58	33.78	31.23	30.14	26.81	28.18
	Average	40	8.9	42.27	41.25	40.77	39.88	38.26	35.67	32.75	31.04	28.89	28.82
	STDV	40	0.6	2.9	2.0	2.8	2.4	1.6	1.8	1.3	0.9	2.1	1.6
	CV, (%)	40	7.0	6.8	4.8	6.8	6.0	4.2	4.9	4.1	3.0	7.1	5.4
SR15 (Mix 1)	SR15-1	54.4	11.2	69.70	74.98	70.96	63.17	53.78	47.08	47.99	35.05	35.27	41.01
	SR15-2	54.4	10.9	67.42	67.19	59.04	52.68	51.13	46.90	44.49	53.55	48.77	50.45
	SR15-3	54.4	11.5	69.92	61.02	70.53	59.87	57.78	56.74	51.21	53.85	50.13	46.31
	Average	54.4	11.2	69.01	67.73	66.84	58.57	54.23	50.24	47.90	47.48	44.72	45.92
	STDV	54.4	0.3	1.4	7.0	6.8	5.4	3.3	5.6	3.4	10.8	8.2	4.7
	CV, (%)	40	2.4	2.0	10.3	10.1	9.2	6.2	11.2	7.0	22.7	18.4	10.3
US24 (Mix 2)	US24-7	54.4	9.6	67.62	69.92	65.90	59.53	54.78	53.41	31.42	82.61	30.94	55.84
	US24-9	54.4	10.3	66.98	66.24	71.75	59.39	59.66	57.71	56.44	50.40	50.68	52.20
	US24-10	54.4	8.5	67.01	61.23	55.27	53.19	45.15	43.44	30.73	31.57	27.85	28.75
	US24-11	54.4	9.5	63.74	59.75	55.37	49.49	45.11	51.06	29.77	36.75	28.35	22.27
	Average	54.4	9.5	66.34	64.29	62.07	55.40	51.18	51.41	37.09	50.33	34.46	39.77
	STDV	54.4	0.7	1.8	4.7	8.2	4.9	7.3	6.0	12.9	22.9	10.9	16.7
SR161 (Mix 4)	SR161-1	54.4	11.2	64.09	63.51	61.38	51.68	46.93	33.77	42.77	37.63	53.14	26.36
	SR161-2	54.4	10.3	65.42	64.80	63.17	56.88	50.96	48.10	41.39	41.63	47.76	36.16
	SR161-3	54.4	10.8	66.83	64.86	61.82	58.86	52.68	52.29	52.07	40.56	35.23	25.41
	Average	54.4	10.8	65.45	64.39	62.12	55.81	50.19	44.72	45.41	39.94	45.38	29.31
	STDV	54.4	0.4	1.4	0.8	0.9	3.7	3.0	9.7	5.8	2.1	9.2	6.0
	CV, (%)	40	4.0	2.1	1.2	1.5	6.6	5.9	21.7	12.8	5.2	20.3	20.3

Mix	Sample ID	Temp. (°C)	Va (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR56 (Mix 5)	SR56-1-C	54.4	10.0	68.55	65.23	61.16	55.65	51.43	44.22	45.64	37.73	40.40	32.78
	SR56-1-K	54.4	9.9	65.38	63.40	62.48	59.04	55.31	53.92	41.16	41.47	56.65	42.91
	SR56-1-L	54.4	8.8	72.44	72.42	71.15	65.93	58.58	51.36	49.17	45.79	43.79	42.65
	Average	54.4	9.6	68.79	67.02	64.93	60.21	55.11	49.83	45.32	41.66	46.95	39.45
	STDV	54.4	0.7	3.5	4.8	5.4	5.2	3.6	5.0	4.0	4.0	8.6	5.8
	CV, (%)	40	6.8	5.1	7.1	8.4	8.7	6.5	10.1	8.9	9.7	18.3	14.6
US30 (Mix 9)	US30-1	54.4	6.7	66.73	60.71	52.88	51.35	44.91	41.69	38.33	28.54	43.30	25.97
	US30-2	54.4	6.5	71.13	69.48	65.99	59.92	52.78	46.24	42.24	30.61	35.95	30.86
	US30-3	54.4	6.3	60.94	56.70	55.79	51.03	48.50	44.39	39.70	40.05	25.14	7.50
	Average	54.4	6.5	66.27	62.30	58.22	54.10	48.73	44.11	40.09	33.07	34.80	21.44
	STDV	54.4	0.2	5.1	6.5	6.9	5.0	3.9	2.3	2.0	6.1	9.1	12.3
	CV, (%)	40	3.3	7.7	10.5	11.8	9.3	8.1	5.2	4.9	18.6	26.3	57.5
SR66 (Mix 11)	SR66-01	54.4	13.5	64.94	62.35	61.06	54.42	48.57	46.87	37.37	34.60	42.17	23.93
	SR66-02	54.4	12.5	63.41	60.94	56.62	54.34	47.69	45.29	41.11	36.65	33.37	32.05
	SR66-03	54.4	11.8	66.23	64.48	62.53	61.37	56.79	59.73	49.11	39.80	46.31	39.60
	Average	54.4	12.6	64.86	62.59	60.07	56.71	51.02	50.63	42.53	37.02	40.62	31.86
	STDV	54.4	0.8	1.4	1.8	3.1	4.0	5.0	7.9	6.0	2.6	6.6	7.8
	CV, (%)	40	6.5	2.2	2.8	5.1	7.1	9.8	15.6	14.1	7.1	16.3	24.6
SR135 (Mix 12)	SR135-1	54.4	8.7	63.63	65.99	56.89	50.24	46.15	39.18	43.92	31.03	38.05	30.68
	SR135-2	54.4	8.4	63.41	56.34	44.94	39.15	31.78	27.76	19.89	10.96	17.55	15.52
	SR135-3	54.4	8.5	65.48	62.67	61.86	54.13	48.80	51.66	40.46	29.04	34.07	33.24
	Average	54.4	8.6	64.17	61.67	54.56	47.84	42.24	39.53	34.76	23.68	29.89	26.48
	STDV	54.4	0.2	1.1	4.9	8.7	7.8	9.2	12.0	13.0	11.1	10.9	9.6
	CV, %	54.4	2.0	1.8	8.0	15.9	16.2	21.7	30.2	37.4	46.7	36.4	36.2
US31 (Mix 8S)	US31-01	54.4	7.8	52.51	49.27	44.29	42.09	41.47	41.00	39.86	40.93	42.61	43.16
	US31-02	54.4	7.8	49.86	46.33	41.68	38.59	36.50	33.42	30.34	29.85	28.76	30.83
	US31-03	54.4	9.2	49.88	46.71	43.28	38.42	35.91	30.93	29.70	28.71	24.45	30.74
	Average	54.4	8.3	50.75	47.44	43.08	39.70	37.96	35.12	33.30	33.16	31.94	34.91
	STDV	54.4	0.8	1.5	1.6	1.3	2.1	3.1	5.2	5.7	6.8	9.5	7.1
	CV, (%)	40	9.4	3.0	3.4	3.1	5.2	8.0	14.9	17.1	20.4	29.7	20.5
I74 (Mix 9S)	I74-1	54.4		50.11	49.88	44.88	43.41	40.16	40.28	35.33	32.27	30.42	28.84
	I74-2	54.4		51.68	48.26	49.06	46.52	43.98	43.31	42.72	44.33	44.37	45.25
	I74-3	54.4		55.07	54.23	48.60	48.20	44.13	37.48	37.34	36.53	39.44	41.99
	Average	54.4		52.29	50.79	47.51	46.04	42.76	40.36	38.46	37.71	38.08	38.69
	STDV	54.4		2.5	3.1	2.3	2.4	2.3	2.9	3.8	6.1	7.1	8.7
	CV, (%)	40		4.8	6.1	4.8	5.3	5.3	7.2	9.9	16.2	18.6	22.5
SR64 (Mix 11S)	SR64-01	54.4		52.94	50.34	47.09	44.47	41.50	39.97	36.49	36.84	21.25	30.96
	SR64-02	54.4		59.57	59.21	55.72	54.86	56.87	55.81	53.52	55.26	54.66	57.06
	SR64-03	54.4		56.86	53.68	51.69	51.21	45.88	39.59	43.38	36.08	49.64	38.14
	Average	54.4		56.46	54.41	51.50	50.18	48.08	45.12	44.46	42.73	41.85	42.05
	STDV	54.4		3.3	4.5	4.3	5.3	7.9	9.3	8.6	10.9	18.0	13.5
	CV, (%)	40		5.9	8.2	8.4	10.5	16.5	20.5	19.3	25.4	43.0	32.1
I65 (Mix 12S)	I65-01	54.4	8.2	50.29	45.96	42.45	39.27	36.27	32.62	26.61	27.44	21.35	22.33
	I65-03	54.4	9.3	48.84	44.99	42.42	39.63	36.65	31.92	29.91	29.59	27.74	26.14
	I65-04	54.4	9.3	48.17	45.74	43.27	40.21	38.08	33.55	29.57	27.01	21.93	22.90
	Average	54.4	8.9	49.10	45.56	42.71	39.70	37.00	32.70	28.70	28.01	23.67	23.79
	STDV	54.4	0.6	1.1	0.5	0.5	0.5	1.0	0.8	1.8	1.4	3.5	2.1
	CV, (%)	40	7.0	2.2	1.1	1.1	1.2	2.6	2.5	6.3	4.9	14.9	8.6

Mix	Sample ID	Temp. (°C)	Va (%)	Shear (Complex) Modulus [G*] (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR15 (Mix 1)	SR15-1	40	9.4	406.2	307.9	202.3	141.5	97.4	61.3	42.2	28.8	19.1	11.6
	SR15-2	40	10.0	156.4	112.4	76.1	53.8	38.7	24.1	17.1	12.6	9.0	5.2
	SR15-3	40	9.6	376.9	272.9	165.5	116.3	79.6	45.8	31.9	20.0	11.9	8.2
	Average	40	9.6	313.2	231.1	148.0	103.8	71.9	43.7	30.4	20.4	13.3	8.3
	STDV	40	0.3	136.6	104.2	64.9	45.2	30.1	18.7	12.6	8.1	5.2	3.2
	CV, %	40	3.1	43.6	45.1	43.9	43.5	41.9	42.8	41.5	39.7	38.9	38.5
US24 (Mix 2)	US24-1	40	4.7	469.0	336.9	214.4	149.1	104.6	63.6	46.0	33.6	23.9	15.7
	US24-2	40	4.8	542.1	373.1	231.2	162.7	113.0	72.0	53.3	37.6	34.1	19.4
	US24-3	40	5.2	493.4	346.9	222.3	151.7	103.4	62.0	42.2	29.7	17.2	11.5
	Average	40	4.9	501.5	352.3	222.6	154.5	107.0	65.9	47.2	33.6	25.1	15.5
	STDV	40	0.3	37.2	18.7	8.4	7.2	5.2	5.4	5.6	3.9	8.5	3.9
	CV, %	40	5.6	7.4	5.3	3.8	4.6	4.9	8.2	11.9	11.7	34.0	25.4
SR161 (Mix 4)	SR161-1	40	10.6	551.9	424.6	287.9	212.4	155.9	98.8	69.9	49.2	31.3	18.7
	SR161-2	40	10.7	485.0	369.1	237.5	173.8	124.8	78.7	55.9	40.9	23.3	17.9
	SR161-3	40	10.8	604.7	449.4	300.7	215.9	151.6	94.7	66.0	46.8	27.5	21.1
	Average	40	10.7	547.2	414.4	275.4	200.7	144.1	90.7	63.9	45.6	27.4	19.2
	STDV	40	0.1	60.0	41.1	33.4	23.4	16.8	10.6	7.3	4.3	4.0	1.7
	CV, %	40	1.0	11.0	9.9	12.1	11.6	11.7	11.7	11.4	9.4	14.7	8.7
SR56 (Mix 5)	SR56-1	40	8.7	500.9	378.0	247.1	174.6	121.7	74.6	48.7	32.7	22.2	12.5
	SR56-2	40	7.6	874.9	650.0	419.1	296.3	203.6	122.6	82.3	51.0	32.0	21.7
	SR56-3	40	6.1	629.5	464.8	292.5	204.3	142.9	88.7	59.2	41.9	23.9	16.3
	Average	40	7.5	668.5	497.6	319.6	225.1	156.1	95.3	63.4	41.9	26.1	16.9
	STDV	40	1.3	190.0	138.9	89.1	63.4	42.5	24.7	17.2	9.1	5.2	4.6
	CV, %	40	17.0	28.4	27.9	27.9	28.2	27.2	25.9	27.1	21.8	20.1	27.3
US30 (Mix 9)	US30-1	40	3.4	516.9	417.0	312.2	252.8	207.5	161.5	134.0	110.7	87.5	72.1
	US30-2	40	3.3	619.2	444.2	277.5	190.1	137.1	87.7	61.2	48.3	30.0	22.7
	US30-3	40	4.0	460.3	326.6	201.4	137.2	94.4	57.7	40.3	28.0	16.9	16.0
	Average	40	3.6	532.1	395.9	263.7	193.4	146.4	102.3	78.5	62.3	44.8	36.9
	STDV	40	0.4	80.6	61.6	56.7	57.9	57.1	53.4	49.2	43.1	37.5	30.7
	CV, %	40	10.3	15.1	15.6	21.5	29.9	39.0	52.2	62.6	69.2	83.8	83.0
SR66 (Mix 11)	SR66-01	40	7.9	306.5	231.0	150.8	108.4	77.5	49.1	33.7	24.3	14.5	12.7
	SR66-02	40	8.7	371.0	278.6	190.2	138.1	99.7	64.9	47.7	34.2	22.3	18.3
	SR66-03	40	9.0	330.2	252.1	162.9	116.9	81.8	51.0	34.1	25.9	17.7	9.1
	Average	40	8.5	335.9	253.9	168.0	121.1	86.3	55.0	38.5	28.1	18.2	13.4
	STDV	40	0.6	32.6	23.9	20.2	15.2	11.8	8.6	8.0	5.3	3.9	4.6
	CV, %	40	6.8	9.7	9.4	12.0	12.6	13.7	15.7	20.8	18.9	21.5	34.5
SR135 (Mix 12)	SR135-1	40	3.3	585.5	420.4	267.1	189.3	134.0	85.7	59.0	46.3	31.8	23.6
	SR135-2	40	3.6	675.0	516.7	342.6	248.3	178.6	112.4	81.4	56.9	37.6	23.6
	SR135-3	40	3.7	851.7	639.5	441.0	305.5	218.8	145.6	109.5	79.8	54.6	42.0
	Average	40	3.5	704.1	525.5	350.2	247.7	177.2	114.6	83.3	61.0	41.3	29.7
	STDV	40	0.2	135.5	109.8	87.2	58.1	42.4	30.0	25.3	17.1	11.9	10.6
	CV, %	40	5.6	19.2	20.9	24.9	23.5	24.0	26.2	30.4	28.0	28.7	35.8

Mix	Sample ID	Temp. (°C)	Va (%)	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
US31 (Mix 8S)	US31-01	40	9.3	346.1	259.3	168.4	125.1	94.6	66.3	54.3	40.4	31.7	27.1
	US31-02	40	9.4	286.6	213.3	136.2	102.7	76.2	53.9	43.3	30.1	23.2	24.7
	US31-03	40	8.9	313.3	235.2	155.6	115.7	86.5	60.6	50.4	40.6	30.7	23.9
	Average	40	9.2	315.3	235.9	153.4	114.5	85.7	60.3	49.3	37.0	28.6	25.2
	STDV	40	0.3	29.8	23.0	16.2	11.2	9.2	6.2	5.6	6.0	4.6	1.7
	CV, %	40	3.2	9.5	9.8	10.6	9.8	10.7	10.3	11.3	16.2	16.2	6.7
I74 (Mix 9S)	I74-1	40	5.4	494.2	357.4	238.0	171.4	125.0	82.6	63.3	48.2	34.5	25.8
	I74-2	40	5.5	465.0	352.8	236.8	173.7	128.9	86.0	65.2	49.6	37.0	28.7
	I74-3	40	7.2	401.2	301.4	205.0	150.3	112.6	77.8	59.0	46.0	32.3	26.4
	Average	40	6.0	453.4	337.2	226.6	165.1	122.1	82.1	62.5	47.9	34.6	27.0
	STDV	40	1.0	47.6	31.1	18.7	12.9	8.5	4.1	3.2	1.8	2.3	1.5
	CV, %	40	16.7	10.5	9.2	8.3	7.8	7.0	5.0	5.1	3.7	6.7	5.7
SR64 (Mix 11S)	SR64-01	40	10.6	1150.0	884.0	613.3	457.2	330.3	216.3	155.7	113.3	75.3	55.2
	SR64-02	40	10.2	1073.9	831.9	591.7	439.9	326.7	220.3	164.9	124.0	85.0	62.8
	SR64-03	40	11.0	752.2	601.3	435.7	331.6	251.6	172.8	131.1	96.8	67.9	52.5
	Average	40	10.6	992.0	772.4	546.9	409.6	302.9	203.1	150.6	111.4	76.0	56.9
	STDV	40	0.4	211.2	150.5	96.9	68.1	44.4	26.3	17.5	13.7	8.6	5.3
	CV, %	40	3.9	21.3	19.5	17.7	16.6	14.7	13.0	11.6	12.3	11.3	9.4
I65 (Mix 12S)	I65-01	40	12.4	402.7	315.6	219.9	161.1	125.4	89.1	70.2	56.6	44.2	36.5
	I65-02	40	12.1	519.4	410.3	282.8	225.5	181.6	128.5	106.1	83.0	69.1	65.0
	I65-03	40	12.7	390.5	301.4	206.4	154.1	116.3	79.5	62.8	48.0	38.1	28.7
	Average	40	12.4	437.5	342.4	236.4	180.2	141.1	99.0	79.7	62.5	50.5	43.4
	STDV	40	0.3	71.2	59.2	40.8	39.4	35.3	26.0	23.2	18.3	16.4	19.1
	CV, %	40	2.1	16.3	17.3	17.3	21.8	25.1	26.3	29.1	29.2	32.6	44.0
SR15 (Mix 1)	SR15-1	54.4	9.4	134.3	99.1	62.0	42.8	30.0	21.4	16.1	12.3	10.3	12.5
	SR15-2	54.4	10.0	151.7	123.4	85.8	74.9	71.5	60.0	55.8	40.7	44.5	42.2
	SR15-3	54.4	9.6	155.7	128.5	83.2	63.4	49.9	39.0	30.6	24.7	25.8	24.7
	Average	54.4	9.6	147.2	117.0	77.0	60.4	50.5	40.1	34.2	25.9	26.9	26.5
	STDV	54.4	0.3	11.4	15.7	13.0	16.3	20.8	19.3	20.1	14.2	17.1	15.0
	CV, %	54.4	3.1	7.7	13.4	16.9	26.9	41.2	48.2	58.8	54.8	63.7	56.5
US24 (Mix 2)	US24-1	54.4	4.7	144.5	102.0	60.0	38.4	26.5	16.0	11.6	10.4	9.5	7.2
	US24-2	54.4	4.8	166.0	120.1	80.7	59.5	45.4	35.8	33.3	25.1	24.8	24.6
	US24-3	54.4	5.2	180.5	141.1	88.4	63.8	51.5	36.7	28.5	26.3	24.8	21.3
	Average	54.4	4.9	163.7	121.0	76.4	53.9	41.1	29.5	24.5	20.6	19.7	17.7
	STDV	54.4	0.3	18.1	19.6	14.7	13.6	13.0	11.7	11.4	8.8	8.8	9.3
	CV, %	54.4	5.6	11.1	16.2	19.2	25.2	31.7	39.6	46.5	42.9	44.7	52.3
SR161 (Mix 4)	SR161-1	54.4	10.6	105.5	75.1	45.3	36.2	28.9	22.1	18.6	18.3	16.8	12.6
	SR161-2	54.4	10.7	98.7	70.5	43.9	30.8	22.5	16.0	11.1	11.3	7.9	6.2
	SR161-3	54.4	10.8	170.5	121.1	74.2	50.5	33.5	20.7	15.9	9.8	7.4	6.5
	Average	54.4	10.7	124.9	88.9	54.5	39.2	28.3	19.6	15.2	13.1	10.7	8.4
	STDV	54.4	0.1	39.6	28.0	17.1	10.1	5.5	3.2	3.8	4.6	5.3	3.6
	CV, %	54.4	1.0	31.7	31.5	31.4	25.9	19.6	16.4	25.0	34.6	49.3	42.9

Mix	Sample ID	Temp. (°C)	Va (%)	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR56 (Mix 5)	SR56-1	54.4	8.7	147.1	103.5	64.4	44.4	30.5	19.8	15.6	10.5	8.0	8.1
	SR56-2	54.4	7.6	163.2	113.4	68.9	46.8	30.8	19.7	19.0	12.1	8.2	5.6
	SR56-3	54.4	6.1	175.0	121.9	71.1	47.4	31.3	19.9	11.1	9.5	6.6	3.2
	Average	54.4	7.5	161.8	113.0	68.1	46.2	30.9	19.8	15.2	10.7	7.6	5.6
	STDV	54.4	1.3	14.0	9.2	3.4	1.6	0.4	0.1	4.0	1.3	0.9	2.4
	CV, %	54.4	17.0	8.7	8.1	5.0	3.4	1.2	0.4	26.0	11.9	11.6	43.0
US30 (Mix 9)	US30-1	54.4	3.4	314.3	288.4	250.9	205.1	164.5	137.2	113.5	104.5	92.6	79.1
	US30-2	54.4	3.3	226.5	192.5	153.6	127.2	101.7	80.8	66.7	61.2	48.1	47.7
	US30-3	54.4	4.0	215.2	179.0	140.5	102.6	81.6	66.8	60.8	48.9	42.0	43.4
	Average	54.4	3.6	252.0	220.0	181.7	145.0	115.9	94.9	80.4	71.5	60.9	56.7
	STDV	54.4	0.4	54.3	59.6	60.3	53.5	43.3	37.3	28.9	29.2	27.6	19.5
	CV, %	54.4	10.3	21.5	27.1	33.2	36.9	37.3	39.3	35.9	40.8	45.3	34.4
SR66 (Mix 11)	SR66-01	54.4	7.9	117.5	87.1	56.7	41.0	30.9	20.9	14.1	12.6	10.0	6.7
	SR66-02	54.4	8.7	138.2	100.7	63.6	44.8	33.4	21.0	15.3	13.4	9.3	9.8
	SR66-03	54.4	9.0	122.9	92.3	59.8	42.6	30.9	20.7	16.4	12.0	9.3	4.9
	Average	54.4	8.5	126.2	93.4	60.1	42.8	31.8	20.9	15.3	12.7	9.5	7.1
	STDV	54.4	0.6	10.7	6.9	3.5	1.9	1.4	0.1	1.2	0.7	0.4	2.5
	CV, %	54.4	6.8	8.5	7.3	5.8	4.5	4.4	0.7	7.6	5.6	4.0	34.7
SR135 (Mix 12)	SR135-1	54.4	3.3	262.9	213.0	168.2	122.5	94.8	77.8	62.5	52.1	47.5	45.2
	SR135-2	54.4	3.6	232.7	194.9	136.3	104.7	77.0	60.8	50.8	48.8	38.3	38.7
	SR135-3	54.4	3.7	223.2	175.0	109.0	86.4	67.7	50.8	44.7	35.8	36.1	34.8
	Average	54.4	3.5	239.6	194.3	137.8	104.5	79.8	63.1	52.7	45.6	40.6	39.6
	STDV	54.4	0.2	20.7	19.0	29.6	18.1	13.7	13.7	9.0	8.6	6.0	5.2
	CV, %	54.4	5.6	8.6	9.8	21.5	17.3	17.2	21.6	17.1	18.8	14.8	13.3
US31 (Mix 8S)	US31-01	54.4	9.3	69.3	58.8	42.7	35.7	31.8	27.1	25.0	22.9	22.8	24.5
	US31-02	54.4	9.4	77.8	56.1	38.5	28.1	21.7	17.0	12.9	9.8	7.5	7.6
	US31-03	54.4	8.9	69.7	49.2	35.6	27.6	21.2	17.3	14.4	11.1	9.3	8.8
	Average	54.4	9.2	72.3	54.7	38.9	30.5	24.9	20.5	17.4	14.6	13.2	13.6
	STDV	54.4	0.3	4.8	5.0	3.6	4.6	6.0	5.7	6.6	7.2	8.3	9.4
	CV, %	54.4	3.2	6.6	9.1	9.2	15.0	24.1	27.9	38.0	49.3	63.2	69.0
I74 (Mix 9S)	I74-1	54.4	5.4	128.7	98.2	63.0	44.2	34.5	23.5	18.3	14.5	12.4	11.2
	I74-2	54.4	5.5	153.6	113.4	73.5	52.7	39.6	26.6	20.3	15.9	14.6	12.0
	I74-3	54.4	7.2	110.8	80.1	51.3	36.0	26.6	18.7	15.0	12.4	11.4	7.3
	Average	54.4	6.0	131.0	97.2	62.6	44.3	33.5	22.9	17.8	14.3	12.8	10.2
	STDV	54.4	1.0	21.4	16.7	11.1	8.4	6.6	4.0	2.6	1.8	1.6	2.5
	CV, %	54.4	16.7	16.4	17.2	17.7	18.8	19.6	17.4	14.8	12.3	12.8	24.9
SR64 (Mix 11S)	SR64-01	54.4	10.6	173.8	123.9	77.5	54.9	38.9	26.5	19.9	15.4	11.1	12.8
	SR64-02	54.4	10.2	170.7	123.9	82.1	59.9	42.5	29.0	21.6	15.1	13.8	10.9
	SR64-03	54.4	11.0	142.3	109.2	69.1	50.2	39.8	29.0	23.8	20.6	16.8	14.0
	Average	54.4	10.6	162.3	119.0	76.2	55.0	40.4	28.1	21.7	17.0	13.9	12.6
	STDV	54.4	0.4	17.4	8.5	6.6	4.9	1.9	1.4	2.0	3.1	2.9	1.6
	CV, %	54.4	3.9	10.7	7.1	8.7	8.8	4.6	5.1	9.0	18.1	20.5	12.4
I65 (Mix 12S)	I65-01	54.4	12.4	156.0	121.1	81.5	62.3	47.7	34.9	28.6	23.2	19.3	17.4
	I65-02	54.4	12.1	122.5	91.9	62.2	46.2	35.4	26.6	22.2	17.3	15.3	14.3
	I65-03	54.4	12.7	139.2	99.6	67.2	49.1	36.1	24.7	20.4	12.9	12.1	9.3
	Average	54.4	12.4	139.2	104.2	70.3	52.5	39.7	28.7	23.8	17.8	15.6	13.7
	STDV	54.4	0.3	16.8	15.1	10.0	8.6	6.9	5.4	4.3	5.2	3.6	4.1
	CV, %	54.4	2.1	12.0	14.5	14.2	16.3	17.4	18.7	18.1	29.1	22.9	29.8

Mix	Sample ID	Temp. (°C)	Va (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR15 (Mix 1)	SR15-1	40	9.4	46.26	47.49	51.05	53.19	52.87	53.43	52.11	48.20	46.76	39.77
	SR15-2	40	10.0	67.53	60.96	60.01	57.02	53.48	49.22	47.92	51.90	47.13	40.94
	SR15-3	40	9.6	51.11	51.74	51.71	55.80	55.39	53.59	52.71	56.29	48.66	22.69
	Average	40	9.6	54.97	53.40	54.26	55.34	53.91	52.08	50.91	52.13	47.52	34.47
	STDV	40	0.3	11.1	6.9	5.0	2.0	1.3	2.5	2.6	4.0	1.0	10.2
	CV, %	40	3.1	20.3	12.9	9.2	3.5	2.4	4.8	5.1	7.8	2.1	29.6
US24 (Mix 2)	US24-1	40	4.7	50.1	52.1	52.2	53.0	51.2	50.3	47.76	49.14	46.73	36.48
	US24-2	40	4.8	53.4	54.0	55.4	53.8	50.8	49.0	45.76	40.94	35.69	34.71
	US24-3	40	5.2	50.8	52.5	54.1	54.5	55.0	51.9	51.69	54.52	43.01	64.03
	Average	40	4.9	51.43	52.87	53.88	53.74	52.33	50.40	48.40	48.20	41.81	45.07
	STDV	40	0.3	1.7	1.0	1.6	0.7	2.3	1.4	3.0	6.8	5.6	16.4
	CV, %	40	5.6	3.4	1.8	2.9	1.4	4.4	2.8	6.2	14.2	13.4	36.5
SR161 (Mix 4)	SR161-1	40	10.6	40.38	40.73	42.34	43.30	44.86	44.98	45.75	47.48	48.24	47.69
	SR161-2	40	10.7	44.00	43.60	46.06	46.25	47.34	47.01	45.68	41.92	46.84	41.94
	SR161-3	40	10.8	43.04	43.60	45.59	47.72	48.56	50.36	51.40	49.79	45.65	51.35
	Average	40	10.7	42.47	42.64	44.66	45.76	46.92	47.45	47.61	46.40	46.91	46.99
	STDV	40	0.1	1.9	1.7	2.0	2.3	1.9	2.7	3.3	4.0	1.3	4.7
	CV, %	40	1.0	4.4	3.9	4.5	4.9	4.0	5.7	6.9	8.7	2.8	10.1
SR56 (Mix 5)	SR56-1	40	8.7	44.45	44.33	46.87	49.50	49.83	51.12	52.68	52.36	51.45	49.40
	SR56-2	40	7.6	44.60	45.73	47.69	49.63	51.37	52.37	52.83	52.43	50.15	51.82
	SR56-3	40	6.1	47.21	47.63	49.90	50.10	51.12	50.85	52.24	52.31	53.04	48.79
	Average	40	7.5	45.42	45.90	48.15	49.74	50.77	51.45	52.58	52.37	51.55	50.00
	STDV	40	1.3	1.6	1.7	1.6	0.3	0.8	0.8	0.3	0.1	1.4	1.6
	CV, %	40	17.0	3.4	3.6	3.3	0.6	1.6	1.6	0.6	0.1	2.8	3.2
US30 (Mix 9)	US30-1	40	3.4	39.27	36.98	35.19	33.19	31.17	30.03	28.98	28.26	28.24	29.44
	US30-2	40	3.3	53.03	52.29	54.27	53.49	51.39	48.05	46.48	45.55	36.98	43.06
	US30-3	40	4.0	51.80	51.87	53.17	53.88	53.52	52.91	50.27	51.99	43.06	41.20
	Average	40	3.6	48.03	47.05	47.54	46.85	45.36	43.66	41.91	41.93	36.09	37.90
	STDV	40	0.4	7.6	8.7	10.7	11.8	12.3	12.1	11.4	12.3	7.4	7.4
	CV, %	40	10.3	15.9	18.5	22.5	25.3	27.2	27.6	27.1	29.3	20.6	19.5
SR66 (Mix 11)	SR66-01	40	7.9	47.48	46.43	48.43	48.29	48.21	48.27	48.10	49.01	39.19	46.20
	SR66-02	40	8.7	44.87	44.41	45.52	46.31	46.58	46.53	47.37	43.75	47.57	39.95
	SR66-03	40	9.0	48.32	47.15	48.10	49.60	49.38	48.47	47.59	47.20	48.34	50.28
	Average	40	8.5	46.89	46.00	47.35	48.07	48.06	47.76	47.69	46.65	45.03	45.48
	STDV	40	0.6	1.8	1.4	1.6	1.7	1.4	1.1	0.4	2.7	5.1	5.2
	CV, %	40	6.8	3.8	3.1	3.4	3.4	2.9	2.2	0.8	5.7	11.3	11.4
SR135 (Mix 12)	SR135-1	40	3.3	48.59	48.79	49.47	49.34	48.92	47.07	44.73	43.97	33.62	38.84
	SR135-2	40	3.6	41.78	42.92	45.88	46.82	47.07	47.16	46.64	43.22	37.05	42.17
	SR135-3	40	3.7	43.80	44.03	45.17	47.74	46.64	44.53	41.07	39.66	36.01	38.49
	Average	40	3.5	44.72	45.25	46.84	47.97	47.54	46.25	44.15	42.28	35.56	39.83
	STDV	40	0.2	3.5	3.1	2.3	1.3	1.2	1.5	2.8	2.3	1.8	2.0
	CV, %	40	5.6	7.8	6.9	4.9	2.7	2.5	3.2	6.4	5.4	4.9	5.1

Mix	Sample ID	Temp. (°C)	Va (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
US31 (Mix 8S)	US31-01	40	9.3	50.44	47.70	46.88	44.28	41.60	38.95	36.88	34.61	30.68	34.53
	US31-02	40	9.4	53.52	49.54	47.25	44.89	42.30	37.40	35.36	36.63	43.35	24.11
	US31-03	40	8.9	50.77	47.32	45.13	43.52	41.48	37.19	32.93	33.18	31.89	28.07
	Average	40	9.2	51.58	48.19	46.42	44.23	41.79	37.85	35.06	34.81	35.31	28.90
	STDV	40	0.3	1.7	1.2	1.1	0.7	0.4	1.0	2.0	1.7	7.0	5.3
	CV, %	40	3.2	3.3	2.5	2.4	1.6	1.1	2.5	5.7	5.0	19.8	18.2
I74 (Mix 9S)	I74-1	40	5.4	49.16	47.43	46.69	46.02	45.45	42.75	40.26	40.23	39.74	34.38
	I74-2	40	5.5	46.75	45.11	45.51	45.32	44.93	42.97	43.96	42.36	38.74	42.48
	I74-3	40	7.2	48.00	45.99	45.32	43.97	42.95	41.02	38.56	40.06	39.29	37.89
	Average	40	6.0	47.97	46.18	45.84	45.10	44.44	42.25	40.93	40.88	39.26	38.25
	STDV	40	1.0	1.2	1.2	0.7	1.0	1.3	1.1	2.8	1.3	0.5	4.1
	CV, %	40	16.7	2.5	2.5	1.6	2.3	3.0	2.5	6.7	3.1	1.3	10.6
SR64 (Mix 11S)	SR64-01	40	10.6	39.17	39.60	40.90	41.99	44.15	44.91	45.19	45.98	44.09	44.54
	SR64-02	40	10.2	37.07	37.39	39.01	40.75	41.31	41.21	40.31	40.97	40.71	41.51
	SR64-03	40	11.0	37.33	36.68	37.41	38.42	38.60	38.98	39.38	39.73	39.23	38.89
	Average	40	10.6	37.86	37.89	39.11	40.39	41.35	41.70	41.63	42.23	41.34	41.65
	STDV	40	0.4	1.1	1.5	1.7	1.8	2.8	3.0	3.1	3.3	2.5	2.8
	CV, %	40	3.9	3.0	4.0	4.5	4.5	6.7	7.2	7.5	7.8	6.0	6.8
I65 (Mix 12S)	I65-01	40	12.4	46.95	45.90	48.24	48.54	47.69	45.31	43.78	41.57	43.49	40.07
	I65-02	40	12.1	47.38	47.15	48.59	46.80	45.68	47.40	45.94	45.86	45.28	48.45
	I65-03	40	12.7	47.48	46.70	47.11	47.39	46.92	45.16	42.77	43.18	36.08	37.30
	Average	40	12.4	47.27	46.58	47.98	47.58	46.76	45.96	44.16	43.54	41.62	41.94
	STDV	40	0.3	0.3	0.6	0.8	0.9	1.0	1.3	1.6	2.2	4.9	5.8
	CV, %	40	2.1	0.6	1.4	1.6	1.9	2.2	2.7	3.7	5.0	11.7	13.8
SR15 (Mix 1)	SR15-1	54.4	9.4	65.08	63.77	64.89	64.22	60.70	62.66	70.32	74.23	56.62	49.30
	SR15-2	54.4	10.0	82.40	77.91	71.02	56.23	56.36	49.55	48.17	40.90	45.85	53.70
	SR15-3	54.4	9.6	66.77	62.30	68.05	61.23	59.22	59.91	59.12	60.45	56.26	61.41
	Average	54.4	9.6	71.42	67.99	67.99	60.56	58.76	57.37	59.20	58.53	52.91	54.80
	STDV	54.4	0.3	9.5	8.6	3.1	4.0	2.2	6.9	11.1	16.7	6.1	6.1
	CV, %	54.4	3.1	13.4	12.7	4.5	6.7	3.8	12.0	18.7	28.6	11.6	11.2
US24 (Mix 2)	US24-1	54.4	4.7	64.92	64.93	64.73	62.50	58.92	56.03	51.73	70.71	48.32	38.94
	US24-2	54.4	4.8	70.76	70.53	66.02	55.84	56.07	52.07	50.29	46.02	50.82	50.43
	US24-3	54.4	5.2	70.45	65.61	71.00	65.75	59.47	55.04	57.29	58.29	60.14	63.64
	Average	54.4	4.9	68.71	67.02	67.25	61.36	58.15	54.38	53.10	58.34	53.09	51.00
	STDV	54.4	0.3	3.3	3.1	3.3	5.1	1.8	2.1	3.7	12.3	6.2	12.4
	CV, %	54.4	5.6	4.8	4.6	4.9	8.2	3.1	3.8	7.0	21.2	11.7	24.2
SR161 (Mix 4)	SR161-1	54.4	10.6	60.77	60.04	59.04	56.66	54.80	53.71	52.60	53.60	54.92	50.28
	SR161-2	54.4	10.7	62.08	61.18	57.52	60.45	56.12	53.90	48.75	49.63	54.32	41.56
	SR161-3	54.4	10.8	58.54	57.23	57.38	57.21	55.55	52.46	53.09	51.61	51.26	13.49
	Average	54.4	10.7	60.46	59.48	57.98	58.11	55.49	53.36	51.48	51.61	53.50	35.11
	STDV	54.4	0.1	1.8	2.0	0.9	2.0	0.7	0.8	2.4	2.0	2.0	19.2
	CV, %	54.4	1.0	3.0	3.4	1.6	3.5	1.2	1.5	4.6	3.8	3.7	54.8

Mix	Sample ID	Temp. (°C)	Va (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
SR56 (Mix 5)	SR56-1	54.4	8.7	61.33	58.49	59.01	55.48	56.48	57.43	58.05	48.07	51.77	36.64
	SR56-2	54.4	7.6	62.35	61.09	59.92	59.09	55.98	52.42	41.32	31.79	40.94	53.70
	SR56-3	54.4	6.1	62.42	60.59	60.35	58.12	57.22	57.08	44.76	41.77	50.17	34.52
	Average	54.4	7.5	62.03	60.06	59.76	57.56	56.56	55.64	48.04	40.54	47.63	41.62
	STDV	54.4	1.3	0.6	1.4	0.7	1.9	0.6	2.8	8.8	8.2	5.8	10.5
	CV, %	54.4	17.0	1.0	2.3	1.1	3.2	1.1	5.0	18.4	20.2	12.3	25.3
US30 (Mix 9)	US30-1	54.4	3.4	55.69	45.90	51.00	54.44	52.17	49.52	46.46	42.79	44.63	42.42
	US30-2	54.4	3.3	68.36	56.93	58.60	56.84	58.16	56.75	58.72	56.20	54.30	54.17
	US30-3	54.4	4.0	65.19	59.36	62.75	59.28	60.31	58.72	56.91	57.31	55.95	59.66
	Average	54.4	3.6	63.08	54.06	57.45	56.85	56.88	55.00	54.03	52.10	51.63	52.08
	STDV	54.4	0.4	6.6	7.2	6.0	2.4	4.2	4.8	6.6	8.1	6.1	8.8
	CV, %	54.4	10.3	10.5	13.3	10.4	4.3	7.4	8.8	12.2	15.5	11.8	16.9
SR66 (Mix 11)	SR66-01	54.4	7.9	58.47	56.33	55.45	52.50	50.19	47.27	43.67	41.90	46.52	32.17
	SR66-02	54.4	8.7	59.34	57.50	55.73	54.17	53.27	48.38	51.31	42.33	50.60	37.79
	SR66-03	54.4	9.0	56.99	54.45	55.23	52.63	50.38	48.20	51.74	46.95	56.81	29.25
	Average	54.4	8.5	58.27	56.09	55.47	53.10	51.28	47.95	48.91	43.73	51.31	33.07
	STDV	54.4	0.6	1.2	1.5	0.3	0.9	1.7	0.6	4.5	2.8	5.2	4.3
	CV, %	54.4	6.8	2.0	2.7	0.5	1.7	3.4	1.2	9.3	6.4	10.1	13.1
SR135 (Mix 12)	SR135-1	54.4	3.3	63.24	59.95	63.32	63.28	62.31	58.07	57.74	56.63	58.52	56.12
	SR135-2	54.4	3.6	66.83	61.48	65.42	65.91	62.29	59.05	55.16	53.72	55.34	53.47
	SR135-3	54.4	3.7	67.31	63.55	61.29	56.40	54.91	50.94	49.09	45.19	38.30	26.78
	Average	54.4	3.5	65.79	61.66	63.34	61.86	59.84	56.02	54.00	51.85	50.72	45.46
	STDV	54.4	0.2	2.2	1.8	2.1	4.9	4.3	4.4	4.4	5.9	10.9	16.2
	CV, %	54.4	5.6	3.4	2.9	3.3	7.9	7.1	7.9	8.2	11.5	21.4	35.7
US31 (Mix 8S)	US31-01	54.4	9.3	53.03	47.98	45.44	42.39	40.36	40.33	40.39	40.54	43.40	44.98
	US31-02	54.4	9.4	55.82	52.12	51.23	48.86	45.17	44.41	29.08	38.37	36.52	44.81
	US31-03	54.4	8.9	53.09	50.20	45.36	42.26	39.89	34.10	34.07	30.35	34.21	26.84
	Average	54.4	9.2	53.98	50.10	47.34	44.50	41.81	39.61	34.51	36.42	38.04	38.88
	STDV	54.4	0.3	1.6	2.1	3.4	3.8	2.9	5.2	5.7	5.4	4.8	10.4
	CV, %	54.4	3.2	3.0	4.1	7.1	8.5	7.0	13.1	16.4	14.7	12.6	26.8
I74 (Mix 9S)	I74-1	54.4	5.4	56.79	52.17	49.93	47.77	44.26	40.12	40.53	37.28	26.68	29.16
	I74-2	54.4	5.5	56.07	52.95	52.05	51.46	49.92	46.40	40.32	49.18	37.86	40.94
	I74-3	54.4	7.2	58.55	54.26	53.53	50.32	46.30	45.13	43.03	39.12	49.09	13.35
	Average	54.4	6.0	57.14	53.13	51.84	49.85	46.83	43.88	41.29	41.86	37.88	27.82
	STDV	54.4	1.0	1.3	1.1	1.8	1.9	2.9	3.3	1.5	6.4	11.2	13.8
	CV, %	54.4	16.7	2.2	2.0	3.5	3.8	6.1	7.6	3.7	15.3	29.6	49.8
SR64 (Mix 11S)	SR64-01	54.4	10.6	57.67	54.45	55.14	54.89	51.89	47.34	49.70	51.74	44.61	38.43
	SR64-02	54.4	10.2	53.83	50.76	48.10	47.56	43.96	42.36	49.31	46.45	38.75	38.26
	SR64-03	54.4	11.0	54.33	51.55	51.66	50.81	50.01	50.42	50.15	50.99	52.49	51.00
	Average	54.4	10.6	55.28	52.25	51.63	51.09	48.62	46.71	49.72	49.73	45.28	42.56
	STDV	54.4	0.4	2.1	1.9	3.5	3.7	4.1	4.1	0.4	2.9	6.9	7.3
	CV, %	54.4	3.9	3.8	3.7	6.8	7.2	8.5	8.7	0.8	5.8	15.2	17.2
I65 (Mix 12S)	I65-01	54.4	12.4	53.38	48.33	48.06	44.31	42.12	40.55	38.65	29.12	36.29	32.63
	I65-02	54.4	12.1	53.70	52.90	48.96	46.80	43.38	39.32	33.90	38.40	35.02	31.26
	I65-03	54.4	12.7	55.11	52.70	49.42	47.40	45.94	42.03	39.91	41.87	34.93	23.01
	Average	54.4	12.4	54.06	51.31	48.81	46.17	43.81	40.63	37.49	36.46	35.41	28.97
	STDV	54.4	0.3	0.9	2.6	0.7	1.6	1.9	1.4	3.2	6.6	0.8	5.2
	CV, %	54.4	2.1	1.7	5.0	1.4	3.5	4.4	3.3	8.5	18.1	2.1	18.0

Road No.	Sample ID	Diameter (mm)	Thickness (mm)	Air Voids (%)	Temp. (°C)	Loading Rate (mm/min)	Max. Compressive Force (kN)	Tensile Strength (kPa)	Strain at Failure (%)
SR15	SR15C-1-10	143.01	38.87	11.4	35	0.06	0.378	43.29	1.32
SR15	SR15C-1-12	149.39	32.65	11.6	35	0.06	0.252	32.89	2.32
SR15	SR15C-1-11	143.99	37.09	11.5	35	0.39	0.407	48.52	1.96
US24	US24C-1-08	152.88	45.36	9.3	35	0.06	0.098	9.00	1.67
US24	US24C-1-09	152.63	47.45	9.6	35	0.06	0.134	11.78	0.95
US24	US24C-1-10	152.51	43.79	8.9	35	0.39	0.374	35.65	2.27
SR161	SR161C-1-10	152.44	34.21	14.1	35	0.06	0.352	42.97	1.88
SR161	SR161C-1-11	153.13	34.24	13.3	35	0.06	0.434	52.70	3.94
SR161	SR161C-1-12	153.2	30.4	12.9	35	0.39	0.317	43.33	2.66
SR56	SR56C-1-11	145.04	57.95	10.6	35	0.06	0.467	35.37	3.59
SR56	SR56C-1-12	145.17	54.03	9.0	35	0.06	0.428	34.74	2.60
SR56	SR56C-1-10	145.74	52.45	10.3	35	0.39	0.600	49.97	3.97
US30	US30C-1-11	150.25	29.02	7.5	35	0.06	0.526	76.80	3.38
US30	US30C-1-12	149.94	33.93	7.1	35	0.06	0.573	71.70	2.09
US30	US30C-1-10	151.31	32.51	7.2	35	0.39	0.778	100.69	3.09
SR66	SR66C-1-10	152.25	38.09	11.6	35	0.06	0.050	5.49	1.84
SR66	SR66C-1-11	153.25	38.59	12.1	35	0.06	0.095	10.23	1.79
SR66	SR66C-1-12	152.45	37.59	10.7	35	0.39	0.201	22.33	6.05
SR135	SR135C-1-10	144.76	30.61	6.9	35	0.06	0.427	61.35	1.53
SR135	SR135C-1-11	145.19	37.59	6.3	35	0.06	0.619	72.20	2.19
SR135	SR135C-1-12	144.56	34.31	7.9	35	0.39	0.904	116.03	1.95
US31	US31C-1-10	152.5	39.07	8.7	35	0.06	1.002	107.06	5.42
US31	US31C-1-12	152.45	38.46	8.0	35	0.06	0.659	71.55	3.77
US31	US31C-1-11	152.61	38.8	8.2	35	0.39	1.270	136.54	5.74
I74	I74C-1-10	143.49	49.52	8.5	35	0.06	1.276	114.32	2.66
I74	I74C-1-11	143.75	46.04	6.3	35	0.06	1.286	123.70	3.39
I74	I74C-1-12	143.89	48.51	8.9	35	0.39	1.208	110.18	4.49
SR64	SR64C-1-11	144.23	36.10	5.6	35	0.06	0.549	67.13	3.97
SR64	SR64C-1-13	145.02	37.64	4.8	35	0.06	0.988	115.23	3.13
SR64	SR64C-1-12	145.56	37.46	3.5	35	0.39	1.021	119.21	2.43
I65	I65C-1-10	152.20	36.00	7.4	35	0.06	0.855	99.34	2.97
I65	I65C-1-12	152.39	34.07	7.2	35	0.06	1.086	133.16	3.96
I65	I65C-1-11	151.66	35.62	7.1	35	0.39	1.732	204.11	3.38

Road No.	Sample ID	Diameter (mm)	Thickness (mm)	Air Voids (%)	Temp. (°C)	Loading Rate (mm/min)	Max. Compressive Force (kN)	Tensile Strength (kPa)	Strain at Failure (%)
SR15	SR15C-2-09	149.74	30.60	10.1	35	0.06	0.091	12.64	0.50
SR15	SR15C-2-10	149.69	27.70	10.2	35	0.06	0.158	24.26	0.56
SR15	SR15C-2-05	149.66	31.00	9.8	35	0.39			
US24	US24C-2-04	149.55	48.41	4.9	35	0.06	0.515	45.29	0.60
US24	US24C-2-05	149.52	43.81	5.3	35	0.06	0.456	44.31	0.74
US24	US24C-2-11	149.40	43.42	5.1	35	0.39	1.082	106.20	1.08
SR161	SR161C-2-05	153.09	30.15	13.8	35	0.06	0.424	58.49	1.88
SR161	SR161C-2-12	152.72	27.82	13.4	35	0.06	0.526	78.81	1.30
SR161	SR161C-2-15	153.00	28.30	11.8	35	0.39	0.911	133.94	1.97
SR56	SR56C-2-05	151.90	49.79	7.0	35	0.06	0.656	55.22	2.24
SR56	SR56C-2-07	151.70	49.47	6.0	35	0.06	0.542	45.98	2.10
SR56	SR56C-2-08	151.83	51.57	5.0	35	0.39	1.635	132.93	2.81
US30	US30C-2-07	149.56	35.23	4.4	35	0.06	1.088	131.45	1.94
US30	US30C-2-08	149.50	34.84	4.4	35	0.06	0.867	105.96	2.12
US30	US30C-2-12	149.41	36.98	4.6	35	0.39	1.525	175.70	2.03
SR66	SR66C-2-06	152.89	31.50	9.3	35	0.06	0.460	60.81	1.45
SR66	SR66C-2-08	152.81	35.35	8.0	35	0.06	0.494	58.22	2.26
SR66	SR66C-2-11	152.69	32.09	7.1	35	0.39	0.916	119.00	1.74
SR135	SR135C-2-08	151.98	37.07	4.5	35	0.06	0.566	63.95	0.88
SR135	SR135C-2-14	152.08	38.17	4.6	35	0.06	0.851	93.33	1.24
SR135	SR135C-2-15	152.03	36.69	5.2	35	0.39	1.179	134.58	1.55
US31	US31C-2-06	152.78	36.08	6.7	35	0.06	0.922	106.47	3.18
US31	US31C-2-10	152.17	36.02	6.7	35	0.06	0.841	97.67	2.40
US31	US31C-2-12	152.45	34.89	6.4	35	0.39	1.572	188.14	2.92
I74	I74C-2-11	152.64	36.70	8.5	35	0.06	0.055	6.25	0.67
I74	I74C-2-12	152.48	39.31	6.3	35	0.06	0.565	60.01	2.20
I74	I74C-2-13	152.52	34.32	8.9	35	0.39	0.918	111.65	1.53
SR64	SR64C-2-04	144.10	31.28	5.3	35	0.06	0.373	52.69	3.15
SR64	SR64C-2-05	143.86	42.54	5.6	35	0.06	0.703	73.12	3.15
SR64	SR64C-2-08	143.45	51.87	3.4	35	0.39	1.252	107.11	3.49
I65	I65C-2-07	152.29	38.06	11.1	35	0.06	0.925	101.59	1.89
I65	I65C-2-12	151.98	38.20	11.3	35	0.06	0.667	73.14	1.93
I65	I65C-2-15	152.31	36.88	10.5	35	0.39	1.021	115.71	1.93

Unconfined Testing

Mix	Sample ID	Temp. °C	V _a %	Unconfined Dynamic (Complex) Modulus E* (MPa)						Phase Angle φ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
Shelf	SR161-04	40	7.4	2635.0	1997.0	1527.0	833.0	665.0	463.0	34.62	35.09	34.65	31.52	29.13	23.67
	SR161-06			3245.0	2368.0	1831.0	1084.0	897.0	677.0	31.29	32.93	32.87	29.17	26.78	20.96
	SR161-10			2622.0	1863.0	1474.0	808.0	630.0	430.0	33.31	35.12	35.18	33.14	31.18	26.16
	Average	40	7.4	2834.0	2076.0	1610.7	908.3	730.7	523.3	33.07	34.38	34.23	31.28	29.03	23.60
	STDV	40	#DIV/0!	356.0	261.6	192.6	152.6	145.1	134.1	1.68	1.26	1.21	2.00	2.20	2.60
	CV, %	40	#DIV/0!	12.6	12.6	12.0	16.8	19.9	25.6	5.1	3.7	3.5	6.4	7.6	11.0
Freezer	SR161-01	40	7.6	3079.0	2243.0	1722.0	980.0	790.0	512.0	30.40	33.43	34.10	32.56	30.93	26.01
	SR161-02			2822.0	2091.0	1614.0	899.0	711.0	460.0	31.78	34.82	35.49	33.97	32.06	26.95
	SR161-05			3096.0	2135.0	1612.0	904.0	728.0	484.0	31.48	33.88	34.82	33.80	32.46	27.39
	Average	40	7.6	2999.0	2156.3	1649.3	927.7	743.0	485.3	31.22	34.04	34.80	33.44	31.82	26.78
	STDV	40	#DIV/0!	153.5	78.2	62.9	45.4	41.6	26.0	0.73	0.71	0.70	0.77	0.79	0.70
	CV, %	40	#DIV/0!	5.1	3.6	3.8	4.9	5.6	5.4	2.3	2.1	2.0	2.3	2.5	2.6

Mix	Sample ID	Temp. °C	V _a %	Unconfined Dynamic (Complex) Modulus E* (MPa)						Phase Angle φ (Degree)					
				25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
Shelf	SR161-04R			2595.0	1808.0	1357.0	757.0	599.0	407.0	35.53	37.54	37.39	34.25	32.14	26.46
	SR161-06R	40	7.9	3458.0	2491.0	1928.0	1069.0	852.0	544.0	31.60	34.71	35.16	32.94	31.29	26.86
	SR161-10R	40	7.8	3063.0	2184.0	1657.0	932.0	747.0	493.0	33.31	35.58	35.86	32.96	31.05	26.41
	Average	40	7.9	3038.7	2161.0	1647.3	919.3	732.7	481.3	33.48	35.94	36.14	33.38	31.49	26.58
	STDV	40	0.1	432.0	342.1	285.6	156.4	127.1	69.2	1.97	1.45	1.14	0.75	0.57	0.25
	CV, %	40	0.9	14.2	15.8	17.3	17.0	17.3	14.4	5.9	4.0	3.2	2.2	1.8	0.9
Freezer	SR161-01R	40	7.6	3595.0	2477.0	1842.0	989.0	790.0	527.0	33.86	36.18	36.30	34.56	32.40	27.32
	SR161-02R	40		2490.0	1709.0	1257.0	679.0	527.0	337.0	35.95	37.94	38.41	35.60	33.62	28.34
	SR161-05R	40		2533.0	1748.0	1337.0	722.0	577.0	383.0	34.20	36.81	37.00	34.79	32.79	26.90
	Average	40	7.6	2872.7	1978.0	1478.7	796.7	631.3	415.7	34.67	36.98	37.24	34.98	32.94	27.52
	STDV	40	#DIV/0!	625.9	432.6	317.2	167.9	139.7	99.1	1.12	0.89	1.07	0.55	0.62	0.74
	CV, %	40	#DIV/0!	21.8	21.9	21.5	21.1	22.1	23.8	3.2	2.4	2.9	1.6	1.9	2.7

Penetration (0.1 mm) at 25C								
Binder	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average	STDV	CV%
SR15	73	79	69	70		72.8	4.5	6.2
US24	65	64	66			65.0	1.0	1.5
SR161	53	55	57			55.0	2.0	3.6
SR56	30	41	41	41		38.3	5.5	14.4
US30	50	54	42	51	51	49.6	4.5	9.1
SR66	36	36	38	32	31	34.6	3.0	8.6
SR135	50	45	43	41	41	44.0	3.7	8.5
US31	55	53	52			53.3	1.5	2.9
I74	38	40	43	38	37	39.2	2.4	6.1
SR64								
I65	32	42	50	41	43	41.6	6.4	15.4

Ring and Ball Softening point, °C					
Site	ball1	ball2	Average	STDV	CV%
SR15	48.5	49	48.8	0.4	0.7
US24	48	48	48.0	0.0	0.0
SR161	51	51	51.0	0.0	0.0
SR56	51.5	52	51.8	0.4	0.7
US30	56	56	56.0	0.0	0.0
SR66	53	53.5	53.3	0.4	0.7
SR135	53	53	53.0	0.0	0.0
US31	66	66	66.0	0.0	0.0
I74	59	59	59.0	0.0	0.0
SR64					
I65	73	74	73.5	0.7	1.0

Site	Rotational Viscosity (20 rpm, spindle27)				Rotational Viscosity (spindle27)					
	175°C	135°C	120°C	90°C	90°C	speed	80°C	speed	60°C	speed
	cP	cP	cP	cP	cP	rpm	cP	rpm	cP	rpm
SR15	102.1	400.0	947.9		7887.5	5 and 10	22400.0	5 and 10		
US24	93.8	635.4	958.3	8323.0						
SR161	100.0	410.4	1064.8	1064.8			22325.0	5 and 10	O of R	
SR56	118.8	685.4	1641.8		15508.3	5 and 10				
US30	227.1	1058.5	2552.2							
SR66	143.8	633.3	1625.0							
SR135	152.1	635.4	1562.5		15591.7	5 and 10				
US31	412.5	1887.5	5166.7							
I74	293.8	1620.7	4123.0		43564.7	4 and 5				
SR64										
I65	287.5	1589.2	4764.7	O of R	O of R		O of R		O of R	

Tested by Heritage Research: Surface Mix

Location	Sample ID	Temp. (°C)	Va (%)	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
East Bound Left Wheel Path	9A10A	40	3.9	110.1	75.4	49.4	39.9	33.5	28.1	25.4	23.3	21.8	21.2
	11A12A	40	4.0	168.2	98.4	58.4	43.1	34.2	27.3	23.9	22.3	20.8	20.0
	13A14A	40	2.3	217.7	158.8	116.6	96.7	81.8	68.2	59.8	54.4	49.7	47.6
	15A16A	40	2.1	245.6	183.0	131.1	105.4	87.9	70.3	61.1	54.6	48.4	46.3
	23A24A	40	3.7	108.8	73.5	48.8	39.5	32.8	26.8	24.2	22.6	21.0	19.9
	Average	40	3.2	170.1	117.8	80.9	64.9	54.0	44.2	38.9	35.4	32.4	31.0
	STDV	40	0.9	61.9	50.2	39.8	33.2	28.2	22.9	19.7	17.4	15.3	14.6
	CV, %	40	28.9	36.4	42.6	49.2	51.0	52.2	51.9	50.7	49.2	47.2	47.1
West Bound Left Wheel Path	31A32A	40	6.5	237.8	169.6	109.2	82.3	64.4	47.8	39.9	34.4	29.9	27.6
	Average	40	6.5	237.8	169.6	109.2	82.3	64.4	47.8	39.9	34.4	29.9	27.6
	STDV	40											
East Bound Center of Lane		40											
	CV, %	40											
	1A2A	50	5.3	44.2	38.4	30.9	27.3	24.9	22.5	20.9	20.3	18.8	18.8
	3A4A	50	4.7	42.0	35.1	28.4	25.5	22.9	20.8	19.4	17.9	17.0	16.5
	5A6A	50	5.1	49.4	40.0	31.5	27.6	24.8	21.8	19.7	19.2	18.1	17.9
	7A8A	50	5.1	75.8	57.8	43.1	37.6	33.2	29.3	27.1	25.7	24.1	23.8
	17A18A	50	5.5	54.3	42.1	32.1	27.6	24.3	21.4	19.8	18.7	17.3	16.7
	19A20A	50	6.0	73.7	53.3	39.1	32.9	28.6	24.5	22.9	20.9	19.2	18.7
	Average	50	5.3	56.6	44.4	34.2	29.8	26.4	23.4	21.7	20.4	19.1	18.7
	STDV	50	0.4	14.7	9.0	5.7	4.6	3.8	3.2	3.0	2.8	2.6	2.7
West Bound Center of Lane	CV, %	50	8.0	26.0	20.2	16.6	15.4	14.4	13.5	13.7	13.8	13.6	14.4
	25A26A	50	7.5	77.3	58.0	41.5	34.3	29.2	24.2	21.9	19.8	18.0	17.8
		50											
		50											
	Average	50	7.5	77.3	58.0	41.5	34.3	29.2	24.2	21.9	19.8	18.0	17.8
	STDV	50											
East Bound Center of Lane	CV, %	50											
	1A2A	30	5.3	291.4	205.6	131.5	95.6	71.9	51.4	42.1	35.6	30.7	27.9
	3A4A	30	4.7	259.8	185.1	117.1	85.0	64.0	46.3	38.2	32.1	27.8	25.5
	5A6A	30	5.1	320.5	233.4	146.4	107.6	80.2	56.2	44.2	36.5	29.1	25.0
	7A8A	30	5.1	502.0	363.7	225.9	165.0	122.4	82.9	61.7	49.6	38.3	33.6
	17A18A	30	5.5	404.7	295.7	185.9	130.8	95.2	64.2	48.5	38.6	28.8	25.2
	19A20A	30	6.0	505.9	371.1	243.1	176.8	131.6	90.1	68.0	54.7	42.5	37.3
	Average	30	5.3	380.7	275.7	175.0	126.8	94.2	65.2	50.5	41.2	32.9	29.1
	STDV	30	0.4	106.9	80.2	51.8	37.6	27.6	17.7	11.8	8.9	6.1	5.2
West Bound Center of Lane	CV, %	30	8.0	28.1	29.1	29.6	29.6	29.3	27.1	23.4	21.6	18.5	17.8
	25A26A	30	7.5	554.4	421.7	291.3	220.3	169.5	119.0	91.7	74.1	56.3	47.1
		30											
		30											
	Average	30	7.5	554.4	421.7	291.3	220.3	169.5	119.0	91.7	74.1	56.3	47.1
West Bound Center of Lane	STDV	30											
	CV, %	30											

Location	Sample ID	Temp. (°C)	Va (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
East Bound Left Wheel Path	9A10A	40	3.9	50.2	52.5	44.2	43.0	39.8	36.7	34.0	31.5	30.3	29.1
	11A12A	40	4.0	63.2	61.2	54.6	48.8	47.9	43.8	41.2	38.2	36.3	34.5
	13A14A	40	2.3	50.2	46.5	42.7	40.1	38.2	36.4	34.7	32.8	31.5	30.6
	15A16A	40	2.1	44.4	43.2	40.6	39.2	36.8	36.1	33.8	32.5	30.2	28.8
	23A24A	40	3.7	50.9	48.8	42.1	41.5	39.6	37.2	34.8	32.2	31.2	29.7
	Average	40	3.2	51.8	50.5	44.8	42.5	40.5	38.0	35.7	33.5	31.9	30.6
	STDV	40	0.9	6.9	6.9	5.6	3.8	4.3	3.3	3.1	2.7	2.5	2.3
	CV, %	40	28.9	13.3	13.7	12.5	8.9	10.7	8.6	8.8	8.1	7.9	7.6
West Bound Left Wheel Path	31A32A	40	6.5	44.0	48.5	45.6	42.8	40.8	39.1	36.4	33.5	30.3	28.7
	Average	40	6.5	44.0	48.5	45.6	42.8	40.8	39.1	36.4	33.5	30.3	28.7
	STDV	40											
East Bound Center of Lane		40											
	CV, %	40											
	1A2A	50	5.3	39.5	38.8	37.2	36.8	36.0	35.6	35.3	34.8	34.6	33.5
	3A4A	50	4.7	39.6	38.4	34.2	33.0	34.4	32.8	32.7	31.1	31.0	30.7
	5A6A	50	5.1	38.7	37.6	35.2	35.0	34.4	32.8	31.5	31.0	29.1	28.1
	7A8A	50	5.1	45.8	42.8	38.0	36.7	33.9	30.3	28.4	27.0	24.8	24.7
	17A18A	50	5.5	43.2	41.0	37.1	36.6	36.0	34.0	32.7	31.8	30.4	30.0
	19A20A	50	6.0	47.2	44.5	38.9	36.2	35.3	32.7	30.7	29.5	28.5	28.5
	Average	50	5.3	42.3	40.5	36.8	35.7	35.0	33.0	31.9	30.9	29.7	29.3
	STDV	50	0.4	3.6	2.7	1.8	1.5	0.9	1.8	2.3	2.6	3.2	3.0
West Bound Center of Lane	CV, %	50	8.0	8.5	6.7	4.9	4.2	2.6	5.3	7.2	8.3	10.9	10.2
	25A26A	50	7.5	44.6	43.1	40.3	39.7	39.1	35.9	35.8	34.5	32.7	33.5
		50											
		50											
	Average	50	7.5	44.6	43.1	40.3	39.7	39.1	35.9	35.8	34.5	32.7	33.5
	STDV	50											
East Bound Center of Lane	CV, %	50											
	1A2A	30	5.3	46.3	48.7	49.0	47.9	48.1	46.1	43.7	41.1	39.6	37.7
	3A4A	30	4.7	47.5	49.4	51.9	49.4	49.4	49.0	46.7	44.3	42.6	40.9
	5A6A	30	5.1	45.6	48.8	49.5	50.1	49.1	50.6	47.8	46.3	44.6	42.9
	7A8A	30	5.1	43.9	48.7	51.7	50.3	49.6	50.5	49.7	47.4	43.0	41.6
	17A18A	30	5.5	45.2	47.9	50.8	51.8	51.5	52.5	51.2	50.1	46.6	45.0
	19A20A	30	6.0	43.3	45.4	47.7	47.7	47.5	47.2	46.4	43.9	39.7	38.3
	Average	30	5.3	45.3	48.1	50.1	49.5	49.2	49.3	47.6	45.5	42.7	41.1
	STDV	30	0.4	1.6	1.4	1.6	1.6	1.4	2.4	2.7	3.1	2.7	2.8
	CV, %	30	8.0	3.4	3.0	3.3	3.1	2.8	4.8	5.6	6.8	6.4	6.7
West Bound Center of Lane	25A26A	30	7.5	38.3	40.8	42.2	42.7	42.7	44.3	43.8	43.0	40.5	39.4
		30											
		30											
	Average	30	7.5	38.3	40.8	42.2	42.7	42.7	44.3	43.8	43.0	40.5	39.4
	STDV	30											
	CV, %	30											

Tested by Heritage Research: Intermediate Mix

Location	Sample ID	Temp. (°C)	Va (%)	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
East Bound Left Wheel Path	9b	40	3.9	184.7	121.4	72.9	51.6	39.6	28.1	23.3	20.2	17.1	15.3
	10b	40	3.7	203.4	145.0	82.8	56.9	42.4	29.8	23.2	19.7	16.2	14.8
	11b	40	4.0	215.6	139.1	81.6	57.0	41.8	29.7	23.7	20.2	16.6	15.4
	12b	40	4.0	205.2	126.7	81.4	59.8	47.1	35.7	30.4	26.1	23.1	21.6
	13b	40	4.1	164.0	112.8	69.7	50.2	39.4	29.2	24.4	21.4	18.1	16.8
	14b	40	3.7	173.2	116.5	71.2	52.6	41.2	30.2	25.1	21.7	18.7	16.9
	15b	40	3.9	148.4	101.9	64.8	49.6	39.4	30.7	26.2	23.3	20.6	18.9
	16b	40	4.5	134.0	90.1	56.8	43.3	34.8	26.0	21.9	19.0	16.1	15.3
	21b	40	4.8	186.7	124.7	78.6	58.2	45.3	34.4	28.7	25.4	22.0	20.3
	22b	40	4.5	167.0	112.6	70.2	52.4	41.5	30.9	25.5	22.5	20.0	18.6
	23b	40	4.5	187.3	129.0	85.6	65.4	52.8	40.3	34.1	30.5	27.3	25.5
	24b	40	4.8	182.5	118.9	72.6	54.8	42.6	32.8	27.3	24.4	21.4	20.5
	Average	40	4.2	179.3	119.9	74.0	54.3	42.3	31.5	26.2	22.9	19.8	18.3
	STDV	40	0.4	23.7	15.0	8.4	5.7	4.5	3.8	3.5	3.3	3.3	3.2
	CV, %	40	9.3	13.2	12.5	11.3	10.5	10.6	12.1	13.4	14.5	17.0	17.7
West Bound Left Wheel Path	29b	40	6.5	368.4	245.6	158.2	116.2	87.2	61.7	49.3	41.2	33.6	30.7
	30b	40	7.4	326.3	229.5	154.6	116.7	86.3	61.8	49.5	41.4	33.5	30.0
	31b	40	6.9	266.6	193.2	131.4	98.0	77.0	56.4	46.1	39.2	33.0	30.6
	32b	40	6.5	327.6	221.3	142.9	106.8	78.4	55.3	44.1	36.6	29.9	27.0
	Average	40	6.8	322.2	222.4	146.8	109.4	82.2	58.8	47.2	39.6	32.5	29.6
	STDV	40	0.4	41.9	22.0	12.2	8.9	5.3	3.4	2.6	2.2	1.8	1.8
	CV, %	40	6.1	13.0	9.9	8.3	8.1	6.4	5.9	5.6	5.7	5.4	6.0
East Bound Center of Lane	1b	50	5.5	84.4	60.1	43.5	35.7	29.9	25.8	23.8	22.4	20.1	19.5
	2b	50	5.4	79.5	54.1	39.7	33.2	28.5	23.7	20.8	18.9	17.4	16.5
	3b	50	5.6	73.0	52.9	38.5	31.7	27.6	23.2	21.3	20.0	18.6	17.7
	4b	50	5.5	78.8	56.8	41.1	35.0	30.3	25.7	23.5	21.4	20.0	19.2
	5b	50	6.5	81.3	58.7	41.3	35.1	29.4	24.2	21.5	20.2	18.6	17.2
	6b	50	5.9	92.3	66.3	45.9	38.1	32.4	27.2	24.2	22.0	20.7	20.2
	7b	50	6.4	101.1	71.0	50.2	41.8	36.0	29.9	26.9	25.2	23.4	22.8
	8b	50	5.9	87.3	62.8	43.6	36.2	31.1	26.7	24.0	22.1	21.0	20.3
	Average	50	5.8	84.7	60.3	43.0	35.8	30.6	25.8	23.2	21.5	20.0	19.2
	STDV	50	0.4	8.8	6.1	3.8	3.1	2.6	2.2	2.0	1.9	1.8	2.0
	CV, %	50	7.4	10.4	10.2	8.8	8.6	8.6	8.5	8.6	8.8	9.2	10.5
West Bound Center of Lane	25b	50	6.4	168.2	118.6	77.5	58.5	46.7	36.1	30.8	27.0	23.4	22.5
	26b	50	6.6	184.5	127.2	81.9	60.8	48.6	37.2	31.3	26.5	22.9	21.9
	27b	50	6.6	174.2	122.5	79.0	58.9	47.1	35.7	29.8	25.1	21.1	20.2
	28b	50	7.3	182.5	131.1	87.4	66.5	53.4	41.9	36.0	31.5	28.4	27.1
	33b	50	6.8	132.8	96.5	68.9	54.4	45.2	35.5	30.8	27.7	24.9	23.7
	34b	50	6.1	165.9	115.8	76.9	57.8	46.3	35.9	30.9	27.1	24.8	23.9
	35b	50	6.4	177.7	124.5	82.5	63.4	52.3	40.6	34.9	32.2	29.7	27.9
	36b	50	6.8	164.5	116.0	78.0	61.6	50.9	39.7	34.2	30.9	28.6	27.5
	Average	50	6.6	168.8	119.0	79.0	60.2	48.8	37.8	32.3	28.5	25.5	24.3
	STDV	50	0.3	16.3	10.6	5.4	3.7	3.0	2.5	2.3	2.6	3.1	2.9
	CV, %	50	5.2	9.7	8.9	6.8	6.1	6.2	6.7	7.2	9.3	12.1	11.7

Location	Sample ID	Temp. (°C)	Va (%)	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
East Bound Center of Lane	1b	30	5.5	632.2	470.9	302.2	220.4	162.5	112.3	86.5	69.5	53.2	47.2
	2b	30	5.4	578.6	417.0	264.6	192.0	137.9	90.1	67.3	52.0	37.7	32.3
	3b	30	5.6	478.4	345.3	222.5	161.5	119.0	82.2	63.4	50.5	38.6	33.8
	4b	30	5.5	559.7	399.0	251.9	184.7	129.9	85.1	63.9	50.4	37.5	32.2
	5b	30	6.5	583.1	421.8	274.2	197.2	143.4	99.4	75.6	60.3	45.7	63.3
	6b	30	5.9	594.2	431.1	280.2	201.7	146.2	96.4	70.1	53.9	40.1	33.5
	7b	30	6.4	674.6	491.3	318.4	231.9	169.5	110.9	82.2	63.0	46.2	38.4
	8b	30	5.9	552.0	402.8	257.3	184.5	134.7	91.1	68.6	55.0	41.7	35.7
	Average	30	5.8	581.6	422.4	271.4	196.7	142.9	95.9	72.2	56.8	42.6	39.5
	STDV	30	0.4	57.8	44.8	29.9	22.0	16.6	11.1	8.5	6.8	5.5	10.8
	CV, %	30	7.4	9.9	10.6	11.0	11.2	11.6	11.6	11.7	12.0	12.8	27.3
West Bound Center of Lane	25b	30	6.4	924.7	729.4	497.9	378.9	287.7	200.6	149.4	114.6	84.9	69.3
	26b	30	6.6	1086.9	849.1	567.2	424.9	313.5	211.0	152.4	113.8	78.9	63.8
	27b	30	6.6	987.8	780.2	561.6	420.9	313.0	210.6	150.7	112.3	76.9	62.3
	28b	30	7.3	935.1	735.8	521.7	399.8	307.2	218.1	164.0	126.1	90.3	73.2
	33b	30	6.8	786.4	587.2	392.4	287.6	214.7	150.4	116.0	93.3	70.5	60.1
	34b	30	6.1	983.8	767.8	521.8	394.1	294.0	205.5	152.6	117.2	83.4	69.1
	35b	30	6.4	1050.9	815.6	563.7	419.6	312.6	217.8	157.7	121.9	89.1	74.7
	36b	30	6.8	826.9	630.7	445.6	344.7	273.4	202.9	155.4	126.5	96.0	82.1
	Average	30	6.6	947.8	737.0	509.0	383.8	289.5	202.1	149.8	115.7	83.8	69.3
	STDV	30	0.3	103.0	88.9	62.4	47.1	33.5	21.9	14.4	10.6	8.2	7.3
	CV, %	30	5.2	10.9	12.1	12.3	12.3	11.6	10.8	9.6	9.1	9.8	10.5

Location	Sample ID	Temp. (°C)	Va (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
East Bound Left Wheel Path	9b	40	3.9	52.0	52.1	49.6	47.2	46.3	44.9	41.7	38.4	35.1	36.0
	10b	40	3.7	49.1	58.1	56.9	52.9	51.1	49.2	45.3	43.6	40.5	38.0
	11b	40	4.0	51.9	57.7	55.0	52.5	51.6	50.4	47.0	45.2	41.6	38.9
	12b	40	4.0	64.1	57.7	52.5	47.9	46.1	43.0	40.0	36.7	33.9	31.7
	13b	40	4.1	51.6	52.8	50.5	46.9	45.0	44.0	41.4	39.0	35.6	34.2
	14b	40	3.7	51.8	52.1	48.9	46.3	46.3	44.7	42.0	40.1	37.0	36.2
	15b	40	3.9	50.2	49.7	46.2	43.2	42.3	39.5	36.7	34.1	31.0	29.5
	16b	40	4.5	50.5	50.0	45.8	44.1	43.9	42.2	39.9	37.9	35.9	34.6
	21b	40	4.8	51.5	52.3	48.7	45.5	43.2	40.6	37.7	34.4	33.0	30.1
	22b	40	4.5	51.2	50.6	48.8	46.3	44.6	41.8	37.8	34.8	31.9	31.4
	23b	40	4.5	49.4	49.3	47.1	43.1	42.3	40.5	37.4	35.7	32.0	30.7
	24b	40	4.8	56.1	54.6	51.6	47.3	45.6	42.3	38.9	36.8	34.6	31.4
	Average	40	4.2	52.5	53.1	50.1	46.9	45.7	43.6	40.5	38.0	35.2	33.6
	STDV	40	0.4	4.1	3.2	3.4	3.1	3.0	3.3	3.2	3.5	3.3	3.2
	CV, %	40	9.3	7.8	6.1	6.7	6.6	6.6	7.7	7.9	9.2	9.3	9.5
West Bound Left Wheel Path	29b	40	6.5	51.7	55.7	52.5	49.8	47.8	47.2	45.9	43.0	38.7	37.2
	30b	40	7.4	45.8	47.0	46.0	44.1	44.0	44.2	43.0	40.6	37.7	36.3
	31b	40	6.9	46.5	46.8	45.9	44.1	43.9	42.6	40.4	37.1	34.5	33.3
	32b	40	6.5	48.0	52.7	50.1	46.2	46.4	47.1	44.2	41.6	38.7	36.6
	Average	40	6.8	48.0	50.5	48.6	46.1	45.5	45.3	43.4	40.6	37.4	35.9
	STDV	40	0.4	2.6	4.4	3.3	2.7	1.9	2.3	2.3	2.5	2.0	1.8
	CV, %	40	6.1	5.5	8.6	6.7	5.9	4.2	5.0	5.4	6.2	5.3	4.9
East Bound Center of Lane	1b	50	5.5	46.0	44.5	39.6	36.9	35.3	31.6	29.3	27.9	26.3	25.1
	2b	50	5.4	47.7	47.2	41.7	39.4	36.5	33.5	32.4	30.1	27.6	26.8
	3b	50	5.6	46.4	45.3	40.8	38.7	37.1	34.1	32.0	30.0	28.0	26.6
	4b	50	5.5	45.0	43.2	37.5	36.7	34.7	32.1	29.8	28.7	26.5	25.7
	5b	50	6.5	46.0	44.1	39.4	37.4	34.6	34.5	32.0	29.6	28.4	27.8
	6b	50	5.9	49.4	47.5	42.3	40.1	38.8	36.6	34.9	33.3	30.7	29.8
	7b	50	6.4	49.8	47.3	42.0	39.9	38.1	36.0	34.4	33.0	29.9	29.7
	8b	50	5.9	48.8	46.6	41.1	38.6	37.8	33.8	32.8	30.4	28.2	27.0
	Average	50	5.8	47.4	45.7	40.6	38.5	36.6	34.0	32.2	30.4	28.2	27.3
	STDV	50	0.4	1.8	1.6	1.6	1.3	1.6	1.7	2.0	1.9	1.5	1.7
	CV, %	50	7.4	3.8	3.6	4.0	3.4	4.3	5.0	6.1	6.2	5.3	6.3
West Bound Center of Lane	25b	50	6.4	48.9	48.7	46.9	43.9	42.9	42.4	38.8	37.5	34.5	32.3
	26b	50	6.6	51.8	51.4	48.1	44.8	43.3	41.5	38.6	36.3	33.5	32.0
	27b	50	6.6	49.4	49.4	47.5	45.0	44.7	42.7	41.1	38.8	36.0	35.5
	28b	50	7.3	49.0	48.5	45.1	41.9	41.2	39.2	37.2	34.7	31.6	30.2
	33b	50	6.8	46.4	44.7	42.1	40.2	39.5	37.8	35.7	32.9	30.2	29.4
	34b	50	6.1	50.9	50.4	46.2	43.1	41.9	40.0	37.1	33.8	30.3	28.4
	35b	50	6.4	51.7	51.2	47.3	43.1	41.2	38.3	36.2	32.6	29.3	28.4
	36b	50	6.8	48.6	48.7	45.1	41.8	40.2	38.9	36.1	33.0	30.3	28.4
	Average	50	6.6	49.6	49.1	46.0	43.0	41.9	40.1	37.6	35.0	32.0	30.6
	STDV	50	0.3	1.8	2.1	1.9	1.6	1.7	1.9	1.8	2.3	2.4	2.5
	CV, %	50	5.2	3.7	4.3	4.2	3.8	4.1	4.7	4.8	6.7	7.5	8.2

Location	Sample ID	Temp. (°C)	Va (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
East Bound Center of Lane	1b	30	5.5	39.0	43.0	45.2	45.3	44.8	45.9	44.7	42.7	38.4	37.0
	2b	30	5.4	40.7	47.9	47.8	48.7	47.6	51.0	50.7	48.9	45.5	42.8
	3b	30	5.6	44.3	46.0	47.2	47.5	47.3	47.9	46.3	45.0	41.8	39.6
	4b	30	5.5	43.2	46.8	49.4	49.0	49.1	50.6	49.1	46.6	43.5	41.6
	5b	30	6.5	43.1	45.9	47.5	48.4	48.5	48.8	47.3	45.9	41.8	
	6b	30	5.9	41.8	45.1	49.3	51.1	48.9	51.5	52.5	50.7	48.4	45.4
	7b	30	6.4	43.2	48.2	49.2	50.7	48.9	50.7	51.7	49.5	46.2	44.1
	8b	30	5.9	42.9	46.8	48.7	49.3	49.3	49.2	48.3	45.8	42.1	40.2
	Average	30	5.8	42.3	46.2	48.0	48.8	48.1	49.4	48.8	46.9	43.5	41.5
	STDV	30	0.4	1.7	1.7	1.4	1.8	1.5	1.9	2.7	2.7	3.1	2.9
	CV, %	30	7.4	4.1	3.6	3.0	3.7	3.1	3.8	5.6	5.7	7.2	6.9
West Bound Center of Lane	25b	30	6.4	32.6	36.7	42.4	43.9	44.6	45.4	48.3	48.1	46.6	45.3
	26b	30	6.6	34.9	40.5	44.3	46.2	47.1	48.6	50.7	50.3	48.9	47.6
	27b	30	6.6	34.5	35.5	41.4	44.4	45.6	46.0	50.8	51.2	51.2	49.3
	28b	30	7.3	35.4	37.9	42.3	44.4	45.6	46.6	48.5	48.5	47.4	46.0
	33b	30	6.8	37.2	41.7	43.9	44.8	45.2	45.8	45.7	44.6	42.7	42.3
	34b	30	6.1	34.4	38.6	42.9	44.0	46.6	47.4	48.9	48.1	47.0	44.1
	35b	30	6.4	37.4	40.0	45.4	47.6	48.2	47.9	50.8	49.1	47.4	45.1
	36b	30	6.8	38.7	42.6	43.4	44.5	44.5	43.9	45.5	44.0	42.3	41.0
	Average	30	6.6	35.6	39.2	43.3	45.0	45.9	46.4	48.7	48.0	46.7	45.1
	STDV	30	0.3	2.0	2.5	1.3	1.3	1.3	1.5	2.1	2.5	3.0	2.7
	CV, %	30	5.2	5.5	6.3	3.0	2.8	2.8	3.2	4.4	5.3	6.3	6.0

Location	Sample	Temp. (°C)	Va (%)	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
East Bound Lane	I74-11	40	4.9	149.5	100.4	60.3	39.8	26.3	16.6	12.2	8.0	7.0	4.5
	I74-12	40	4.4	136.6	93.9	59.5	42.6	29.9	19.7	14.3	12.3	8.8	7.4
	I74-13	40	4.2	131.1	107.2	67.9	49.4	36.2	25.5	20.0	16.2	15.0	8.9
	Average	40	4.5	139.1	100.5	62.6	43.9	30.8	20.6	15.5	12.2	10.3	6.9
	STDV	40	0.3	9.4	6.6	4.6	5.0	5.0	4.6	4.0	4.1	4.2	2.2
	CV, %	40	7.5	6.8	6.6	7.4	11.3	16.3	22.1	25.9	33.6	40.8	32.2
West Bound Lane	I74-21	40	6.3	398.7	298.9	184.1	122.8	90.1	54.4	41.2	34.2	19.3	21.7
	I74-22	40	7.7	367.5	269.8	163.4	117.3	81.3	50.2	35.5	25.6	16.8	11.3
	I74-23	40	8.1	441.4	320.3	202.4	147.9	105.7	67.0	48.3	36.4	24.7	16.1
	Average	40	7.4	402.5	296.3	183.3	129.3	92.3	57.2	41.7	32.1	20.3	16.4
	STDV	40	0.9	37.1	25.3	19.5	16.3	12.3	8.7	6.4	5.7	4.0	5.2
	CV, %	40	12.3	9.2	8.5	10.6	12.6	13.4	15.2	15.3	17.7	19.8	31.8
East Bound Lane	I74-11	54.4	4.9	42.5	29.9	19.7	15.7	12.3	10.3	7.8	6.9	6.0	7.5
	I74-12	54.4	4.4	39.7	29.1	19.0	15.8	12.0	9.3	8.9	7.8	7.3	6.1
	I74-13	54.4	4.2										
	Average	54.4	4.5	41.1	29.5	19.4	15.7	12.1	9.8	8.4	7.4	6.6	6.8
	STDV	54.4	0.3	2.0	0.6	0.5	0.1	0.3	0.7	0.8	0.6	0.9	1.0
	CV, %	54.4	7.5	4.8	2.0	2.4	0.6	2.3	7.2	9.6	8.5	13.2	14.4
West Bound Lane	I74-21	54.4	6.3	81.7	58.1	35.4	24.4	16.4	11.4	9.5	7.6	4.6	3.8
	I74-22	54.4	7.7	73.6	51.5	30.3	21.9	16.5	11.4	10.2	7.7	6.1	6.7
	I74-23	54.4	8.1	87.3	60.5	37.8	26.8	20.1	13.0	10.7	8.3	5.4	6.1
	Average	54.4	7.4	80.9	56.7	34.5	24.4	17.7	11.9	10.1	7.8	5.4	5.5
	STDV	54.4	0.9	6.8	4.7	3.9	2.4	2.1	0.9	0.6	0.4	0.7	1.5
	CV, %	54.4	12.3	8.5	8.2	11.2	10.0	12.0	7.4	6.0	4.6	13.4	27.7

Location	Sample ID	Temp. (°C)	Va (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
East Bound Lane	I74-11	40	4.9	61.78	61.95	62.72	60.99	57.84	55.04	50.91	56.04	47.22	39.87
	I74-12	40	4.4	58.32	56.21	54.51	53.41	49.42	41.72	37.49	35.94	24.14	19.80
	I74-13	40	4.2	51.06	51.28	50.53	47.13	43.43	39.33	32.95	34.17	27.95	23.82
	Average	40	4.5	57.05	56.48	55.92	53.84	50.23	45.36	40.45	42.05	33.10	27.83
	STDV	40	0.3	5.5	5.3	6.2	6.9	7.2	8.5	9.3	12.1	12.4	10.6
	CV, %	40	7.5	9.6	9.5	11.1	12.9	14.4	18.7	23.1	28.9	37.4	38.2
West Bound Lane	I74-21	40	6.3	59.0	60.2	66.4	65.9	62.3	60.8	58.14	57.86	62.17	47.75
	I74-22	40	7.7	54.4	55.4	55.9	55.9	56.9	54.8	52.16	48.61	50.64	48.59
	I74-23	40	8.1	47.2	48.7	49.0	49.1	48.5	46.9	44.72	42.85	36.94	38.91
	Average	40	7.4	53.53	54.74	57.09	57.00	55.90	54.16	51.67	49.77	49.92	45.08
	STDV	40	0.9	6.0	5.8	8.8	8.5	6.9	7.0	6.7	7.6	12.6	5.4
	CV, %	40	12.3	11.1	10.6	15.4	14.8	12.4	12.9	13.0	15.2	25.3	11.9
East Bound Lane	I74-11	54.4	4.9	59.65	57.55	54.64	42.99	41.49	39.44	28.75	36.15	12.41	29.63
	I74-12	54.4	4.4	61.42	58.54	51.66	45.90	42.05	28.85	28.21	31.36	29.73	21.36
	I74-13	54.4	4.2										
	Average	54.4	4.5	60.54	58.05	53.15	44.45	41.77	34.15	28.48	33.76	21.07	25.50
	STDV	54.4	0.3	1.3	0.7	2.1	2.1	0.4	7.5	0.4	3.4	12.2	5.8
	CV, %	54.4	7.5	2.1	1.2	4.0	4.6	0.9	21.9	1.3	10.0	58.1	22.9
West Bound Lane	I74-21	54.4	6.3	61.76	60.07	57.11	57.38	48.90	46.05	38.59	42.49	27.85	25.43
	I74-22	54.4	7.7	64.81	62.87	60.52	57.56	49.72	43.08	42.60	40.85	35.61	39.74
	I74-23	54.4	8.1	63.10	60.09	57.03	54.80	50.05	46.86	42.30	36.97	37.18	33.70
	Average	54.4	7.4	63.22	61.01	58.22	56.58	49.56	45.33	41.16	40.10	33.55	32.96
	STDV	54.4	0.9	1.5	1.6	2.0	1.5	0.6	2.0	2.2	2.8	5.0	7.2
	CV, %	54.4	12.3	2.4	2.6	3.4	2.7	1.2	4.4	5.4	7.1	14.9	21.8

Location	Sample	Temp. (°C)	Va (%)	Shear (Complex) Modulus G* (MPa)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
East Bound Lane	I74-16	40	4.9	149.8	100.6	53.6	34.6	30.0	20.8	16.9	15.2	13.6	13.8
	I74-17	40	4.5	146.4	94.2	51.6	32.5	21.9	17.6	15.1	12.6	11.1	10.7
	I74-18	40	4.3	144.2	92.8	48.1	30.2	18.8	14.5	14.9	12.5	11.2	11.6
	Average	40	4.6	146.8	95.9	51.1	32.4	23.6	17.6	15.6	13.4	12.0	12.1
	STDV	40	0.3	2.8	4.2	2.8	2.2	5.8	3.2	1.1	1.5	1.4	1.6
	CV, %	40	5.8	1.9	4.3	5.5	6.7	24.5	18.0	7.0	11.3	11.7	13.3
West Bound Lane	I74-37	40	7.4	459.9	328.5	209.3	151.0	108.9	74.8	56.7	44.5	35.3	30.4
	I74-38	40	6.9	301.3	226.1	143.1	101.3	72.5	48.7	37.3	29.3	23.8	20.7
		40											
	Average	40	7.1	380.6	277.3	176.2	126.1	90.7	61.8	47.0	36.9	29.5	25.6
	STDV	40	0.4	112.1	72.4	46.8	35.2	25.8	18.5	13.7	10.8	8.1	6.9
	CV, %	40	5.2	29.5	26.1	26.6	27.9	28.4	29.9	29.1	29.2	27.4	26.9
East Bound Lane	I74-16	54.4	4.9	24.4	18.4	18.9	15.5	13.9	12.6	11.9	11.3	12.0	13.2
	I74-17	54.4	4.5	84.7	75.2	61.7	55.2	49.7	42.0	38.0	38.5	39.2	40.5
	I74-18	54.4	4.3										
	Average	54.4	4.6	54.5	46.8	40.3	35.3	31.8	27.3	24.9	24.9	25.6	26.8
	STDV	54.4	0.3	42.7	40.2	30.3	28.0	25.3	20.8	18.5	19.3	19.2	19.3
	CV, %	54.4	5.8	78.3	85.9	75.0	79.4	79.7	76.3	74.1	77.3	75.0	72.0
West Bound Lane	I74-37	54.4	7.4	64.9	49.0	24.9	17.1	11.7	15.7	14.2	13.2	12.5	13.2
	I74-38	54.4	6.9	186.4	117.9	66.0	60.1	43.0	31.9	26.9	24.3	21.8	20.1
		54.4											
	Average	54.4	7.1	125.7	83.4	45.4	38.6	27.3	23.8	20.6	18.7	17.1	16.7
	STDV	54.4	0.4	85.9	48.7	29.1	30.4	22.2	11.5	9.0	7.8	6.6	4.9
	CV, %	54.4	5.2	68.4	58.4	64.0	78.9	81.1	48.3	43.7	41.9	38.3	29.1

Location	Sample ID	Temp. (°C)	Va (%)	Phase Angle δ (Degree)									
				10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
East Bound Lane	I74-16	40	4.9	65.62	63.96	63.10	60.11	60.86	59.42	59.20	59.57	59.28	60.91
	I74-17	40	4.5	64.52	60.50	60.24	62.25	56.35	57.59	56.67	57.77	56.72	60.68
	I74-18	40	4.3	66.06	68.22	63.71	64.03	62.51	60.23	61.94	61.44	61.81	63.23
	Average	40	4.6	65.40	64.23	62.35	62.13	59.91	59.08	59.27	59.59	59.27	61.61
	STDV	40	0.3	0.8	3.9	1.9	2.0	3.2	1.4	2.6	1.8	2.5	1.4
	CV, %	40	5.8	1.2	6.0	3.0	3.2	5.3	2.3	4.4	3.1	4.3	2.3
West Bound Lane	I74-37	40	7.4	49.8	50.4	51.7	51.8	52.1	49.2	48.27	46.95	46.58	46.56
	I74-38	40	6.9	54.5	52.8	51.5	52.2	50.8	48.4	47.17	45.98	43.97	43.12
		40											
	Average	40	7.1	52.16	51.61	51.61	52.00	51.45	48.80	47.72	46.47	45.28	44.84
	STDV	40	0.4	3.3	1.7	0.1	0.3	1.0	0.6	0.8	0.7	1.8	2.4
	CV, %	40	5.2	6.4	3.3	0.2	0.6	1.9	1.2	1.6	1.5	4.1	5.4
East Bound Lane	I74-16	54.4	4.9	67.88	52.44	50.14	48.51	45.68	42.39	42.12	44.34	48.14	50.67
	I74-17	54.4	4.5	50.67	45.26	41.29	40.35	38.21	38.72	38.52	34.90	35.76	37.52
	I74-18	54.4	4.3										
	Average	54.4	4.6	59.28	48.85	45.72	44.43	41.95	40.56	40.32	39.62	41.95	44.10
	STDV	54.4	0.3	12.2	5.1	6.3	5.8	5.3	2.6	2.5	6.7	8.8	9.3
	CV, %	54.4	5.8	20.5	10.4	13.7	13.0	12.6	6.4	6.3	16.8	20.9	21.1
West Bound Lane	I74-37	54.4	7.4	73.03	56.46	60.95	53.00	49.77	50.67	49.01	48.87	49.84	50.34
	I74-38	54.4	6.9	69.82	63.61	60.66	57.32	54.30	51.92	50.32	49.40	50.23	55.93
		54.4											
	Average	54.4	7.1	71.43	60.04	60.81	55.16	52.04	51.30	49.67	49.14	50.04	53.14
	STDV	54.4	0.4	2.3	5.1	0.2	3.1	3.2	0.9	0.9	0.4	0.3	4.0
	CV, %	54.4	5.2	3.2	8.4	0.3	5.5	6.2	1.7	1.9	0.8	0.6	7.4

Tested by Purdue University: Surface Mix

IDT Strength

Road No.	Sample ID	Diameter (mm)	Thickness (mm)	Air Voids (%)	Temp. (°C)	Loading Rate (mm/min)	Max. Compressive Force (kN)	Tensile Strength (kPa)	Strain at Failure (%)
I74 EB	I74-19	152.10	33.65	5.2	35	0.06	0.340	42.29	0.79
I74 EB	I74-20	152.23	35.02	4.9	35	0.06	0.457	54.57	0.96
I74 WB	I74-39	152.07	30.85	6.8	35	0.06	0.702	95.25	0.95
I74 WB	I74-40	152.13	27.81	7.2	35	0.06	0.681	102.47	1.22

Tested by Heritage Research

Repeat Shear at Constant Height

Road No.	Layer Mixture	Sample ID	Air Voids (%)	Temp. (°C)	Max. Permanent Shear Strain @ 5000 Cycles (%)
I74 EB	Surface	1a2a	5.3	50	3.45
I74 EB	Surface	3a4a	4.7	50	3.70
I74 EB	Surface	5a6a	5.1	50	1.94
I74 EB	Surface	7a8a	5.1	50	1.47
I74 EB	Surface	17a18a	5.5	50	2.28
I74 EB	Surface	19a20a	6.0	50	1.45
I74 WB	Surface	25a26a	7.5	50	1.25
I74 EB	Intermediate	1b	5.5	50	3.82
I74 EB	Intermediate	2b	5.4	50	4.37
I74 EB	Intermediate	4b	5.5	50	3.39
I74 EB	Intermediate	5b	6.5	50	3.72
I74 EB	Intermediate	6b	5.9	50	4.89
I74 EB	Intermediate	8b	5.9	50	3.74
I74 WB	Intermediate	25b	6.4	50	1.11
I74 WB	Intermediate	26b	6.6	50	1.90
I74 WB	Intermediate	27b	6.6	50	1.60
I74 WB	Intermediate	28b	7.3	50	1.63
I74 WB	Intermediate	33b	6.8	50	1.53
I74 WB	Intermediate	34b	6.1	50	1.13
I74 WB	Intermediate	35b	6.4	50	0.74
I74 WB	Intermediate	36b	6.8	50	0.94