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HMA PAVEMENT PERFORMANCE AND DURABILITY

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16. Abstract It has long been argued that at densities higher than approximately 92 percent (air void contents lower than 8 percent), a hot-mix asphalt mixture is impermeable to water. However, as densities become lower (air void contents higher) than this, small decreases in the density can yield exponential increases in permeability. The objectives of this study were to better understand the increases in hot-mix asphalt pavement performance and durability that can be gained by increasing the initial pavement density and to better quantify the inter-relationship among pavement density, permeability, and moisture-induced damage. The long-term performance and durability of four hot-mix asphalt mixtures at four different air void contents were evaluated with the dynamic modulus and beam fatigue apparatus. The mixtures differed in both aggregate size and gradation. In order to evaluate durability effects, performance tests were performed on unconditioned, moisture conditioned and oven-aged samples. The results indicate that density (air void content) is a significant factor in the performance and durability of hot-mix asphalt mixtures. Its effects vary with aggregate size and gradation, but increases in mixture density (reductions in air voids content) produce improvements in the dynamic modulus (reduction of rutting potential) and fatigue life of a mixture. Further, the fatigue life appears to be less sensitive to density (air voids content) than to moisture damage.			
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LIST OF SYMBOLS

ϕ = Phase angle
 AASHTO = American Association of State Highway and Transportation Officials
 APA = Asphalt Pavement Analyzer
 ANOVA = Analysis of Variance
 E^* = Complex modulus
 $|E^*|$ = Dynamic modulus
 EAV = Effective air voids
 ESAL = Equivalent Single Axle Load
 G^* = Shear modulus
 GLWT = Georgia Loaded Wheel Tester
 G_{mb} = Bulk specific gravity
 G_{mm} = Maximum theoretical specific gravity
 HMA = Hot-mix asphalt
 HSWT = Hamburg Steel Wheel Tracking Device
 ITS = Indirect Tensile Strength
 K = Permeability
 MDL = Maximum density line
 N_f = Number of cycles to failure (fatigue life)
 NCHRP = National Cooperative Highway Research Program
 NMAS = Nominal maximum aggregate size
 p = Porosity
 PurWheel = Purdue University laboratory wheel tracking device
 S_o = Initial flexural stiffness
 SGC = Superpave Gyratory Compactor
 SSD = Surface-saturated dry
 SST = Superpave Shear Tester
 TSR = Tensile strength ratio
 VMA = Voids in the mineral aggregate
 VTM = Voids in the total mixture

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CHAPTER 1 INTRODUCTION

1.1 Problem Statement

In the last several years the United States has observed an increase in hot-mix asphalt (HMA) pavement rutting. From surveys (1) it has been concluded that most of the rutting comes from the HMA layers. The causes of this rutting are many and include changes in asphalt binder properties, increased traffic volumes and weight, and higher tire pressures. In 1987 the Strategic Highway Research Program (SHRP) funded a \$50 million, five years study to address and provide solutions for performance problems. One of the major products of the study was the Superpave volumetric mixture design method. As a result of this new design method, premature permanent deformation has decreased. However, there are still questions about the long-term performance and durability of the Superpave designed mixtures.

The amount of air voids in a HMA mixture is inversely related to the degree of compaction, or density, of the mixture. Density is considered an important factor because it affects the performance of the HMA pavement. The compacted HMA mixture must have adequate air voids to resist permanent deformation due to plastic flow (rutting and shoving), but not so many that the mixture is permeable to moisture and air so as to allow moisture damage and oxidation, along with raveling and cracking. Thus air voids are one of the most important factors affecting permeability. As in-place air voids increase, permeability also increases.

1.2 Objectives and Scope of Study

Since HMA pavement performance and durability are directly related to the air voids contents and thereby permeability of the HMA pavement, the objectives of this study are to:

1. Better understand the increase in HMA pavement performance and durability that can be gained by increasing the initial pavement density; and
2. Better quantify the inter-relationship among HMA pavement density, permeability, and moisture-induced damage.

To achieve these objectives, various HMA mixture parameters were evaluated for their role in mixture performance and durability. All the analyses were made in relationship to air void content (initial density).

1.3 Research Approach and Methodology

Pavement density is an important parameter that can influence the performance and durability of HMA, but it is unclear to what extent long-term performance and durability can be improved by increasing initial density. In this project, the long-term performance and durability of four HMA mixtures at four different air voids contents were evaluated in the laboratory. Three factors that can affect long-term HMA mixture performance and durability were examined. These were density (the percent of maximum theoretical specific gravity (G_{mm})), nominal maximum aggregate size (NMAS), and gradation. Density had four factor levels (90, 92, 94, and 96 percent (air void contents of 10, 8, 6, and 4 percent)), NMAS two factor levels, (9.5- and 19-mm), and gradation two factor levels (fine- and coarse-graded).

After completing four mixture designs, test appropriate specimens were prepared and tested to determine the relationship among the experimental factors and long-term pavement performance and durability as measured in laboratory tests. The experimental study was completed using three groups of

test methods; permeability and porosity testing, moisture susceptibility testing, and performance and durability testing.

Permeability testing was completed using the falling head permeability and Corelok tests. The falling head permeability equipment and test method developed by the Florida Department of Transportation (FDOT) were used. The Corelok method was used to determine the porosity of the mixture samples. Some studies (12) have shown that porosity is a better indicator of permeability than air void content. Both permeability and porosity testing used specimens prepared in the Superpave Gyratory Compactor (SGC).

Moisture sensitivity testing was completed using the American Association of State Highway and Transportation Officials (AASHTO) T283 and laboratory wheel tracking test methods. AASHTO T283 is a widely used and accepted test method. The Purdue University laboratory wheel tracking device (PurWheel) passes a loaded wheel back and forth over a compacted HMA slab. The moisture susceptibility of the sample is determined by submerging the specimen in hot water during the test. Experience has shown that the PurWheel is accurate in determining an HMA mixture's susceptibility to moisture damage.

The dynamic modulus and beam fatigue tests were used as measures of HMA performance and durability. HMA mixture samples were tested in both unconditioned and conditioned states. Two types of specimen conditioning were used for the project, moisture and air. For moisture conditioning, the samples were partially saturated and placed in a 60C water bath for 24 hours prior to testing. Conditioning in air was completed by placing the specimens in an 85C forced draft oven for 5 days prior to testing. Moisture conditioning tends to promote moisture damage, thereby enabling the decrease in performance and durability due to this damage to be quantified by the dynamic modulus and beam fatigue tests. Oven conditioning tends to reduce the durability and performance as measured by the beam fatigue test. Dynamic modulus samples were not tested after oven conditioning because such conditioning serves to stiffen an HMA mixture thereby reducing the potential for permanent deformation.

This report presents the details, results, and conclusion of the testing. Chapter 2 is a theoretical review of each test method and the influence of its parameters in the study. Chapter 3 contains information about the materials used (asphalt binder and aggregates) and the experimental design of the project. Chapters 4, 5, 6, and 7 contain details of the testing, test results, and statistical analyses of the results for permeability, moisture susceptibility, dynamic modulus, and beam fatigue tests, respectively. Chapter 8 is a summary of the results along with conclusions and recommendations.

CHAPTER 2 LITERATURE REVIEW

2.1 Permeability

Permeability is the ability of a material (in this case HMA) to transmit fluids (in this case water) through its pores when subjected to pressure, or a difference in head, and is expressed in units of volume of fluid per unit time per cross sectional area of material for a given hydraulic head.

Previous studies have been conducted pertaining to the parameters and properties of HMA mixtures that influence their performance and durability at certain climatic and load conditions. Some indicated that air voids content is the most influential factor affecting the performance and durability of a mixture. Others stated that permeability has the most influence and that air voids content is simply an indicator of permeability. Brown (2) states that the quantity of air voids in an HMA mixture (or degree of compaction or density) is the most important factor that affecting the performance of an HMA pavement. A properly compacted mixture must have adequate air voids to prevent permanent deformation due to plastic flow, but not too many so as to prevent permeability. Brown also concludes that initial in-place air voids must be below 8 percent and the terminal air voids above 3 percent (2). Ford (3) similarly concluded that HMA mixtures must be designed and constructed to maintain a terminal in-place air voids content above a minimum value (2.5 %) to avoid developing a rut depth great enough to result in hydroplaning. Other studies by Brown and Cross (4) and Huber and Heiman (5) concluded that significant rutting is likely to occur when in-place air voids contents reach approximately 3 percent. Harvey et al. (6) concluded that air voids in a mixture must be sufficiently small to avoid degradation when loaded and sufficiently large to ensure structural stability and avoid bleeding. However, McLaughlin and Goetz (7) affirmed that how an HMA

prevents water ingress is more indicative of how a pavement will perform than is its density.

2.1.1 Effect of Air Voids Content

As air voids contents increase (or density decreases) in a mixture, permeability increases. At a maximum critical air voids content value, the mixture becomes permeable to air and water. Zube (8) performed studies to correlate air voids and permeability in dense-graded mixtures and concluded that HMA mixtures became permeable to water at air voids contents of approximately 8 percent. He also concluded that above this percentage, the permeability rapidly increases (8). Brown et al. (9) reached the same conclusion in a study of segregated mixtures in Georgia. In a similar way, Santucci et al. (10) concluded that mixtures must have an air voids contents lower than 8 percent to avoid rapid oxidation and subsequent cracking and/or raveling. These studies indicate that 8 percent air voids content appears to be a critical value dividing permeable and impermeable HMA mixtures.

In addition to air voids content, porosity can also be used as a factor to predict permeability. Kanitpong et al. (11) concluded that air voids content is the most influential factor in permeability and that effective air voids (EAV), or percent of porosity (water permeable voids), influences permeability. In a separate study (12), Kanitpong et al. concluded that EAV is a better indicator of permeability than air voids, explaining the different conclusions in the two studies as being due to the variability in the degree of saturation of the samples in the two studies.

2.1.2 Effect of Aggregate Gradation and Size

Different studies have evaluated the effect of aggregates on permeability. In general, it has been concluded that gradation and NMAS do influence permeability. After the development of the Superpave mixture design method, numerous studies were carried out that concluded that, at a given air voids

content, coarse-graded Superpave mixtures are more permeable than conventionally designed HMA mixtures. In addition to air voids, Cooley et al. (13) studied other factors that affect permeability and found that NMAS and gradation influence permeability. They concluded that as NMAS increases, the sizes of the voids in the mixture also increase (13). The authors reason that if a maximum field permeability of 100×10^{-5} cm/s were part of the construction specification, the mixtures tested in their research would need to be compacted to air voids contents of 7.7, 5.5, and 4.4% for the 9.5- and 12.5-, 19.0-, and 25.0-mm mixtures, respectively.

If sufficiently low air voids contents are not achieved during construction, the result is the potential for these voids to become interconnected causing mixture permeability to increase. Water and air use these interconnected voids as a means to flow (14). The researches also concluded that coarse-graded mixtures (gradations that pass below the maximum density line (MDL)) are more permeable than fine-graded mixtures (gradations that pass above the MDL). This same conclusion was noted by Choubane et al. (15) in a study of the permeability of coarse-graded Superpave mixtures. Gradation appears to affect the size of air voids within a compacted HMA mixture. Similar to NMAS, in a coarse-graded mixture, as the percentage of coarse particles increases, the potential for inter-connected air voids increases. In both cases (greater NMAS and coarser gradation) the lack of fines to fill void spaces results in more potential for permeability. In his study, Prowell (16) also concluded that fine-graded mixtures tend to be less permeable than coarse-graded mixtures.

Choubane et al. (15) conducted research that found the size and interconnectivity of the air voids significantly influenced pavement permeability. They concluded that not only do the size, orientation, and interconnectivity of voids have an influence on permeability, but also that coarse-graded Superpave mixtures can have permeability problems even when the air voids content is below 8 percent. They did not find significant changes in permeability when air void contents were below 7 percent. Below 6 percent the pavement became

nearly impermeable. For a small increase in air voids over 7 percent, however, there was a large increase in permeability. When FDOT conducted the same permeability study using fine-graded Marshall designed mixtures, those mixtures with air voids contents higher than 7 percent were impermeable. This suggests that voids are not as interconnected in fine-graded mixtures compared to coarse-graded mixtures.

Masad et al. (17) completed research investigating the importance of the shape and size distribution of aggregates in permeability. They developed an empirical equation (2.1) to predict mixture permeability that uses the air voids content and aggregate surface area as parameters. Their equation is:

$$k = \frac{V_a^m}{c S_{agg}^2} \frac{\gamma}{\mu} \quad (2.1)$$

where,

k = permeability (m/s);

V_a = air voids of porous media (%);

m = regression coefficient;

c = constant that depends of the idealized shape of the air voids;

S_{agg} = average specific surface area of given gradation and NMAS
(1/mm²);

γ = unit weight of water at 20C (9.79 kN/m³); and

μ = viscosity of water (10⁻³ kg/m-s).

The permeability of HMA mixtures has always been assumed to be directly proportional to the air voids content of the mixture. However, Hudson and Davis (18) concluded that permeability in an HMA mixture is dependent not only on the air voids content, but also on the size of the voids as well. It appears that if the voids are not inter-connected, the mixture can have higher air voids and still be resistant to moisture intrusion.

2.1.3 Comparison of In-Service and Laboratory Results

Research work comparing in-service (field) permeability to the results of laboratory permeability tests has been completed by Cooley et al. (19) and Maupin (20). In his report, Maupin concludes that five of the six mixtures tested indicated that the permeability of field cores was in reasonable agreement with that of the laboratory compacted specimens. In the one case, Maupin reasoned that the lack of agreement was due to the large variability in the field core results (20).

Cooley et al. (19) had similar success in relating the permeabilities of field cores and laboratory prepared specimens. For the five mixtures in their study, the authors concluded that the permeabilities of field cores and laboratory specimens of only one mixture (9.5-mm NMAS) did not compare favorably. The other four compared very well. With additional data, the authors postulate that the comparisons would be much better. Additionally, Cooley et al. compared the results of laboratory permeability tests to the results of field permeability tests. Their conclusion was that for field permeability values below approximately 500×10^{-5} cm/s, the field and laboratory tests yielded similar results. Since the suggested field permeability criterion is well below this level, laboratory test results should be reliable indicators of field performance.

2.2 Moisture Susceptibility

Moisture susceptibility is defined as the weakening and/or eventual loss of the adhesive bond between the aggregate surface and the binder in an HMA mixture due to the presence of moisture. Often called stripping, it can also occur in the presence of moisture due to the loss of the cohesive resistance of the binder film that coats the aggregate (21). Figure 2.1 shows a photograph of an HMA sample that has both cohesive and adhesive failures. Moisture can weaken the binder matrix, subsequently lowering HMA mixture stability and load-carrying capacity. The results of stripping can manifest themselves as rutting, shoving, and fatigue cracking.

FIGURE 2.1 Cohesive and Adhesive Failures (after [21])

The six most commonly accepted mechanisms that explain the stripping process are (22 and 23): detachment, displacement, spontaneous emulsification, film rupture, pore pressure, and hydraulic scouring. Detachment refers to the separation of the binder film from the aggregate by a thin layer of water with no break of the binder film. Displacement is explained as the removal of the binder film from the aggregate surface by water. Water can access the binder-aggregate interface through binder film rupture and/or uncoated aggregate. Spontaneous emulsification hypothesizes that adhesion between the binder and aggregate is lost due to an inverted emulsification (water suspended within binder). This mechanism leads to cohesion failure and is difficult to observe in the field because there is not a loss of binder coating. Film rupture occurs when the binder film ruptures when exposed to sharp aggregate points. This rupture can be caused by construction and/or traffic loads, or can be induced by freeze-thaw cycling. After the binder film ruptures, moisture can access the binder-aggregate interface thus causing damage. The pore pressure theory suggests that stripping is caused by water pressure that results from the increased temperature and expansion of water that is trapped in the mixture voids, or from the stress induced by traffic. This pressure can exceed the adhesive strength between the binder and aggregate breaking the bond and allowing water to flow around the aggregates. In highly permeable mixtures, water can flow through the voids and

out of the mixture thus relieving the pressure. The water pressure required to produce stripping is inversely proportional to the diameter of the pores; the potential for stripping is higher for pores of larger diameters (lower water pressure required to produce stripping). Hydraulic scouring occurs in surface layers when the passing vehicles push water into the HMA mixture in front of the tires and suck water out of the mixture behind the tires. This form of stripping can cause raveling.

Moisture damage is a serious problem nationwide and has been responsible for millions of dollars in reconstruction and maintenance costs since the implementation of the Superpave specification. Usually, stripping starts at the bottom of the HMA layer and cannot be observed at the surface until the problem is critical (23). It is therefore important to control the factors that increase the potential for stripping.

2.2.1 Causes of Stripping

One of the principal causes of stripping is inadequate compaction. The percentage of air voids in a HMA mixture is important and must be carefully controlled. Mixtures with 4-5 percent air voids contents are typically impervious to moisture because the voids are not interconnected. When a pavement is newly constructed, a maximum in-place air voids content of 8 percent is usually specified. It is assumed that traffic will further compact the mixture over two to three years until the design air voids content is reached. When the initial in-place air voids are not carefully controlled and become too high, the HMA pavement can become permeable and the ingress of water can produce stripping.

Other causes of stripping are the presence of a dust and/or clay coating on the aggregates, inadequate aggregate drying, the presence of weak and friable aggregates, and inadequate pavement drainage. When the aggregate is coated with dust and/or clay, the binder-aggregate bond is reduced and channels are formed where moisture can penetrate. If aggregates are not properly dried before the HMA is mixed, inadequate adhesion between binder and aggregate

can result, thus increasing the stripping potential. Weak, friable aggregates can degrade under traffic loading thus exposing uncoated faces that can absorb moisture. Finally, if water is not properly drained from the pavement it can often enter into the pavement thus increasing the chance of moisture damage.

2.2.2 Laboratory Testing

Since 1945, various methods have been developed to predict moisture susceptibility in HMA mixtures. These include: Immersion-Compression test, Lottman test, Root/Tunnicliff test, Marshall Immersion test, Resilient Modulus, and the Double Punch Method. Details about each of these can be found in reference (22). Wheel tracking devices originally designed to predict rutting in HMA mixtures can also be used to predict moisture susceptibility when tests are performed in the presence of water.

The work reported herein uses the AASHTO T283, “Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage,” as well as the PurWheel to determine the stripping potential in HMA mixtures. AASHTO T283 is the conventional method used by the Indiana Department of Transportation (INDOT) to predict moisture damage. It is based on the indirect tensile strength ratio (TSR) of conditioned and unconditioned samples. The PurWheel was developed by Purdue University and is a laboratory tracking test that is performed on specimens submerged in water. Chapter 5 describes these tests procedures in detail.

2.2.2.1 Conventional Test Method

AASHTO T283 is the most widely used and accepted test method to predict stripping potential despite the fact that its accuracy in predicting in-service moisture damage has been criticized. Kandhal (23) suggested that the AASHTO T283 was the most appropriate to predict moisture damage. Choubane et al. (24) studied the effects of different levels of saturation on the test results and suggested modifications to the method in order to more appropriately assess

stripping potential. They recommended a minimum wet tensile strength of 410 kPa in addition to a minimum TSR; a high correlation was observed between the degree of saturation and TSR results. Considering the moisture damage observed in the field, they recommended a saturation level higher than 90 percent and the inclusion of a freeze-thaw cycle.

Pan and White (25) indicated that AASHTO T283 does not accurately reflect an HMA mixture's stripping potential since higher TSR values were observed in 150-mm diameter samples as compared to 100-mm diameter specimens; the larger specimens were less affected by the conditioning procedures. Additionally, they recommended a minimum conditioned tensile strength of 600 kPa. Mahoney and Stephens (26) indicated that many of the HMA samples tested in Connecticut did not pass the TSR limit specified in AASHTO T283, yet most of the mixtures had no stripping problems in the field.

2.2.2.2 PurWheel

The PurWheel is a laboratory wheel tracking test created at Purdue University (25). At the time of its implementation there were three different laboratory wheel tracking devices. The Laboratory Central de Ponts et Chaussées (LCPC) French Rutting Tester, the Georgia Loaded Wheel Tester (GLWT), and the Hamburg Steel Wheel Tracking Device (HSWT). The PurWheel is based on the HSWT with some improvements designed to better reflect field conditions. The PurWheel is capable of testing in dry or wet conditions and it can use either a steel or rubber wheel. It can also incorporate wheel wander and uses a larger sample size to minimize boundary effects. Additionally, the rut depth can be measured over the entire length of a specimen using movable transducers. With these modifications, the PurWheel can create the conditions associated with rutting and stripping; high moisture, high temperature, and a moving wheel load.

Pavement deformation consists of two components, compactive deformation in the wheel path and plastic deformation, which is the rise in the HMA mixture that can occur between and outside the wheel paths. The

PurWheel measures the compactive deformation at every wheel pass; the total deformation (compactive plus plastic deformation) can be measured at the end of the test. When the PurWheel specimens are tested in the presence of water, additional rutting damage can occur due to the hydraulic scouring mechanism and excessive pore pressure caused by the moving wheel loading (25). The potential for moisture damage can be predicted by plotting the compactive deformation as a function of the number of wheel passes. Izzo and Tahmoressi (27) described three distinct portions of such a plot as shown in Figure 2.2. The first is the creep slope. This portion of the curve is related to the rutting that comes primarily from plastic flow. The second portion is the stripping slope. This rutting is primarily due to moisture damage. Finally, the stripping inflection point is defined as the number of passes at the intersection of the creep and stripping slope.

FIGURE 2.2 Wheel Tracking Results (after [25])

2.2.3 Effect of Aggregate Gradation

Kandhal (23) indicated that stripping of fine aggregate is more critical and Pan and White (25) observed that fine aggregate could be a major factor in the loss of adhesion of asphalt binder film. They also observed that maximum

aggregate size and mixture gradation have a significant effect on rutting resistance, and that the presence of crushed sand may help to reduce moisture damage. Pan and White (25) also suggested that fine aggregate angularity and/or gradation appear to be related to mixture instability.

2.2.4 Comparison of In-Service and Laboratory Results

Research has shown the effectiveness of laboratory wheel tracking to predict stripping potential in HMA mixtures. Pan and White (25) concluded that the PurWheel is an effective tool to evaluate the stripping potential of a mixture in a hot/wet environment. Williams and Prowell (28) tested samples taken from the WestTrack and concluded that the HSWT produced a satisfactory correlation with pavement deformation observed at the track. However, the proper selection of test temperature is an important issue in the success of the test. Izzo and Tahmoressi (27) found some unexpected results in samples they tested with the HSWT and indicated that 50C was too extreme a temperature, and performance measured by the HSWT may not be accurate at this temperature for mixtures with AC-20. Pan and White (25) showed that mixtures deform rapidly without a creep deformation stage at 60C because the mixture has already lost integrity and cannot resist tire loading.

2.3 Long-Term Performance and Durability

The principal distresses in an HMA pavement are permanent deformation, fatigue cracking, and thermal cracking. The appearance of these distresses affects the durability and long-term performance of an HMA pavement.

Permanent deformation and fatigue and thermal cracking are affected by environmental, load, and mixture factors. The engineer responsible for the HMA mixture design must evaluate the external conditions of the pavement location and select materials and combinations thereof to assure optimum performance of the pavement.

2.3.1 Permanent Deformation

Permanent deformation, or rutting as it is often called, is the deformation of the pavement layers due to traffic loads. It can be divided in two stages, compactive deformation and plastic deformation (or plastic flow). Compactive deformation corresponds to a deformed surface lower than the initial pavement surface while plastic deformation is when the deformed surface is higher than the original surface.

According to Zhou and Scullion (1), three stages of rutting can be identified as shown in Figure 2.3. The primary or pre-failure zone is where permanent deformation accumulates rapidly. In this zone there is an increase in total plastic strain because HMA mixtures will work harden with repeated loading. The physical process that explains this stage is motion (micro-flow), or dislocation. The second zone, or steady stage, is where the permanent deformation rate is a constant value. In this stage the occurrence of micro-cracking causes more dislocation to develop. At the same time, there is more “space” for mobility of the dislocations, which further softens the HMA. In this stage the rate of work-hardening is dynamically equal to that of work-softening. Lastly, the tertiary or failure zone, with crack formation and propagation occurs when the permanent deformation rate begins to increase due to the formation and growth of micro-cracks. Micro-cracks gradually propagate and coalesce to form macro-cracks. The initiation and propagation of macro-cracks accelerates the rate of work-softening, causing the permanent deformation rate to increase.

The rutting performance of an HMA mixture depends not only on the properties of the aggregates and binder, but also on how these materials interact in the mixture. Tarefder et al. (29) evaluated Superpave mixtures with the Asphalt Pavement Analyzer (APA) to determine the factors affecting rutting and their significance. They found that the binder type, specimen type, test temperature, and their interactions were the most significant factors. Moisture, wheel load, binder content, and hose pressure were found to be the least significant factors.

FIGURE 2.3 Stages of Permanent Deformation (after [1])

2.3.1.1 Causes

Pavement rutting is caused when the underlying layers, subgrade soil, and/or the HMA layers are overstressed and densification or shear failure occur. Roberts et al. (30) noted several causes of rutting including overstressing of the subgrade soil due to insufficient pavement structure, poor drainage, additional pavement densification due to insufficient initial compaction, and improper HMA mixture design (high binder content, excessive filler material, or excessive rounded particles in either or both the coarse and fine aggregates).

HMA rutting is controlled by the characteristics of the binder and aggregates and their interaction. According to Roberts et al. (30), some recommendations to reduce rutting in the HMA layer include increasing the voids in the mineral aggregate (VMA), establishing minimum and maximum air voids contents, limiting the amount of natural sand, establishing a minimum percentage of crushed coarse and fine aggregates, using stiffer binder, and the use of coarser mixture gradations.

2.3.1.2 Effect of Air Voids

At very low air voids contents, mixtures can lose stability after reaching a critical level (approximately 2 percent). Conversely, at higher air voids contents, the

potential for rutting increases due to the reduction of stiffness and/or the higher probability of moisture damage. Excessive air voids content increases the permeability of HMA mixtures thereby increasing the potential for damage from water and air ingress. Air can cause the binder to become brittle due to oxidation; water can produce stripping of the binder from the aggregate and consequent rutting. Also, at high air voids contents, the stiffness of the mixture decreases and is therefore more prone to permanent deformation.

2.3.1.3 Effect of Aggregates

With the implementation of Superpave, various specifications were incorporated to assist in selecting materials to assure good pavement performance. Part of the specification originally included a “restricted zone” through which the blended aggregate gradation of the mixture could not pass. The purpose of having a restricted zone was to develop a strong stone skeleton to enhance the performance and durability of the pavement. Researches have often separated gradation into three groups based on the restricted zone: Above the restricted zone (equivalent to a fine gradation), below the restricted zone (equivalent to a coarse gradation), and through the restricted zone.

It has been widely held that a coarser gradation produces a more rut-resistant HMA mixture. However, some studies have concluded that finer-graded mixtures present lower rut potential. Cross et al. (34) studied four different gradations from fine to coarse and their relationship to rutting. They concluded that finer gradations had significantly more resistance to shear deformation than the coarse gradations. Tarefder et al. (29) also studied the factors affecting rutting and concluded that finer-graded mixtures are less susceptible to rutting compared to coarser-graded mixtures. Chowdhury et al. (32) studied permanent deformation in Superpave mixtures using the simple shear test and reached the same conclusions. In WestTrack, coarser-graded mixture performed poorly and exhibited more rutting and fatigue cracking than finer-graded mixtures. Tests

conducted by Haddock et al. (35) also indicated that fine-graded mixtures performed better than coarse-graded in wet and dry PurWheel tests.

Other aggregate properties that affect rutting are shape and surface texture. Mixtures with crushed manufactured sand are more rut resistant than mixtures with natural sand. Aggregates with angular particles, that produce better interlock and internal friction, have greater mechanical stability. Rough aggregate surface texture produces a stronger mechanical bond and a higher VMA increasing both a mixture's stability and resistance to permanent deformation.

2.3.1.4 Comparison of In-Service and Laboratory Results

Pellinen and Witczak (31) studied the use of the simple performance test to complement the Superpave volumetric mixture design method and concluded that unconfined dynamic modulus in the linear viscoelastic range gives the best correlation to in-service rutting. The dynamic modulus ($|E^*|$) of an HMA mixture is inversely proportional to rutting. This means that mixtures that are less stiff are more prone to rutting. In previous studies, the permanent deformation of HMA mixtures had typically been evaluated using the Superpave Shear Tester (SST). The SST test determines the shear modulus (G^*) and shear phase angle. Today, the mechanistic-empirical pavement design method uses the dynamic modulus test rather than the SST to determine the rutting potential of an HMA mixture.

Results from the dynamic modulus and SST tests are directly related. Chowdhury et al. (32) studied permanent deformation in Superpave mixtures using the SST and concluded that G^* is reduced at higher temperatures and lower frequencies. This implies that the rutting potential in pavements increases in hot weather and at reduced vehicles speeds. Clyne et al. (33) tested samples in the dynamic modulus apparatus and reached the same conclusion.

2.3.2 Fatigue

The fatigue resistance of an HMA mixture is defined as its ability to withstand repeated bending without fracture. When an in-service HMA mixture is exposed

to traffic loading, the vehicles cause the mixture (pavement) to bend. Fatigue characteristics of an HMA mixture are expressed in terms of the number of load repetitions to failure.

2.3.2.1 Causes

Fatigue occurs in a pavement due to the repetitive nature of traffic. Traditionally, fatigue appears as cracks in the wheel path. These cracks can result from the shear stresses in either the surface of the HMA layer or the tensile stresses at the bottom of this layer. HMA mixture properties that contribute to poor fatigue performance include low binder content and high air voids content. Additionally, HMA layers with inadequate thickness can experience excessive bending followed by fatigue cracking.

2.3.2.2 Effect of Air Voids Content

Harvey et al. (6) studied HMA mixtures in the laboratory beam fatigue apparatus and concluded that for fatigue performance, controlling air voids content was more important than controlling binder content. They also concluded that for strain controlled fatigue test, as the air voids content in an HMA sample increases, fatigue life and stiffness decrease. In mixtures with lower air voids contents, micro-cracks that form due to loading repetitions grow more slowly and take longer to interconnect. Air voids tend to concentrate stresses and allow cracks to extend. They concluded that decreasing air voids content increases HMA stiffness. This relationship was not affected by differences in strain level.

2.3.2.3 Effect of Aggregates

Khosla et al. (36) concluded that fatigue life is influenced by both NMA and aggregate gradation. They observed that 9.5-mm fine-graded mixtures had higher fatigue lives than did 12.5-mm coarse-graded mixtures.

Souza et al. (37) studied fatigue life in HMA and concluded that fine-graded mixtures perform better in fatigue than do coarse-graded mixtures.

Chowdhury et al. (32) analyzed other studies and also concluded that fine-graded mixtures perform better in fatigue than do coarse-graded mixtures.

2.3.2.4 Effect of Conditioning

Harvey et al. (6) concluded that long-term aging had no influence on the effects of binder and air voids contents. Long-term aging in air increased mixture stiffness, but had very little effect, if any, on fatigue life. This was also found to be true in limited in-situ studies.

2.3.2.5 Comparison of In-Service and Laboratory Results

The relationship between in-service fatigue and the results of laboratory fatigue tests is one of scale. HMA mixtures typically fail in laboratory fatigue tests much sooner than they would in the field. This is because on in-service pavements, the wheel loads are not applied at the same location each time a vehicle passes. Also, the rest periods between loading is normally longer in the field than in the laboratory. To account for these differences, scale factors have been determined to establish a relationship between in-service HMA mixture fatigue and laboratory mixture fatigue. For example, the Asphalt Institute uses a scale factor of 18.4 in its fatigue relationship (38). When using laboratory fatigue test results, it should therefore be remembered that the results are relative. While a mixture tested in the laboratory will most likely have a longer fatigue life in the field, the laboratory results of several different mixtures can be used to rank the mixtures by fatigue performance.

CHAPTER 3 EXPERIMENTAL METHODS

3.1 Experimental Design

3.1.1 Plan of Study

The objectives of this study were to evaluate the influence of initial density on the performance of HMA mixtures and to better quantify the relationships among initial HMA density, permeability, and moisture induced damage. To accomplish these, four HMA mixtures were used as shown in Table 3.1. The test variables were NMAS (9.5- and 19.0-mm), gradation (coarse- and fine-graded), and density (90, 92, 94, and 96 percent of G_{mm}). Once the mixture designs were completed, test specimens were prepared and tested to determine each mixture's performance.

TABLE 3.1 Experimental Design

Gradation	Density (% G_{mm})	NMAS (mm)	
		9.5	19.0
Coarse Graded	90	Mixture 1	Mixture 3
	92		
	94		
	96		
Fine Graded	90	Mixture 2	Mixture 4
	92		
	94		
	96		

3.1.2 Test Methods

The research was completed using three groups of test methods; permeability and porosity testing, moisture susceptibility testing, and performance and durability testing.

Permeability testing was completed using the falling head permeability and Corelok tests. The falling head permeability equipment and test method developed by the FDOT were used. The Corelok method was used to determine the porosity of the mixture samples. Both permeability and porosity testing used specimens prepared in the SGC. Moisture sensitivity testing was completed using the AASHTO T283 and PurWheel test methods.

The dynamic modulus and beam fatigue tests were used as measures of HMA performance and durability. HMA mixture samples were tested in both unconditioned and conditioned states. Two types of specimen conditioning were used for the project, moisture and air. For moisture conditioning, the samples were partially saturated and placed in a 60C water bath for 24 hours prior to testing. Conditioning in air was completed by placing the specimens in an 85C forced draft oven for 5 days prior to testing. Moisture conditioning tends to promote moisture damage, thereby enabling the decrease in performance and durability due to this damage to be quantified by the dynamic modulus and beam fatigue tests.

3.2 Materials

3.2.1 Binder

In order to keep the number of variables to a manageable level, binder type was not included as a variable in the project; only one binder type was included. PG 64-22 was chosen because of its wide application throughout Indiana.

3.2.2 Aggregates

The aggregates used in this project were a natural sand fine aggregate and crushed limestone coarse aggregate. The coarse aggregate was tested for gradation, angularity, and flat and elongated particles. The fine aggregate was tested for gradation, angularity, and sand equivalent value. The test results are shown in Appendix A.

3.3 Mixture Designs

Laboratory mixture designs for Mixtures 2, 3, and 4 were completed in the Purdue University Bituminous Laboratory. The Mixture 1 design was completed by a local HMA contractor and actually placed on US-52 in Indiana. All four mixture designs were completed to meet the requirements of the Superpave mixture design specifications for a traffic level of 2,300,000 Equivalent Single Axle Loads (ESAL). This corresponds to ESAL Category 2 according to the INDOT specifications.

The Superpave mixture design method was used to determine the optimum binder content for the mixtures, selected on the basis of 4 percent air voids in samples compacted using the SGC. AASHTO T209 “Standard Method of Test for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures” was used to determine the maximum theoretical specific gravity (G_{mm}) of each mixture. AASHTO T166 “Standard Method of Test for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens” was used to obtain the bulk specific gravity (G_{mb}) of each sample. The air voids contents of all specimens were obtained using the G_{mm} and G_{mb} results. The mixture designs are summarized in Table 3.2. Appendix B presents detailed information for every mixture.

TABLE 3.2 Mixture Design Summary

Mixture Property	Mixture Number			
	1	2	3	4
Binder Type	64-22	64-22	64-22	64-22
NMAS (mm)	9.5	9.5	19	19
Gradation	Coarse	Fine	Coarse	Fine
Binder Content (%)	5.5	6.6	5.9	5.5
Air Voids @ N_{des} (%)	4.0	3.9	4.0	4.3
VMA @ N_{des} (%)	15.5	15.9	15.1	13.8
VFA @ N_{des} (%)	74.5	75.4	73.7	69.1
% Gmm @ Nini	— ¹	86.4	85.9	87.4
% Gmm @ Nmax	— ¹	97.4	97.1	96.9
Tensile Strength Ratio (%)	97.1	80.0	85.0	84.3

¹ Data unavailable

3.4 Analysis Procedures

The Analysis of Variance (ANOVA) and Tukey multiple comparison procedure were used to evaluate the test results. Both were performed using the SAS statistical software.

3.4.1 Analysis of Variance

The statistical analyses were performed using the ANOVA method. This is a statistical tool used to study the relationship between a response variable and one or more explanatory or predictor variables (factors). The analysis is intended to determine the statistical relationship between the mean response and the level(s) of the predictor variables. No type of relationship is assumed or applied a priori. Instead, the method attempts to determine whether the response differs significantly at different levels of the predictor variables.

In the ANOVA output, the F-test corresponds to the goodness of the fit for the relationship analyzed. The F-value is defined as:

$$F = \frac{MSR}{MSE} \quad (3.1)$$

where,

MSR = Mean squares of regression; and

MSE = Mean squares error.

The p-value, calculated in the ANOVA process, refers to the probability of rejecting a hypothesis that the factor levels do not affect the dependent variable response. A p-value less than 0.05 indicates that differences in factor levels do significantly influence the dependent variable response.

3.4.2 Tukey Multiple Comparison Procedure

While the ANOVA process looks at each factor one at time, the multiple comparison procedure allows all variables to be compared at once. This procedure therefore provides information about statistical significance at every level for every factor.

CHAPTER 4 PERMEABILITY

4.1 Falling Head Permeability

4.1.1 Background

One important factor in evaluating permeability is the hydraulic gradient (the head loss per unit length). Darcy showed that water flow is proportional to the hydraulic gradient and the area of a sample according to:

$$Q = kiA \quad (4.1)$$

where,

Q = flow rate (cm^3/s);

k = coefficient of permeability (or simply permeability) (cm/s);

i = hydraulic gradient (cm/cm); and

A = total cross sectional area (cm^2).

The equation assumes a homogeneous material, with steady state, laminar, one-dimensional flow conditions, and that the fluid is incompressible and the material completely saturated.

Due to problems related to permeability and stripping in pavements in Florida, the FDOT develop a falling head device to evaluate the permeability of HMA mixtures (Figure 4.1). With the falling head method, the time required for a sample to lose a head of water is measured and used to determine the permeability. For this approach, Darcy's equation can be expressed as:

$$k = \frac{aL}{At} \ln \left(\frac{h_1}{h_2} \right) \quad (4.2)$$

where,

k = coefficient of permeability (cm/s);

a = area of the stand pipe (cm²);

h_1 and h_2 = water head at the beginning and end of the test (cm);

t = time over which head is allowed to fall (s);

L = length of the sample (cm); and

A = cross-sectional area of the sample (cm²).

FIGURE 4.1 Falling Head Permeameter

4.1.2 Testing Procedures and Parameters

Due to its simplicity and short testing times, the FDOT falling head approach was selected to obtain the permeability of the samples in this project. The standard test method used was the Virginia Test Method–120, “Method of Test for Measurement of Permeability of Bituminous Paving Mixtures Using a Flexible Wall Permeameter.”

Samples were prepared using the SGC and compacted to the heights as specified in the test method. For 9.5-mm NMAS mixtures the required height is 38 ± 2 mm; for 19.0-mm NMAS mixture it is 50 ± 2 mm. The standard does not allow samples to be saw cut to obtain the correct height because sawing can seal the external pores of the sawn surface and reduce the real permeability value. In order to make the specimens without sawing, additional top plates were installed over the bottom plate in the SGC mold.

After compaction, samples were cooled to room temperature for 24 hours, measured, and vacuum-saturated at a residual pressure of 90 ± 2 mm of Hg. The residual pressure was maintained for 15 ± 2 minutes. After vacuum-saturation, each sample was allowed to rest under water for five minutes and then the side surfaces were covered with petroleum jelly to guarantee a proper seal between the membrane and the sample.

Following the conditioning steps, a sample was placed in the testing device with a confining pressure of 96 ± 7 kPa to ensure that water would not flow into the lateral area. The test required measuring the time necessary for water to flow from the upper to the lower marks. If this time exceeds 10 minutes, the lower mark was considered as the position of water at that time. Using these data, permeability values were calculated using Equation 4.2. The test was repeated for each sample until the last three permeability values varied by less than 10 percent. The permeability of the sample is reported as the average of these three values.

4.1.3 Results

The permeability results are presented in Table 4.1 and are plotted as a function of air voids content in Figure 4.2. The figure shows a logarithmic relationship between air voids content and permeability and indicates there are variations in the permeability of the four mixtures. This is most likely due to variations in the size and interconnectivity of the air voids in the mixtures.

FIGURE 4.2 Permeability Results

Figures 4.3 through 4.6 show the permeability for each mixture again plotted as a function of air voids content. For Mixtures 1, 2, and 4, the data indicate low permeabilities (less than 100×10^{-5} cm/s) below 8 percent air voids content with the mixtures having no permeability at approximately 6 percent air voids. Mixture 3 is different in that it has more than twice this permeability (200×10^{-5} cm/s) at 8 percent air voids content. This quickly increases to approximately 850×10^{-5} cm/s as the air voids content reaches 10 percent. Mixture 3 is a coarse-graded, 19.0-mm NMA mixture. The permeability data appears to indicate that this mixture has relatively large, interconnected air voids.

TABLE 4.1 Permeability Results

Mixture	NMAS (mm)	Gradation	Air voids (%)	Average Permeability (10 ⁻⁵ cm /s)
1	9.5	Coarse	4.17	0.25
			4.66	0
			5.53	10.50
			6.17	14.43
			6.21	7.23
			6.64	12.22
			8.32	94.89
			8.76	86.30
			9.52	173.54
			9.63	148.38
2	9.5	Fine	4.34	0.41
			4.55	0.42
			5.94	1.32
			6.38	9.91
			7.83	55.97
			8.03	35.29
			9.54	184.72
			9.83	140.41
3	19.0	Coarse	3.14	0
			3.97	0
			4.88	6.34
			5.10	12.70
			5.52	28.20
			6.06	41.30
			7.91	65.80
			8.54	176.30
			9.01	698.50
			9.17	481.10
			9.51	960.50
			9.91	936.80
4	19.0	Fine	4.09	0
			4.26	0
			4.38	0
			5.72	7.00
			6.92	38.62
			8.40	100.10
			8.76	114.03
			10.17	209.06
			10.32	324.38
			11.15	251.92

FIGURE 4.3 Mixture 1 Permeability

FIGURE 4.4 Mixture 2 Permeability

FIGURE 4.5 Mixture 3 Permeability

FIGURE 4.6 Mixture 4 Permeability

As mentioned in Chapter 2, 8 percent air voids content is thought to be a critical level. Higher values correspond to mixtures with higher permeabilities, which can cause performance problems. In this study, the permeability values at 8 percent air voids content are 52×10^{-5} , 38×10^{-5} , 200×10^{-5} , and 62×10^{-5} cm/s, for Mixtures 1 through 4, respectively. The rule of 8 percent air voids content does not appear suitable for Mixture 3 since it would result in a pavement with unacceptably high permeability.

According to the FDOT, the critical permeability value for the falling head permeameter method is 125×10^{-5} cm/s. FDOT believes that if the in-place HMA mixture permeability is kept at or below this level the mixture (pavement) will perform well. Using this critical permeability value, the four mixtures in this study would need initial air voids contents of 9.0, 9.3, 7.4, and 9.1% for Mixtures 1 through 4, respectively. These correspond to initial densities of 91.0, 90.7, 92.6, and 90.9% for the four mixtures. Westerman (39) suggested a critical permeability value of 10×10^{-5} cm/s, which corresponds to air voids contents of 6.3, 6.8, 5.0, and 5.7% for Mixtures 1, 2, 3, and 4, respectively. These would mean initial in-place densities of 93.7, 93.2, 95.0, and 94.3% for the four mixtures.

The permeability data seem to indicate that the initial in-place density required of an HMA mixture to ensure adequate permeability (pavement performance) may be a function of both the mixture and critical permeability level chosen. In this case, for a critical permeability of 125×10^{-5} cm/s, Mixture 3 needs to be compacted to an initial density approximately 2 percent higher than the other three mixtures. However, if the critical permeability is lowered to 10×10^{-5} cm/s, Mixture 3 requires an initial in-place density 1.3% higher on average. Of course as the critical permeability level is lowered, the initial densities required increase for all mixtures. Thus a judicious choice of the critical permeability level becomes extremely important.

4.2 CoreLok

4.2.1 Background

The air voids content of each sample was determined using both the AASHTO T166 method and the CoreLok equipment. The later is an alternative method for measuring the bulk specific gravity of a compacted HMA sample, as well to calculate the porosity of the sample.

Cooley et al. (13) compared the G_{mb} results obtained by both the CoreLok and AASHTO T166. They concluded that the results for the two methods were significantly different for coarse-graded mixtures. The differences varied with mixture type (gradation) and air voids content. The results suggested that the CoreLok does not overestimate the G_{mb} values as does AASHTO T166, thus allowing for a more accurate measurement of air voids content, especially at high air voids contents. The difference in results can be explained by the higher interconnectivity of the air voids in coarse-graded samples. For coarse-graded samples with interconnected air voids, when using AASHTO T166, after the sample is removed from the water bath, water can drain from the sample while the surface-saturated dry (SSD) mass is being determined. This yields a lower SSD mass and thereby a higher G_{mb} value (lower air voids content than actually exists).

4.2.2 Testing Procedures and Parameters

To obtain G_{mb} values using the AASHTO T166 method, a dry sample is weighed and its mass in grams is recorded (Mass A). The submerged mass (C) and the SSD mass (B) are also determined. With this information, Equations 4.3 and 4.4 can be used to calculate the G_{mb} and the water absorbed by the sample.

$$G_{mb} = \frac{A}{B - C} \quad (4.3)$$

$$\text{WaterAbsorbed} = \frac{B - A}{B - C} \times 100 \quad (4.4)$$

According to AASHTO T166, if the water absorbed exceeds two percent, the AASHTO T275 method, “Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin Coated Specimens,” must be used instead of T166 in order to obtain the G_{mb} .

The CoreLok device can be used as an alternative to AASHTO T166. In the CoreLok, the specimen is vacuum sealed in a plastic bag prior to determining its density by displacement. In the CoreLok method the dry mass of the sample is determined prior to sealing the sample inside a plastic bag of known density and mass. Air from the bag is then evacuated and the bag sealed. The bag (with sample inside) is then submerged in water and the mass of the sealed sample and bag recorded. Finally, and the bag is opened under water and the mass of the submerged sample and bag again recorded. The G_{mb} and porosity are determined using the equations:

$$G_{mb} = \frac{A}{B - E - \frac{B - A}{F_T}} \quad (4.5)$$

where,

A = mass of dry specimen in air (g);

B = mass of dry sealed specimen (g);

E = mass of sealed specimen under water (g); and

F_T = apparent specific gravity of plastic bag at 25C.

$$p = \left(\frac{\rho_2 - \rho_1}{\rho_2} \right) \times 100 \quad (4.6)$$

where,

p = porosity (%);

ρ_1 = vacuum sealed density of specimen (g/cm^3); and

ρ_2 = apparent or maximum density of the specimen (including the volume of inaccessible air voids). This is determined as the density of the vacuum-sealed specimen after opening under water (g/cm^3).

4.2.3 Results

Table 4.2 presents the AASHTO T166 and CoreLok results. Figure 4.7 shows a comparison of the air voids contents determined by the AASHTO T166 method and the CoreLok. The air voids contents obtained by the AASHTO T166 method tend to be higher than those obtained by the CoreLok.

FIGURE 4.7 Comparison of CoreLok and AASHTO T166

Figures 4.8 and 4.9 present the relationships between porosity and air voids contents determined in the CoreLok and porosity and the air voids contents determined by AASHTO T166, respectively. These plots indicate that Mixtures 1, 3, and 4 have an approximate one-to-one correspondence between air voids content and porosity. However, Mixture 2 (9.5-mm NMAS, fine gradation) has a lower porosity values at every air voids content.

TABLE 4.2 Bulk Specific Gravity, Porosity and Absorption Results

Mixture	CoreLok			AAHTO T166		
	Gmb	Porosity (%)	Air Voids (%)	Gmb	Water Absorbed (%)	Air Voids (%)
1	2.447	2.9	3.1	2.437	0.09	3.8
	2.426	3.4	3.9	2.424	0.07	4.3
	2.400	5.6	4.9	2.396	0.09	5.4
	2.381	5.3	5.7	2.381	0.15	6.0
	2.391	5.1	5.3	2.380	0.15	6.0
	2.338	7.3	7.4	2.335	0.28	7.8
	2.332	7.6	7.6	2.328	0.44	8.1
	2.270	10.3	10.1	2.286	1.05	9.7
	2.265	10.3	10.3	2.286	1.24	9.8
2	2.428	2.5	3.8	2.423	0.06	4.0
	2.425	2.9	4.0	2.420	0.11	4.2
	2.399	3.5	5.0	2.386	0.07	5.5
	2.365	5.2	6.3	2.360	0.04	6.5
	2.356	4.7	6.7	2.333	0.11	7.6
	2.313	7.4	8.4	2.317	0.07	8.2
	2.258	9.0	10.6	2.272	0.44	10.0
	2.275	8.5	9.9	2.271	0.47	10.0
3	2.429	3.9	3.8	2.429	0.10	4.2
	2.424	4.0	4.0	2.426	0.06	4.3
	2.390	5.4	5.3	2.391	0.12	5.7
	2.368	4.8	6.2	2.370	0.08	6.5
	2.320	8.0	8.1	2.334	0.36	7.9
	2.316	8.6	8.3	2.332	0.21	8.0
	2.387	4.0	5.5	2.392	0.27	5.6
	2.292	9.5	9.2	2.304	0.22	9.1
4	2.296	8.3	9.1	2.302	0.59	9.2
	2.457	3.4	2.7	2.473	0.19	3.7
	2.451	2.9	2.9	2.471	0.17	3.8
	2.423	4.3	4.0	2.450	0.20	4.6
	2.396	5.7	5.1	2.426	0.30	5.6
	2.407	3.7	4.7	2.413	0.30	6.0
	2.362	6.7	6.5	2.387	0.36	7.1
	2.383	6.7	5.6	2.387	0.14	7.1
	2.314	9.1	8.4	2.349	0.90	8.6
	2.325	8.0	7.9	2.336	0.21	9.0
	2.306	8.3	8.7	2.324	0.87	9.5

FIGURE 4.8 CoreLok Porosity and Air Voids

FIGURE 4.9 CoreLok Porosity and AASHTO T166 Air Voids

4.3 Statistical Analysis of Results

4.3.1 Permeability

The falling head permeameter was used to test each of the four HMA mixtures at each of the four air voids contents included in the project. Statistical analyses were completed using the SAS computer software and a 95 percent significance level. An ANOVA was first completed in order to determine the significance of each of the main experimental factors as well as to explore interaction effects. The Tukey's Studentized Range procedure was used to explore the differences in factor levels for each of the three main factors (gradation, NMA, air voids content). To properly complete the statistical analyses, air voids content and permeability were both first transformed into natural logarithm values. Gradation was assigned a value of 0 for coarse-graded mixtures and 1 for fine-graded mixtures. Permeability values are 10^{-5} cm/s and air voids content is denoted as voids in the total mixture (VTM).

The ANOVA results are shown in Table 4.3 and the Tukey's Studentized Range results in Table 4.4. The ANOVA results indicate that NMA, gradation, air voids content, and their interactions are significant in predicting HMA mixture permeability. Air voids content (density) appears to have the most influence followed by NMA and finally gradation.

TABLE 4.3 Permeability ANOVA Results

(Dependent variable: permeability)					
F-value = 19.18		Pr > F: <0.0001		Adjusted R ² = 0.92	
Source	DF	Type III SS	Mean Square	F value	Pr > F
NMA	1	101899.43	101899.43	14.54	0.0008
Gradation	1	48667.92	48667.92	6.94	0.0145
NMA×Gradation	1	33656.73	33656.73	4.80	0.0384
VTM	3	733030.54	244343.51	34.86	< 0.0001
NMA×SVTM	3	208880.48	69626.83	9.93	0.0002
Gradation×VTM	3	109655.51	36551.84	5.21	0.0065
NMA×Gradation×VTM	3	124286.93	41428.98	5.91	0.0036

From Table 4.4, one observes that 19.0-mm coarse-graded mixture at 10 percent air voids content had the highest permeability and the fine-graded mixture with a 9.5-mm NMAS and 4 percent air voids content was the least permeable. Also, on average, the permeability of fine-graded mixtures is 55 percent less than that of the coarse-graded mixtures. The 9.5-mm NMAS mixtures are 73 percent less permeable than the 19.0-mm mixtures. Specimens at 10 percent air voids had the highest permeability. As the air voids contents go to 8, 6, and 4 percent, the permeability is reduced 78, 96, and 100 percent, respectively. However, the differences in permeability at 8, 6, and 4 percent are not statistically different. This suggests that these HMA mixtures may be impervious to moisture at air voids contents lower than 8 percent, but at higher air voids can become significantly permeable.

TABLE 4.4 Tukey Groups (Permeability)

Tukey Group	Mean Permeability ($\times 10^{-5}$ cm/s)	No. of Observations	Gradation
A	179.79	22	Coarse
B	81.86	18	Fine
Tukey Group	Mean Permeability	No. of	NMAS (mm)
A	202.39	22	19.0
B	54.23	18	9.5
Tukey Group	Mean Permeability	No. of	VTM (%)
A	409.94	11	10
B	91.08	8	8
B	16.67	11	6
B	0.74	10	4

In an additional attempt to investigate the relationships among the project factors, a regression analysis was completed. The resulting equation is:

$$k = VTM^{6.8} e^{(-10.97 + 0.11NMAS - 0.89Gradation)} \quad (4.7)$$

where,

k = Permeability (10^{-5} cm/s);

NMAS = Nominal Maximum Aggregate Size (mm);

VTM = Voids in the Total Mixture; and
 Gradation = 0 for coarse-graded, 1 for fine-graded.

The equation has an excellent goodness of fit (adjusted R^2 of 0.93). The air voids content appears to have the most effect on permeability.

Since the air voids content appears to have such an important relation to permeability, each mixture was independently evaluated using regression analysis techniques with air voids content as the only independent factor. The results take the form:

$$k = \text{VTM}^a e^b \quad (4.8)$$

where a and b are regression constants and the other variables are as previously defined. The regression constants determined for each of the mixtures along with estimates of the goodness of fit are given in Table 4.5. The R^2 values indicate that the air voids content alone does a relatively reasonable job of predicting HMA mixture permeability.

TABLE 4.5 Permeability Regression Results

Mixture	A	b	Adjusted R^2
1	7.12	-10.79	0.93
2	7.90	-12.79	0.95
3	6.44	-8.09	0.92
4	5.45	-7.19	0.94

As discussed in Chapter 2, field tests of permeability have shown to correlate well to laboratory permeability test results. This suggests that it might be possible to control permeability during HMA pavement construction. Mixture permeability can be determined in the laboratory after the mixture design is completed and with an acceptable field permeability value selected, specification limits could be established for initial, in-place permeability. Field permeability testing could be completed on the compacted pavement for permeability quality

control purposes. Cores taken from the completed pavement for density analyses could be tested for permeability in the laboratory and used for quality assurance.

Given the relationship between air voids content (density) and HMA mixture permeability, it may be possible, given further study, to use field permeability testing to control in-place HMA pavement density. This would be significant in that destructive testing would no longer need to be accomplished in order to establish in-place density.

4.3.2 Porosity

ANOVA and Tukey procedures were also used to analyze the porosity data. The results are summarized in Tables 4.7 and 4.8. The ANOVA results show that gradation and air voids content are the significant variables. This is confirmed in the Tukey grouping (Table 4.8) where the coarse and fine gradations as well as the four air voids contents are shown to be in different groups. The NMA does not appear to be significantly different. From figures 4.8 and 4.9, one can observe that Mixtures 1, 3, and 4 have similar porosities at the same air voids content values.

TABLE 4.6 Porosity ANOVA Results

GLM Procedure (dependent variable is rut depth)					
F value = 16.64		Pr>F: < 0.001		R ² = 0.93	
Source	DF	Type III SS	Mean Square	F value	Pr > F
Gradation	1	3.8678	3.8678	5.38	0.0310
VTM	3	166.8741	55.6247	77.39	< 0.0001
Gradation×VTM	3	0.9039	0.301	0.42	0.7412
NMAS	1	0.3804	0.3804	0.53	0.4753
Gradation×NMA	1	1.1226	0.1226	1.56	0.2258
NMA×VTM	3	5.9297	1.9766	2.75	0.0697
Gradation×NMA×VTM	3	0.2687	0.0896	0.12	0.9445

TABLE 4.7 Tukey Groups (Porosity)

Tukey Group	Mean Porosity (%)	No. of Observations	Gradation
A	6.3500	18	Coarse
B	5.6944	18	Fine
Tukey Group	Mean Porosity (%)	No. of Observations	NMAS (mm)
A	6.0684	19	19.0
A	5.9706	17	9.5
Tukey Group	Mean Porosity (%)	No. of Observations	VTM (%)
A	9.0250	8	10
B	7.3444	9	8
C	4.8300	10	6
D	3.3556	9	4

Equation 4.9 shows the regression results for porosity as a function of air voids content measured in the CoreLok.

$$p = \text{VTM} + 0.17(\text{NMAS})(\text{Gradation}) - 2.79(\text{Gradation}) \quad (\text{Eq. 4.8})$$

where p is porosity (%) and the other variables are as previously defined. The R^2 value for this equation is 0.95. This result indicates that porosity can be predicted by air voids content as can permeability. However, the porosity results indicate that the gradation and the interaction of NMAS and gradation can also have a very large impact. Thus porosity may include more information relative to an HMA mixture's permeability than does air voids content. Porosity not only accounts for air voids content, but may also account for the size and interconnectedness of the air voids. It may be that porosity is more important to the performance of an HMA mixture than air voids content, but the results from this project are not extensive enough to make any conclusions. Additional work on porosity needs to be accomplished.

CHAPTER 5 MOISTURE SUSCEPTIBILITY

5.1 AASHTO T283

5.1.1 Background

The AASHTO T283 test method is used to evaluate the moisture susceptibility of HMA mixtures and was established in 1985 based on the Modified Lottman Test, which is a combination of the Lottman and the Root-Tunnicliff tests. The T283 test consists of producing six specimens having air voids contents between 6 and 8 percent. This high air voids content helps to accelerate moisture damage in the cores. Two groups of three specimens are used. The first group, without any type of conditioning, is the control group. The second group is moisture saturated to 70 to 80 percent by applying vacuum saturation. These specimens are then further conditioned by placing them in a water bath at 60C for 24 hours. After conditioning, the Indirect Tensile Strength (ITS) test is performed at 25C with a loading rate of 50 mm/minute. The indirect tensile strength of each sample is determined and the average values for the conditioned and control groups are calculated. The ratio of the average conditioned and unconditioned values is calculated and multiplied by 100 to determine the Tensile Strength Ratio (TSR). For most user agencies, a minimum acceptable TSR value for an HMA mixture is 80 percent. The ITS equipment is shown in Figure 5.1.

5.1.2 Specimen Preparation

After mixing and short-term aging the HMA mixtures for two hours at 145C, the samples were compacted in the SGC. The specimens are 150 mm in diameter and 95 mm in height. The day after compaction (24±3 hours), the samples were tested according to AASHTO T166 to determine their bulk specific gravities

(G_{mb}). The six samples were separated into two groups of three so that the average air voids content of the two groups was approximately equal.

FIGURE 5.1 Indirect Tensile Strength Equipment

5.1.3 Testing Procedures

After compaction and determination of the G_{mb} , the unconditioned samples were placed in a plastic bag and submerged in a 25C water bath for two hours after which time they were tested in the ITS apparatus. The conditioned samples were first vacuum-saturated at a pressure of 250 to 660 mm of Hg until reaching a saturation level of 70 to 80 percent. The samples were then placed in a $60 \pm 1^\circ\text{C}$ water bath for 24 ± 1 hours, followed by a $25 \pm 0.5^\circ\text{C}$ water bath for 2 hours. At the end of the two hour period the conditioned samples were tested.

The indirect tensile breaking apparatus uses two steel loading strips to apply a load along the diameter of the specimen. Once the sample has broken, the tensile strength is calculated by the equation:

$$S_t = \frac{2P}{\pi t D} \quad (5.1)$$

where,

S_t = tensile strength (kPa);

P = maximum load (kN);

t = specimen thickness (average of three measurements) (cm); and

D = specimen diameter (average of three measurements) (cm).

The TSR is calculated according to the equation:

$$TSR = \frac{S_1}{S_2} \times 100 \quad (5.2)$$

where,

TSR = retained tensile strength (%);

S_1 = average tensile strength of three conditioned samples (kPa); and

S_2 = average tensile strength of three unconditioned samples (kPa).

INDOT specifications require HMA mixtures to have a minimum TSR of 80 percent.

5.1.4 Results

For Mixture 1, the mixture actually placed in the field, the mixture design formula indicated a TSR of 97 percent. Mixtures 2, 3, and 4 were prepared and tested in the laboratory for this project. The results are presented in Table 5.1. According to INDOT specifications, none of the four mixtures is considered susceptible to moisture.

Figure 5.2 shows the four mixtures after conditioning and testing. As can be seen, some of the asphalt binder has been stripped from the aggregates. However, these samples do not appear to be moisture damaged beyond what might be considered normal for the AASHTO T283 test.

TABLE 5.1 Moisture Susceptibility Test Results

Mixture 2			Mixture 3			Mixture 4		
S _t (kPa)	Average S _t (kPa)	TSR (%)	S _t (kPa)	Average S _t (kPa)	TSR (%)	S _t (kPa)	Average S _t (kPa)	TSR (%)
Unconditioned		80.1	Unconditioned		82.9	Unconditioned		84.3
850.3	860.8		751.0	748.0		914.4	857.1	
886.4			773.3			828.9		
845.7			719.7			827.9		
Conditioned			Conditioned			Conditioned		
699.4	689.3		640.0	619.8		667.9	722.4	
629.6			602.3			766.3		
738.9			617.1			733.0

FIGURE 5.2 AASHTO T283 Conditioned Samples

5.2 PurWheel

5.2.1 Background

The Purdue laboratory wheel tracking device (PurWheel) was developed to recreate the conditions associated with rutting and stripping. It simulates field conditions of high moisture, high temperature, and traffic, all of which can

contribute to rutting and stripping. The load is applied with a pneumatic tire typically inflated to produce a contact pressure of 690 kPa. Pan and White's report (25) gives a detailed description of the PurWheel parameters of testing. In this project, the PurWheel was used to evaluate the stripping potential of the four mixtures at each of the four air voids contents in hot, moist conditions.

5.2.2 Specimen Preparation

After mixing and short-term-oven aging laboratory prepared HMA mixture at 135C for four hours, the PurWheel samples were compacted at 145C in a linear compactor to achieve the target air voids of 4, 6, 8, and 10 percent. The linear compactor (Figure 5.3) includes a rectangular mold attached to an air cylinder, a set of steel plates, a loading frame with a steel roller and hydraulic ram to apply a compaction force (hydraulic pressure supplied by an electric powered hydraulic pump). Once the sample is compacted and cooled, it is cut into halves. After overnight drying, the length and width dimensions are taken at three different points and the thickness measured at eight different points. With the average dimensions the volume is calculated and using this in conjunction with the theoretical maximum density of the mixture, the air voids content is determined.

FIGURE 5.3 Linear Compactor

Typical specimen dimensions are 290 mm wide and 310 mm long. The thickness varies with the NMAS of the mixtures. For 9.5-mm NMAS mixtures a 50 mm thick test specimen is used. For 19.0-mm NMAS mixtures, a 63.5 mm thick specimen is used.

5.2.3 Testing Procedures and Parameters

After the air voids content in each slab specimen was determined, they were placed in the PurWheel apparatus using plaster-of-paris to secure them in the mold. After drying for approximately six hours, the testing was performed. A contact pressure of 690 kPa was used. Before running every test, the pressure of the wheel was checked to verify the established wheel pressure and the wheel speed set to 33 ± 2 cm/s. Since the purpose was to evaluate the moisture susceptibility of the samples, the tests were performed with the samples submerged in 50°C water. Prior to testing, the samples were conditioned in the water at the test temperature for 20 minutes. During the test, the computer records the number of wheel passes, the deformation and the elapsed test time. The test ends automatically when a 20 mm rut depth is reached or 20,000 wheel passes are applied, whichever occurs first. Figure 5.4 shows the PurWheel machine with the two test specimens (slabs) in place. Figure 5.5 shows the samples after the application of 20,000 wheel passes.

FIGURE 5.4 PurWheel

FIGURE 5.5 PurWheel Samples after Testing

5.2.4 Results

The PurWheel data are shown in Table 5.2. The rut depth is the compactive deformation, or downward deformation measured in the sample during the test. Total deformation is measured at the end of the test and includes both the compactive and upward lift deformation.

Figures 5.6 through 5.9 show the PurWheel results for each mixture. In these plots, it is seen that none of the samples had a stripping inflection point as defined earlier (Chapter 2). It is therefore concluded that none of the four mixtures is susceptible to moisture damage. This agrees with the AASHTO T283 results. However, since none of the four mixtures has a stripping inflection point at any of the four air voids contents, no analyses can be completed to determine if the moisture susceptibility is dependent upon the air voids content. It may be possible that the air voids contents of these particular mixtures must be higher than 10 percent before the mixtures begin to become more susceptible to moisture.

TABLE 5.2 PurWheel Test Results

Mixture	Target Air Voids (%)	Air Voids (%)	Average Air Voids (%)	Rut Depth (mm)	Average Rut Depth (mm)	Total Deformation (mm)	Average Total Deformation (mm)
1	4	4.03	4.0	2.65	2.79	4.26	4.31
		3.95		2.92		4.36	
	6	6.58	6.3	3.13	3.77	5.56	6.53
		5.91		4.41		7.49	
	8	8.12	8.0	5.73	5.03	11.92	10.31
		7.84		4.32		8.70	
	10	10.40	10.2	9.24	10.93	17.79	19.91
		10.03		12.62		22.02	
2	4	4.03	3.6	2.98	3.36	6.02	6.15
		3.10		3.73		6.28	
	6	6.70	6.6	3.34	3.40	6.00	6.62
		6.40		3.45		7.23	
	8	8.56	7.9	4.38	4.37	7.58	7.75
		7.24		4.35		7.92	
	10	10.20	10.3	6.71	5.87	17.01	12.89
		10.40		5.03		8.77	
3	4	4.51	4.7	3.79	3.42	4.51	4.15
		4.88		3.05		3.78	
	6	--- ⁽¹⁾	5.9	--- ⁽¹⁾	3.18	--- ⁽¹⁾	5.06
		5.90		3.18		5.06	
	8	8.23	8.1	3.73	3.40	5.38	4.88
		7.97		3.06		4.37	
	10	10.57	9.8	4.18	4.12	5.92	5.86
		8.93		4.05		5.80	
4	4	3.63	4.2	1.86	1.99	3.91	4.20
		4.81		2.11		4.48	
	6	5.75	5.9	3.46	3.12	4.47	5.25
		5.90		2.77		6.03	
	8	7.62	8.4	2.62	3.08	5.46	5.90
		9.12		3.53		6.34	
	10	8.68	9.7	3.93	4.67	5.48	6.60
		10.76		5.40		7.71	

⁽¹⁾ Sample was damaged and discarded

FIGURE 5.6 Mixture 1 (9.5-mm NMAS, Coarse-graded) PurWheel Results

FIGURE 5.7 Mixture 2 (9.5-mm NMAS, Fine-graded) PurWheel Results

FIGURE 5.8 Mixture 3 (19.0-mm NMAAS, Coarse-graded) PurWheel Results

FIGURE 5.9 Mixture 4 (19.0-mm NMAAS, Fine-graded) PurWheel Results

CHAPTER 6 PERMANENT DEFORMATION

6.1 Background

Permanent deformation of HMA can be evaluated in the laboratory using several different test methods. The National Cooperative Highway Research Program (NCHRP) 1-37A project developed a new pavement design guide based on mechanistic principles. In order to use this method, a modulus value for the HMA is required. Pellinen and Witczak (31) found that the complex modulus obtained in the dynamic modulus test is a suitable parameter to use with the new design method to predict permanent deformation of HMA mixtures. For this reason, dynamic modulus testing was adopted for this research project.

The complex modulus and phase angle of an HMA mixture sample define its viscoelastic characteristics. Complex, or dynamic, modulus (E^*) is defined as the stress-strain relationship in linear viscoelastic materials under continuous sinusoidal load in the frequency domain. The complex modulus is a complex number and contains a real and imaginary component. It is obtained by dividing the amplitude of the sinusoidal stress by the amplitude of the sinusoidal strain, both at a given time (t) and angular load frequency (ω) as shown in Equation 6.1.

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_0 e^{i\omega t}}{\varepsilon_0 e^{i(\omega t - \phi)}} = \frac{\sigma_0 \sin(\omega t)}{\varepsilon_0 \sin(\omega t - \phi)} \quad (6.1)$$

where,

σ_0 = peak, or maximum stress (kPa);

ε_0 = peak, or maximum strain;

ϕ = phase angle (degree);

ω = angular velocity (rad/s);

t = time (s); and

i = imaginary component of the complex modulus.

The dynamic modulus is the absolute value of the complex modulus as shown in Equation 6.2.

$$|E^*| = \frac{\sigma_0}{\epsilon_0} \quad (6.2)$$

Figure 6.1 is a representation of the dynamic modulus test results. The dynamic modulus test can apply loads in a uniaxial or triaxial condition in either compression or tension. In this project, the test method corresponds to the uniaxial condition in compression. The stress level was selected with the purpose of maintaining samples in the linear viscoelastic range.

FIGURE 6.1 Stress and Strain in the Dynamic Modulus Test

The phase angle is the angle by which ϵ_0 lags behind σ_0 and defines the elastic-viscous properties of the mixture. It is obtained by equation 6.3. For a purely elastic material, $\phi = 0$. For a purely viscous material $\phi = 90$ degrees.

$$\phi = \frac{t_i}{t_p} \times 360 \quad (6.3)$$

where,

t_i = time lag between a cycle of stress and strain (s); and

t_p = time for a stress cycle (s).

The viscoelastic response of HMA under cyclic loading gives a storage modulus (elastic characteristics), loss modulus (viscous properties), and phase angle between stress and strain (time dependency). According to Clyne et al. (33), at cold temperatures, mixture stiffness depends on binder stiffness, and at high temperatures, mixture stiffness depends on aggregate interlock stiffness.

6.2 Specimen Preparation

Dynamic modulus samples were compacted using the SGC. Samples were compacted to be 150 mm in diameter and 170 mm in height. The test samples were then made by coring and sawing to meet the testing requirements of 100 mm in diameter and 150 mm in height. After the sample was cored, sawed, and dried, it was instrumented. Three Linear Variable Differential Transducers (LVDT) were placed at the third points of the lateral surface of the sample at mid-height to measure axial deformation. According to the protocol, for two replicates and three LVDTs, the estimated limit of accuracy is 13.1 percent. Figure 6.2 shows an instrumented sample.

FIGURE 6.2 Dynamic Modulus Sample

6.3 Testing Procedures and Parameters

Dynamic modulus tests were performed on all mixtures at the four target air voids contents in both the unconditioned and moisture conditioned states. Table 6.1 summarizes the test parameters. For moisture conditioning, dynamic modulus samples were vacuum-saturated until a saturation level between 70 and 80 percent was achieved. They were then placed in a water bath at 60C for 24 hours before being tested. The dynamic modulus test temperatures were 20 and 40C.

Test specimens were brought to test temperatures by leaving them in the environmental chamber for three hours to reach 20C, or four hours to reach 40C prior to testing. Initially, the samples were tested at 20C, then left overnight and tested at 40C the following day. When samples reached the proper test temperature, they were placed in the testing apparatus with double rubber membranes on the top and bottom to minimize end friction. The two membranes were separated with vacuum grease. Samples conditioned in water were first left to dry overnight and brought to the test temperature as described.

TABLE 6.1 Dynamic Modulus Testing Parameters

NMAS	9.5, 19.0 mm
Gradation	Coarse and fine
Type of conditioning	None, moisture
Air voids	4, 6, 8 and 10
Asphalt content	Optimum
Strain Level ($\mu\epsilon$)	< 150
Replicates	2
Temperature (C)	20 and 40
Frequency (Hz)	25, 10, 5, 1, 0.5 and 0.1
Specimen type	Cylinder
Specimen dimension (mm)	100 diameter, 150 high
Method of compaction	SGC
Mode of loading	Stress control
Type of loading	Sinusoidal

Before testing began, 200 cycles of load conditioning at 25 Hz were applied to properly seat the equipment. The samples were then tested at the frequencies indicated in Table 6.2. The testing began at 25Hz and proceeded to 0.1 Hz.

TABLE 6.2 Dynamic Modulus Test Conditions

Frequency (Hz)	Test cycles
25	200
10	200
5	100
1	20
0.5	15
0.1	15

6.4 Results

6.4.1 Dynamic Modulus

The complete dynamic modulus data set is shown in Appendix C. Figures 6.3 through 6.6 show plots of the dynamic modulus at 10 Hz as a function of air voids content for the conditioned and unconditioned samples at both temperatures. Figure 6.7 compares the dynamic modulus of unconditioned and moisture conditioned samples.

FIGURE 6.3 Unconditioned Dynamic Modulus at 10 Hz (20C)

FIGURE 6.4 Moisture Conditioned Dynamic Modulus at 10 Hz (20C)

FIGURE 6.5 Unconditioned Dynamic Modulus at 10 Hz (40C)

FIGURE 6.6 Moisture Conditioned Dynamic Modulus at 10 Hz (40C)

FIGURE 6.7 Dynamic Modulus Results

6.4.2 Phase Angle

The phase angles of the specimens were also determined during the dynamic modulus testing. The complete results are presented in Appendix C. Figures 6.8 through 6.11 present the plots of the phase angle for Mixture 1 as a function of frequency. Figures 6.12 through 6.15 compare the phase angle for all mixtures at 10 Hz as a function of the air voids. Figure 6.16 shows the results of phase angle for unconditioned and moisture conditioned samples.

As seen in Figures 6.8 through 6.11, the results indicate that at 20C, the phase angle decreases as frequency increases. At 40C the opposite trend is observed. These results are consistent with the literature (33). At 20C, the effect of the binder is more pronounced than at 40C. Thus as frequency increases, the mixture appears more elastic because the binder seems more elastic (lower phase angle). At 40C, the aggregate skeleton becomes more important than the binder and the mixture appears more viscous as frequency increases.

FIGURE 6.8 Unconditioned Mixture 1 Phase Angle (20C)

FIGURE 6.9 Moisture Conditioned Mixture 1 Phase Angle (20C)

FIGURE 6.10 Unconditioned Mixture 1 Phase Angle (40C)

FIGURE 6.11 Moisture Conditioned Mixture 1 Phase Angle (40C)

FIGURE 6.12 Unconditioned Phase Angle at 10 Hz (20C)

FIGURE 6.13 Moisture Conditioned Phase Angle at 10 Hz (20C)

FIGURE 6.14 Unconditioned Phase Angle at 10 Hz (40C)

FIGURE 6.15 Moisture Conditioned Phase Angle at 10 Hz (40C)

FIGURE 6.16 Phase Angle Results

6.5 Statistical Analysis of Results

The modulus test results were evaluated using ANOVA and Tukey multiple comparison techniques as previously described. The results show that air voids content, NMAS, gradation, frequency, type of conditioning, temperature, and their interactions are statistically significant in predicting dynamic modulus. The comparison results are shown in Table 6.3. This table shows that the levels of each of the factors appear to be significantly different in predicting dynamic modulus. The data show that as the air voids content is decreased from 10 to 4 percent, the $|E^*|$ value increases by 67 percent. Coarse-graded mixtures have a mean $|E^*|$ value smaller than fine-graded mixtures. Also, 19-mm NMAS mixtures have $|E^*|$ values approximately 18 percent higher than do 9.5-mm NMAS mixtures. Moisture conditioning reduces the mean $|E^*|$ by 8 percent compared to the unconditioned mean $|E^*|$.

TABLE 6.3 Tukey Group of Factors for Dynamic Modulus

Tukey Group	Mean $ E^* $ (MPa)	No. of Observations	Gradation
A	3601.4	384	Fine
B	2765.1	384	Coarse
Tukey Group	Mean $ E^* $ (MPa)	No. of Observations	NMAS (mm)
A	3497.5	384	19
B	2869.0	384	9.5
Tukey Group	Mean $ E^* $ (MPa)	No. of Observations	Temperature (C)
A	5365.9	384	20
B	1000.7	384	40
Tukey Group	Mean $ E^* $ (MPa)	No. of Observations	Frequency (Hz.)
A	5360.5	128	25
B	4280.4	128	10
C	3625.4	128	5
D	2445.2	128	1
E	2046.9	128	0.5
F	1341.2	128	0.1
Tukey Group	Mean $ E^* $ (MPa)	No. of Observations	Conditioning Method
A	3322.6	384	Unconditioned
B	3043.9	384	Moisture conditioned
Tukey Group	Mean $ E^* $ (MPa)	No. of Observations	VTM (%)
A	4032.7	192	4
B	3458.0	192	6
C	2832.8	192	8
D	2409.5	192	10

Phase Angle results indicate that the phase angle shows more scatter than the dynamic modulus data. Figures 6.8 to 6.11 show an opposite trend of phase angle at 20 and 40C. Samples tested at 20C have lower phase angle at higher frequency; the opposite is observed in samples tested at 40C. For this reason, the phase angle data analysis was divided in two groups, 20 and 40C.

The Tukey groups for these are shown in Tables 6.4 and 6.5. NMAS, gradation, type of conditioning and frequency appear to be significant factors in predicting the phase angle of samples tested at both 20 and 40C. Air voids content is the independent factor less significant in predicting the phase angle. This can be observed in Figures 6.12 to 6.15. They show no trend between phase angle and air voids content.

TABLE 6.4 Tukey Group of Factors for Phase Angle (20C)

Tukey Group	Mean Phase Angle (deg)	No. of Observations	Gradation
A	27.0	192	Coarse
B	25.4	192	Fine
Tukey Group	Mean Phase Angle (deg)	N	NMAS (mm)
A	26.6	192	9.5
B	25.8	192	19.0
Tukey Group	Mean Phase Angle (deg)	No. of Observations	Frequency (Hz)
A	31.3	64	0.1
B	29.8	64	0.5
C	28.6	64	1
D	24.9	64	5
E	23.5	64	10
F	19.3	64	25
Tukey Group	Mean Phase Angle (deg)	No. of Observations	Conditioning Method
A	26.4	192	Moisture conditioned
B	26.0	192	Unconditioned
Tukey Group	Mean Phase Angle (deg)	No. of Observations	VTM (%)
A	26.4	96	10
A	26.4	96	8
B A	26.1	96	4
B	25.9	96	6

TABLE 6.5 Tukey Group of Factors for Phase Angle (40C)

Tukey Group	Mean Phase Angle (deg)	No. of Observations	Gradation
A	26.8	192	Fine
B	26.3	192	Coarse
Tukey Group	Mean Phase Angle (deg)	No. of Observations	NMAS (mm)
A	26.8	192	19.0
B	26.2	192	9.5
Tukey Group	Mean Phase Angle (deg)	No. of Observations	Conditioning Method
A	27.4	192	Unconditioned
B	25.7	192	Water conditioned
Tukey Group	Mean Phase Angle (deg)	No. of Observations	Frequency (Hz)
A	29.9	64	25
B	28.4	64	10
B	28.3	64	5
C	26.4	64	1
D	24.7	64	0.5
E	21.5	64	0.1
Tukey Group	Mean Phase Angle (deg)	No. of Observations	VTM (%)
A	26.7	96	4
A	26.6	96	6
A	26.6	96	8
A	26.2	96	10

To analyze the influence of moisture damage in terms of dynamic modulus, the percent difference between dynamic modulus before and after conditioning was evaluated. An ANOVA showed that none of the factors appeared to be significant in predicting the dynamic modulus changes due to moisture. However, some interactions did appear to be significant. A second ANOVA analysis was therefore completed for each mixture independently. During the analysis, all factors were kept constant except for frequency and air voids content. Table 6.6 shows the Tukey comparison results. The values listed first correspond to the air voids contents that provide the highest differences in dynamic modulus values. Frequency does not appear to be significant. However, in some cases, the change in air voids content does appear to increase the moisture damage. It does not hold true in all cases. The conflicting data is most probably due to the saturation method. Each of the moisture conditioned dynamic modulus specimens were saturated to a level of 70 to 80 percent saturation. Thus the higher air voids content specimens were subjected to the same saturation as the low air voids content specimens. Had the dynamic modulus specimens been subjected to a period of saturation as were the fatigue beams, the air voids content may have been much more significant.

TABLE 6.6 Tukey Groups for Difference between Unconditioned and Moisture Conditioned Dynamic Modulus

Mixture	Temperature (°C)	Tukey Group	Mean ($ E^* _{unc} - E^* _{cond}$)/ $ E^* _{unc}$ (%)	VTM (%)
1	20	A	17.9	10
		A	17.6	8
		B	11.4	6
		C	-1.7	4
1	40	A	21.0	8
		B	12.9	6
		C	0.1	10
		D	-16.2	4
2	20	A	16.1	4
		A	14.7	6
		A	11.7	8
		A	10.6	10
2	40	A	15.7	4
		A	14.3	6
		A	9.5	8
		B	-3.3	10
3	20	A	9.6	10
		A	6.6	4
		A	5.9	6
		B	0.2	8
3	40	A	13.0	8
		A	11.3	6
		A	11.1	4
		B	0.1	10
4	20	A	19.3	10
		B	8.8	8
		C	3.0	6
		C	1.8	4
4	40	A	22.4	10
		A	16.0	4
		A	14.2	6
		B	3.4	8

CHAPTER 7 FATIGUE TESTING

7.1 Background

HMA mixture properties influence the flexural stiffness of HMA pavements and consequently the strain induced by traffic loads, as well as the pavement's fatigue life. The relationship between fatigue performance in the laboratory and in-service pavements is not necessarily direct, but is a matter of scale. In order to predict in-service performance, it is necessary to combine analytical simulations of in-service strains with laboratory fatigue models. In this study, all mixtures were evaluated at the same strain rate in order to compare their fatigue performance.

The beam fatigue test is shown schematically in Figure 7.1 and consists of applying repeated flexural bending to a beam, which is simply supported at four points. This flexural bending is applied by equal loading at two points that trisect the distance between the support points. Flexural stiffness is defined as the ratio between the maximum, or peak tensile stress, and the maximum tensile strain. Equations 7.1, 7.2, and 7.3 present the calculations required to obtain the maximum stress, maximum strain, and flexural stiffness.

$$\sigma_t = \frac{0.357P}{bh^2} \quad (7.1)$$

$$\varepsilon_t = \frac{12\delta h}{(3L^2 - 4a^2)} \quad (7.2)$$

$$S_f = \frac{\sigma_t}{\varepsilon_t} \quad (7.3)$$

where,

σ_t = maximum tensile stress (MPa);

ϵ_t = maximum tensile strain;

S_f = flexural stiffness (MPa);

P = applied load (N);

b = average specimen width (m);

h = average specimen height (m);

δ = maximum deflection at beam center (m);

L = length of beam between outside clamps (m); and

a = distance between inside clamps (m).

FIGURE 7.1 Beam Fatigue Schematic

7.2 Specimen Preparation

Beam fatigue testing was completed according to AASHTO TP8, "Standard Test Method for Determining the Fatigue Life of Compacted Hot Mix Asphalt (HMA) Subjected to Repeated Flexural Bending." Standard specimen dimensions are 380 ± 6 mm in length, 50 ± 6 mm in height, and 63 ± 6 mm in width. To obtain specimens of these dimensions, slabs were compacted in the linear compactor. On average, the slabs were 515 mm tall, 293 mm wide, and 626 mm long. From every slab, four beams were cut to the required dimensions. After sawing the

beams, they were allowed to dry for a day and their G_{mb} values (and consequently their air voids contents) were measured according to AASHTO T166.

As was indicated in Chapter 3, two replicates were to be tested for each data cell (factor combinations of mixture, conditioning, air voids content). In addition to unconditioned samples, samples were also conditioned using both moisture and an oven. Moisture conditioning was completed according to the AASHTO T283 protocol, with the exception of the degree of saturation. AASHTO T283 considers the optimal degree of saturation to be between 70 and 80 percent. After a few trial beam samples, it was found that this minimum level of saturation was difficult to obtain, requiring excessive time. The research team decided that since the research was intended to determine the effects of initial density on fatigue life, that each of the beams should be saturated for a given time rather than to a given saturation percentage. Thus, theoretically, beams with higher air voids contents would take on more water and be more severely damaged. To this end, the specimens were moisture conditioned by applying an average vacuum of 560 mm of Hg for 15 minutes. After vacuum saturation, the samples had on average a degree of saturation between 55 and 70 percent. The samples were then placed in a water bath at $60 \pm 1^\circ\text{C}$ for 24 ± 1 hours. After removing the samples from the water bath, they were left to dry overnight and tested the next day in the beam fatigue apparatus.

To condition samples in the oven (long-term conditioning), the AASHTO R30, "Standard Practice for Mixture Conditioning of Hot-Mix Asphalt (HMA)," was followed. After mixing, short-term conditioning, and compacting, each sample was placed in a forced draft oven at $85 \pm 3^\circ\text{C}$ for 120 ± 0.5 hours. At the end of the conditioning, the oven was turned off and the samples were allowed to cool. The samples were then placed in the environmental chamber of the beam fatigue machine, brought to test temperature, and tested.

7.3 Testing Procedures and Test Parameters

The beam fatigue apparatus consists of a loading device, an environmental chamber, and a control and data acquisition system. A two-point load is applied with free rotation at all four points and free longitudinal translation at the two support points. The test system is computer-controlled to collect the desired data.

The beam fatigue tests were completed at a temperature of 20C, in the strain control mode at a frequency of 10 Hz. In typical pavements, the strain levels can range from between 250 to 500 $\mu\epsilon$; the higher value in the range was selected for this research to minimize the testing time. The strain control, or controlled displacement loading, indicates that the loading is applied to achieve a fixed level of peak displacement (strain) for all loading cycles applied during the test. Loading cycles were applied until the beam failed. In this project, number of cycles to reach failure (or laboratory fatigue life, N_f) is defined as the number of cycles needed to reduce the beam flexural stiffness to 50 percent of its initial stiffness. Table 7.1 shows the beam fatigue parameters.

TABLE 7.1 Beam Fatigue Parameters

NMAS	9.5, 19.0 mm
Gradation	Coarse, fine
Type of conditioning	None, moisture, oven
Air voids, %	4, 6, 8, and 10
Asphalt content	Optimum
Strain Level ($\mu\epsilon$)	500
Replicates	2 and 3
Temperature (C)	20
Frequency (Hz)	10
Specimen type	Beam
Specimen dimension (mm)	50 high, 63 wide, and 380 long
Method of compaction	Kneading
Mode of loading	Strain control
Type of loading	Sinusoidal

7.4 Results

The parameters associated with fatigue testing are initial stiffness (S_o) and number of cycles to failure (N_f). The initial stiffness is defined as the stiffness at 50 loading cycles. The complete test results are shown in Appendix D.

7.4.1 Initial Flexural Stiffness

Plots of the initial flexural stiffness for each of the four mixtures are shown in Figures 7.2 through 7.5. The S_o values in these figures are plotted as a function of air voids content for unconditioned, moisture conditioned, and long-term aged specimens. In general, the plots show that Mixture 4 has the highest S_o value followed by Mixtures 2, 3, and 1. The S_o values as well as the changes due to conditioning are similar for Mixtures 1 and 3 (coarse-graded), although the slopes of the best fit lines might suggest that Mixture 3 is slightly more sensitive to changes in air voids. Mixtures 2 and 4 (fine-graded) also appear to have similar results. From a conditioning standpoint, moisture conditioning decreases S_o and long-term aging increases it. For each of the mixtures, as air voids content increases, the initial flexural stiffness decreases.

FIGURE 7.2 Mixture 1 Initial Flexural Stiffness

FIGURE 7.3 Mixture 2 Initial Flexural Stiffness

FIGURE 7.4 Mixture 3 Initial Flexural Stiffness

FIGURE 7.5 Mixture 4 Initial Flexural Stiffness

7.4.2 Cycles to failure

Plots of the N_f , or laboratory fatigue life, as a function of air voids content are shown in Figures 7.6 through 7.9 for Mixtures 1 through 4, respectively. Each plot shows data for unconditioned, moisture conditioned, and long-term aged specimens. Overall the plots show that N_f is somewhat insensitive to the change in air voids content. At approximately 40 percent, Mixture 1 has the highest change in N_f (unconditioned) over the range of air voids contents included in the testing. Mixture 2 changes about 10 percent while Mixtures 3 and 4 show little to no change.

From a conditioning standpoint, the data in the plots show that moisture conditioning more sharply reduces N_f than does long-term aging. This indicates that moisture damage has more effect on laboratory fatigue life than does aging. Additionally, the 19.0-mm mixtures (Mixtures 3 and 4) seem less affected by both conditioning types than do the 9.5-mm mixtures (Mixtures 1 and 2). There appears to be no interaction between either type of conditioning and air voids content over the range of air voids content used in the experiment.

Finally, one should note that Mixture 1 has the highest N_f while Mixture 4 has the lowest. Mixture 1 also had the lowest S_o and Mixture 4 the highest. This seems logical; the higher the mixtures stiffness, the faster the mixture is likely to fatigue.

FIGURE 7.6 Mixture 1 Fatigue Life

FIGURE 7.7 Mixture 2 Fatigue Life

FIGURE 7.8 Mixture 3 Fatigue Life

FIGURE 7.9 Mixture 4 Fatigue Life

7.5 Statistical Analysis of the Results

ANOVA and the Tukey multiple comparison procedures were used to analyze the beam fatigue test results. The analysis was completed twice, once using the initial flexural stiffness (S_o) as the dependent variable and once using the number of cycles to failure (N_f) as the dependent variable. In each case, the dependent variable results were transformed into natural logarithm values prior to completing the analysis. These transformations simplified the analysis. A 95 percent confidence level was used in both analyses.

7.5.1 Initial Flexural Stiffness

The ANOVA results using initial flexural stiffness as the dependent variable are shown in Table 7.2. For the initial stiffness, the NMAS, air voids content, gradation, conditioning method, and the interactions between NMAS and conditioning method, and gradation and conditioning method appear to be significant.

TABLE 7.2 ANOVA Results for Initial Flexural Stiffness

GLM Procedure (Dependent Variable: Initial Flexural Stiffness)					
F-value = 64.95		Pr>F: <0.0001		R2 = 0.88	
Source	DF	Type III SS	Mean Square	F value	Pr > F
NMAS	1	4600860.54	4600860.54	15.98	0.0001
Air voids	3	41614378.16	13871459.39	48.19	<0.0001
Gradation	1	41818582.88	41818582.88	146.27	<0.0001
Conditioning	2	9938490.96	49691245.48	172.62	<0.0001
NMAS×Conditioning	2	2939720.27	1469860.13	5.11	0.0078
Gradation×Conditioning	2	6023473.36	3011736.68	10.46	<0.0001

For each of the significant factors a Tukey multiple comparison was made using the factor levels within a given factor. The results are shown in Table 7.3. As seen in the table, for each of the main factors, the factor levels are different. The results indicate that to minimize the initial beam stiffness, a coarse-graded, 9.5-mm mixture, compacted at 10 percent air voids is desirable. In general, as the air voids content is decreased from 10 to 8, to 6, and finally to 4 percent, the

S_o increases by 15, 28, and 39 percent, respectively above the S_o at 10 percent air voids content. Also, fine-graded mixtures have S_o values approximately 30 percent higher than do coarse-graded mixtures. Finally, 9.5-mm mixtures have S_o values approximately 10 percent lower than the 19.0-mm mixtures.

TABLE 7.3 Tukey Groups (Initial Flexural Stiffness)

Tukey Group	Mean S_o (MPa)	No. of Observations	Gradation
A	5788.5	57	Fine
B	4454.8	50	Coarse
Tukey Group	Mean S_o (MPa)	No. of Observations	NMAS (mm)
A	5426.8	51	19
B	4927.0	56	9.5
Tukey Group	Mean S_o (MPa)	No. of Observations	Conditioning
A	6515.8	36	Oven-aged
B	4844.7	36	Unconditioned
C	4105.9	35	Moisture
Tukey Group	Mean S_o (MPa)	No. of Observations	VTM (%)
A	5917.4	30	4
B	5448.5	26	6
C	4892.0	26	8
D	4252.3	25	10

Long-term aging (oven-aging) stiffens a mixture while moisture conditioning will make a beam less stiff. This can be seen in Figures 7.10 and 7.11. In the first, the data points are above the line of equality indicating that aging does indeed increase the initial stiffness. Figure 7.11 shows the data points below the line of equality indicating that moisture conditioning makes the beams less stiff. The data in Table 7.3 indicate that on the average, aging increases S_o by 34 percent while moisture conditioning decreases S_o by about 15 percent.

FIGURE 7.10 Initial Stiffness Comparison (Oven-aged)

FIGURE 7.11 Initial Stiffness Comparison (Moisture Conditioned)

7.5.2 Cycles to Failure

The ANOVA results with the number of cycles to failure as the dependent variable are shown in Table 7.4. The significant factors are NMAS, air voids content, gradation, conditioning method, and the interactions of gradation and conditioning method, NMAS and conditioning method, and NMAS, gradation, and conditioning method.

TABLE 7.4 ANOVA Results for Number of Cycles to Failure

GLM Procedure (Dependent Variable: Number of Cycles to Failure)					
F-value = 38.26		Pr>F: <0.0001		R ² = 0.85	
Source	DF	Type III SS	Mean Square	F value	Pr > F
NMAS	1	179422276343	179422276343	211.82	<0.0001
Air voids	3	10265063480	3421687826.5	4.04	0.0095
Gradation	1	6912036867.2	6912036867.2	8.16	0.0053
Conditioning	2	177755403374	88877701687	104.93	<0.0001
NMAS×Conditioning	2	33548270780	16774135390	19.80	<0.0001
Gradation×Conditioning	2	7143911519.8	3571955759.3	4.22	0.0177
NMAS×Gradation×Conditioning	3	9477677127.9	3159225709.3	3.73	0.0140

The Tukey multiple comparison procedure was again applied to the factors and the results shown in Table 7.5. As can be seen, not all of the factor levels are significantly different. The results suggest that to maximize the number of cycles to failure, a coarse-graded, 9.5-mm mixture, compacted to 4 percent air voids content would be most desirable. This is similar to the initial stiffness results except that the effect of air voids content is not as clear. In the case of the number of cycles to failure, less than 6 percent air voids appears to be better than more than 6 percent.

The fatigue life data also appears to show that both aging and moisture conditioning reduce the fatigue life of a mixture. This can be seen in Figures 7.12 and 7.13. In both figures the data points are below the line of equality indicating that the number of cycles to failure is greater for unconditioned samples. The reduction in fatigue life after aging is logical and consistent with the initial stiffness results. Aging the beams increases their initial stiffness and thereby decreases the number of cycles to failure by 44 percent. The moisture relationship is somewhat more complex. Moisture conditioning decreases the

initial stiffness of a beam which should therefore take more cycles to failure. However, the fatigue data shows that despite the softer initial stiffness, the number of cycles to failure actually decreases 75 percent compared to unconditioned beams. Thus one concludes that the moisture has substantially damaged the beams. The significance of the interaction of conditioning with NMAS and gradation would appear to indicate that using 9.5-mm, coarse-graded mixtures can help reduce the ingress of moisture and thereby increase the fatigue life HMA mixtures. Achieving high initial densities can further help in this regard. As the air voids contents of the mixtures goes to 4 percent, the N_f is increased nearly 30 percent.

TABLE 7.5 Tukey Groups (Fatigue Life)

Tukey Group	Mean N_f	No. of Observations	Gradation
A	91739	50	Coarse
B	76273	57	Fine
Tukey Group	Mean N_f	No. of Observations	NMAS (mm)
A	123729	56	9.5
B	39327	51	19.0
Tukey Group	Mean N_f	No. of Observations	Conditioning
A	138931	36	Unconditioned
A	76903	36	Oven-aged
B	33272	35	Moisture
Tukey Group	Mean N_f	No. of Observations	VTM (%)
A	100986	30	4
B	79677	26	6
B	75731	25	10
B	74618	26	8

FIGURE 7.12 Fatigue Life Comparison (Oven-Aged)

FIGURE 7.13 Fatigue Life Comparison (Moisture Conditioned)

CHAPTER 8 CONCLUSIONS AND RECOMENDATIONS

8.1 Summary

This study evaluated the influence of aggregate gradation, nominal maximum aggregate size (NMAS), and initial density (air voids content) on the permeability, durability and performance of hot-mix asphalt mixtures. The objectives were to better understand the increase in HMA pavement performance and durability that are to be gained by increasing initial pavement density, and to better quantify the relationships among HMA pavement density, permeability, and moisture-induced damage. Permeability was measured using a falling head permeameter developed by the Florida Department of Transportation. The moisture susceptibility of each mixture was tested in both the AASHTO T283 test and the PurWheel laboratory wheel tracker. Durability was evaluated using the dynamic modulus and beam fatigue tests. Dynamic modulus specimens were tested in unconditioned and moisture conditioned states, and beam fatigue specimens in unconditioned, moisture conditioned and oven-aged states.

In general, an exponential relationship between air voids content (density) and permeability can be observed in the data. A two percent increment in air voids content, from 6 to 8 percent, can increase the permeability by a factor of seven. All mixtures have a low incremental permeability until approximately 7-8 percent air voids contents (92-93 percent densities) are achieved. At this point, permeability increases exponentially. The critical value of permeability appears to be about 7 percent. Above this level, exponential increases in permeability can occur. However, one should note that porosity testing indicates that porosity may be more suitable in predicting permeability than air voids content.

The results of PurWheel and AASHTO T283 testing suggest that none of the mixtures tested are susceptible to moisture damage. However, moisture conditioning does appear to have a significant detrimental effect on the performance of the HMA specimens as evidenced by other physical test results. After moisture conditioning, the dynamic modulus, initial flexural stiffness and fatigue life are all reduced. The most significant effect of moisture conditioning is observed in the reduction of fatigue life.

For dynamic modulus results, all of the testing factors and their interactions appear to be significant. Larger aggregate sizes and fine-graded mixtures give higher dynamic modulus results. Reductions in air voids contents (density increases) produce increases in the dynamic modulus of a given mixture. At 20C, as stiffness increases, phase angle decreases. At 40C the tendency is opposite. This trend shows how the rheology of the HMA is affected by the aggregate at high temperatures and by the asphalt binder at low temperatures. Lastly, as previously noted, the dynamic modulus of HMA mixtures does appear to decrease after the mixtures are exposed to moisture conditioning.

The fatigue test results indicate that moisture conditioning can reduce the fatigue life of HMA mixtures by as much as 75 percent. In fact, the fatigue life of an HMA mixture appears to be more sensitive to moisture than to air voids content (density). There appears to be no definite relationship between fatigue life and air voids content (density), although, the mixtures with 4 percent air voids content did show a significantly longer fatigue life than mixtures having 6, 8, and 10 percent air voids content. Finally, initial mixture stiffness does appear to be highly correlated to air voids content (density). As the air voids content increases (decrease in density), initial mixture stiffness decreases.

8.2 Conclusions

The laboratory results of this experiment show relationships among HMA mixture density (air voids content), permeability, moisture-induced damage, and mixture performance. The results indicate that at 92 percent density (8 percent air voids

content), HMA mixtures can become highly permeable and thus decrease the rut resistance (dynamic modulus) and fatigue life of an HMA mixtures. The laboratory determined dynamic modulus ($|E^*|$) of an HMA mixture is inversely proportional to rutting in HMA pavement. This means that mixtures that are less stiff when tested in the laboratory are likely to be more prone to rutting. However, if HMA pavement density can be kept relatively high (low air voids), say 93-94 percent of maximum theoretical density, the results from this experiment indicate that moisture intrusion, and thus rutting is minimized.

The experimental results further indicate that laboratory HMA fatigue life is somewhat insensitive to air void content (density) variation, but can rapidly decrease if moisture is allowed to enter the mixture. It is known that the laboratory fatigue results are relative. While a mixture tested in the laboratory will have a longer fatigue life in the field, the laboratory results are a reliable method for predicting fatigue performance in the field. Thus if HMA pavements are maintained in an impermeable state, the fatigue life of the pavement should not be the critical factor.

In general, the following conclusions can be made:

1. HMA density (air voids content), gradation, aggregate size, and moisture and air ingress are significant to HMA performance;
2. HMA mixtures with the lower density (higher air voids content) tend to have higher permeability and the lower dynamic modulus, flexural stiffness and fatigue life;
3. The effect of HMA mixture density (air voids content) on mixture performance is dependent upon the mixture gradation and aggregate size (NMAS);
4. Mixtures with a 19.0-mm NMAS tend to have higher dynamic modulus and flexural stiffness, higher permeability and moisture damage, and lower fatigue life than mixtures with a 9.5-mm NMAS;

5. Coarse-graded mixtures tend to have lower dynamic modulus and flexural stiffness and higher permeability and fatigue life compared to fine-graded mixtures;
6. Mixtures with a higher dynamic modulus (less likely to rut) are those with a 19.0-mm NMAS, fine gradation, and 96 percent density (4 percent air voids);
7. Coarse-graded, 9.5-mm NMAS mixtures compacted to 96 percent density (4 percent air voids content) appear to have the best fatigue life;
8. In relation to rut depth (dynamic modulus), variations in the conditioning method (unconditioned and moisture conditioned) have some significance. In general, the rut potential is significantly reduced with increases in HMA density (reductions in air voids content);
9. The fatigue life is not significantly affected by variations in air voids, but is significantly affected by the conditioning method.

8.3 Recommendations

The data gained from the laboratory study reported herein have produced a better understanding of the inter-relationships among HMA density, permeability, and moisture-induced damage as well as a better understanding of how increases in HMA density can affect the performance and durability of the HMA mixtures. However, these results are from a laboratory study and it is important that they be translated to field performance. With this in mind, the following recommendations are suggested:

1. Since all of the HMA mixtures tested appear to benefit from higher densities (lower air voids), INDOT should consider studying the feasibility of achieving increased HMA pavement densities during construction;

2. Permeability should be further investigated as a predictor of field performance. Testing indicates that permeability may be a reliable indicator of HMA pavement performance and the results of laboratory and field permeability tests are well correlated;
3. Permeability should be investigated for use during both mixture design and field construction. The laboratory permeability determined during the mixture design process could be used to establish limits for pavement permeability during construction.
4. Additional investigations should be done on porosity as well. It may be a better indicator of pavement performance and durability than either permeability or density as porosity accounts for not only density (air voids content), but size also size of the air voids and their interconnectedness.

8.4 Implementation

Implementation of the research results should include the following:

1. Begin a study to determine if it is feasible to increase HMA pavement densities during construction; and
2. Initiate a study to further investigate permeability and porosity. This should include development of methods to use either as a construction control method.

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Appendix A - Aggregates Data

HMA PAVEMENT PERFORMANCE AND DURABILITY*QUALITY CONTROL - LABORATORY***SIEVE ANALYSIS A.1****STANDARD:** ASTM C136-01 "SIEVE ANALYSIS OF FINE AND COARSE AGGREGATES"

QUARRY: Delphi

SAMPLE: Fine Sand - Limestone

FINE AGGREGATE						
Sieve	Retained weigh	% Retained	% Ret.Acu.	% Pass	Grad. 23 fine agg. INDOT	
3/8"	0.00	0.00	0.00	100.00	100.00	100.00
n° 4	0.00	0.00	0.00	100.00	95.00	100.00
n° 8	25.89	3.15	3.15	96.85	80.00	100.00
n° 16	202.57	24.61	27.76	72.24	50.00	85.00
n° 30	188.38	22.89	50.65	49.35	25.00	60.00
n° 50	118.90	14.45	65.10	34.90	5.00	30.00
n° 100	81.39	9.89	74.99	25.01	0.00	10.00
n° 200	51.83	6.30	81.29	18.71	0.00	3.00
Bottom	154.02	18.71	100.00	0.00	0.00	0.00
Total W.	822.99	Initial W.	822.80			

Fineness
Modulus
2.22

Other properties					
Properties	Value 1	Value 2	Average	Standard	Specification
Specific Gravity	2.656	2.697	2.676		
Specific Gravity SSD	2.725	2.746	2.735	ASTM C128-02	
Apparent Spec. Gravity	2.854	2.835	2.845	ASTM C128-03	
Absortion (%)	2.615	1.815	2.215	ASTM C128-04	
Sand Equivalent	53.73	54.55	54.14	AASHTO T176-00	Min. 40
Fine agg. Angularity	47.93	47.93	47.93	AASHTO T304-96	Min. 40

HMA PAVEMENT PERFORMANCE AND DURABILITY

QUALITY CONTROL - LABORATORY

SIEVE ANALYSIS A.2

STANDARD: ASTM C136-01 "SIEVE ANALYSIS OF FINE AND COARSE AGGREGATES"

QUARRY: Delphi

SAMPLE: Stone #24 - Limestone

FINE AGGREGATE						
Sieve	Retained weigh	% Retained	% Ret.Acu.	% Pass	Grad. 24 fine agg. INDOT	
3/8"	0.00	0.00	0.00	100.00		
n° 4	0.00	0.00	0.00	100.00	95.00	100.00
n° 8	85.00	10.80	10.80	89.20	80.00	100.00
n° 16	376.20	47.80	58.60	41.40	50.00	85.00
n° 30	181.80	23.10	81.70	18.30	25.00	60.00
n° 50	96.00	12.20	93.90	6.10	5.00	30.00
n° 100	33.80	4.29	98.20	1.80	0.00	10.00
n° 200	7.90	1.00	99.20	0.80	0.00	3.00
Bottom	6.30	0.80	100.00	0.00		
Total W.	787.00	Initial W.	787.20			

Fineness Modulus
3.43

Other properties					
Properties	Value 1	Value 2	Average	Standard	Specification
Specific Gravity	2.736	2.746	2.741	ASTM C128-01	
Specific Gravity SSD	2.772	2.775	2.774	ASTM C128-02	
Apparent Spec. Gravity	2.838	2.829	2.833	ASTM C128-03	
Absortion (%)	1.317	1.065	1.191	ASTM C128-04	
Sand Equivalent	97.44	97.50	97.47	AASHTO T176-00	Min. 40
Fine agg. Angularity	46.78	46.74	46.76	AASHTO T304-96	Min. 40

HMA PAVEMENT PERFORMANCE AND DURABILITY

QUALITY CONTROL - LABORATORY

SIEVE ANALYSIS A.3

STANDARD: ASTM C136-01 "SIEVE ANALYSIS OF FINE AND COARSE AGGREGATES"

QUARRY: Vulcan

SAMPLE: Natural Sand

FINE AGGREGATE						
Sieve	Retained weigh	% Retained	% Ret.Acu.	% Pass	Grad. 23 fine agg. INDOT	
3/8"	0.00	0.00	0.00	100.00	100.00	100.00
n° 4	4.02	0.55	0.55	99.45	95.00	100.00
n° 8	79.24	10.93	11.48	88.52	80.00	100.00
n° 16	162.50	22.41	33.90	66.10	50.00	85.00
n° 30	208.32	28.73	62.63	37.37	25.00	60.00
n° 50	193.32	26.67	89.30	10.70	5.00	30.00
n° 100	54.61	7.53	96.83	3.17	0.00	10.00
n° 200	13.43	1.85	98.68	1.32	0.00	3.00
Bottom	9.55	1.32	100.00	0.00	0.00	0.00
Total W.	725.00	Initial W.	725.20			

Fineness Modulus
2.95

Other properties					
Properties	Value 1	Value 2	Average	Standard	Specification
Specific Gravity	2.584	2.575	2.580	ASTM C128-01	
Specific Gravity SSD	2.628	2.622	2.625	ASTM C128-02	
Apparent Spec. Gravity	2.702	2.703	2.702	ASTM C128-03	
Absortion (%)	1.680	1.833	1.756	ASTM C128-04	
Sand Equivalent	97.56	97.30	97.43	AASHTO T176-00	Min. 40
Fine agg. Angularity	41.94	41.90	41.92	AASHTO T304-96	Min. 40

HMA PAVEMENT PERFORMANCE AND DURABILITY

QUALITY CONTROL - LABORATORY

SIEVE ANALYSIS A.4

STANDARD: ASTM C136-01 "SIEVE ANALYSIS OF FINE AND COARSE AGGREGATES"

QUARRY: Delphi

SAMPLE: Stone #8

STONE #8						
Sieve	Ret. Weight	% Ret.	% Cum. Ret.	% Pass	Grad. 8 coarse agg. INDOT	
2"	0.00	0.00	0.00	100.00		
1 1/2"	0.00	0.00	0.00	100.00		
1"	0.00	0.00	0.00	100.00	100.00	100.00
3/4"	315.10	10.23	10.23	89.77	75.00	95.00
1/2"	1522.40	49.44	59.67	40.33	40.00	70.00
3/8"	672.10	21.82	81.49	18.51	20.00	50.00
n° 4	505.70	16.42	97.92	2.08	0.00	15.00
n° 8	11.50	0.37	98.29	1.71	0.00	10.00
n°200	15.70	0.51	98.80	1.20		
Bottom	37.00	1.20	100.00	0.00		
Total W.	3079.50	Initial W.	3079.00			
N.M.A.S.	3/8"					
T.M.	1/2"

Other properties					
Properties	Value 1	Value 2	Average	Standard	Specification
Specific Gravity	2.705	2.733	2.719	ASTM C128	
Specific Gravity SSD	2.723	2.762	2.743	ASTM C128	
App. Spec. Gravity	2.779	2.801	2.790	ASTM C128	
Absortion (%)	0.97	0.93	0.95	ASTM C128	

HMA PAVEMENT PERFORMANCE AND DURABILITY

QUALITY CONTROL - LABORATORY

SIEVE ANALYSIS A.5

STANDARD: ASTM C136-01 "SIEVE ANALYSIS OF FINE AND COARSE AGGREGATES"

QUARRY: Delphi

SAMPLE: Stone #11

STONE #11						
Sieve	Ret. Weight	% Ret.	% Cum. Ret.	% Pass	Grad. 11 coarse agg. INDOT	
2"	0.00	0.00	0.00	100.00		
1 1/2"	0.00	0.00	0.00	100.00		
1"	0.00	0.00	0.00	100.00		
3/4"	0.00	0.00	0.00	100.00		
1/2"	16.75	0.28	0.28	99.72	100.00	100.00
3/8"	1038.75	17.06	17.33	82.67	75.00	95.00
n° 4	4068.91	66.82	84.16	15.84	10.00	30.00
n° 8	676.44	11.11	95.27	4.73	0.00	10.00
n° 16	83.47	1.37	96.64	3.36		
n° 200	103.82	1.71	98.34	1.66		
Bottom	100.86	1.66	100.00	0.00		
Total W.	6089.00	Initial W.	6088.50			
N.M.A.S.	3/8"					
T.M.	1/2"

Other properties					
Properties	Value 1	Value 2	Average	Standard	Specification
Specific Gravity	2.740	2.736	2.738	ASTM C128	
Specific Gravity SSD	2.765	2.762	2.764	ASTM C128	
App. Spec. Gravity	2.810	2.809	2.810	ASTM C128	
Absorption (%)	0.91	0.94	0.92	ASTM C128	

HMA PAVEMENT PERFORMANCE AND DURABILITY

QUALITY CONTROL - LABORATORY

SIEVE ANALYSIS A.6

STANDARD: ASTM C136-01 "SIEVE ANALYSIS OF FINE AND COARSE AGGREGATES"

QUARRY: Delphi

SAMPLE: Stone #12

STONE #12						
Sieve	Ret. Weight	% Ret.	% Cum. Ret.	% Pass	Grad. N.8 ASTM C-448	
2"	0.00	0.00	0.00	100.00		
1 1/2"	0.00	0.00	0.00	100.00		
1"	0.00	0.00	0.00	100.00		
3/4"	0.00	0.00	0.00	100.00		
1/2"	0.00	0.00	0.00	100.00	100.00	100.00
3/8"	6.33	0.13	0.13	99.87	95.00	100.00
n° 4	1401.21	29.64	29.78	70.22	50.00	80.00
n° 8	2605.23	55.12	84.90	15.10	0.00	35.00
n° 30	497.55	10.53	95.42	4.58	0.00	4.00
n° 50	89.47	1.89	97.32	2.68		
n° 16	30.02	0.64	97.95	2.05		
n° 200	31.78	0.67	98.62	1.38		
Bottom	65.10	1.38	100.00	0.00		
Total W.	4726.70	Initial W.	6088.50			
N.M.A.S.	3/8"					
T.M.	1/2"

Other properties					
Properties	Value 1	Value 2	Average	Standard	Specification
Specific Gravity	2.715	2.709	2.712	ASTM C128	
Specific Gravity SSD	2.752	2.745	2.748	ASTM C128	
App. Spec. Gravity	2.818	2.817	2.817	ASTM C128	
Absorption (%)				ASTM C128	

Appendix B - Mixtures Data

HMA PAVEMENT PERFORMANCE AND DURABILITY

QUALITY CONTROL - LABORATORY

SUPERPAVE DESIGN MIX FORMULA B.1

SUPERPAVE DMF/JMF COVERSHEET

CONTRACTOR:	<u>Rieth Riley Laf.</u>	DATE:	<u>37321</u>
MIX PRODUCER:	<u>Rieth Riley</u>	CONTRACT:	<u>RS-25957-A</u>
PLANT LOCATION:	<u>Lafayette</u>	ROAD NO.:	<u>SR 18</u>
PLANT NO.:	<u>#3286 or #3310</u>	DISTRICT:	<u>Crawfordville</u>
MIX DESIGN LAB:	<u>Frankfort Testing Lab.</u>	REF. JMF.:	<u>25056 110554</u>
		CONTRACT	DMF

MATERIAL SOURCES

COARSE AGG. (SOURCE & LEDGE):

(#2421) Delphi, dolomite #11(#2421) Delphi, dolomite #12

FINE AGG. (NAT. MAN. & SOURCE):

(#2134) Vulcan, #23 natural sand(#2421) Delphi, dolomite mfg. sand (QA Fines)

PG BINDER (TYPE & SOURCE)

PG 64-22 Seneca @ Burns Harbor or Lemont IL.

ANTI STRIP. AGENT & DOSAGE RATE:

none required**DESIGN MIX FORMULA / JOB MIX FORMULA**

DMF / JMF number	210550	
Material code		
ESAL	2300000	
Mixture type	Coarse graded 9.5 mm.	
Maximum particle size	12.5 mm (1/2")	
	MASS	VOLUME
% Pass 1 1/2 in.		
% Pass 1 in.		
% Pass 3/4 in.		
% Pass 1/2 in.	100	
% Pass 3/8 in.	96	
% Pass No. 4	64.0	
% Pass No. 8	35.0	
% Pass No. 30	17	
% Pass No. 200	4.5	
Gsb	2.709	
Mix temperature min. °F	125	
Mix temperature max. °F	155	
RAP % in mixture	0	
RAP binder % extracted	---	

Ignition oven test temp. °F	
Ignition oven calibration factor	
Ignition oven serial number	
Binder % actual (ig. ov.)	5.8
Binder % extracted	5.6
Binder %	5.6
MSG w/ dry back Yes or No	
Gyrations Nini/Ndes/Nmax	7 / 75 / 115
Density, kg/m ³ @Ndes	2428
Gmb (plot/calculate) @ Nmax	2.471
Gmm (plot/calculate)	2.533
% Air voids @ Ndes	4
VMA @ Ndes	15.5
VFA @ Ndes	74.5
Coarse aggregate angularity	100
Fine aggregate angularity	44.2
Sand equivalency	74
Dust/calculated effective binder	0.9
Tensile strenght ratio	97.1

HMA PAVEMENT PERFORMANCE AND DURABILITY

QUALITY CONTROL - LABORATORY

SUPERPAVE DESIGN MIX FORMULA B.2**SUPERPAVE DMF/JMF COVERSHEET**

CONTRACTOR:	_____	DATE:	Sep-03
MIX PRODUCER:	_____	CONTRACT:	_____
PLANT LOCATION:	_____	ROAD NO.:	_____
PLANT NO.:	_____	DISTRICT:	_____
MIX DESIGN LAB:	Purdue - Mixture 2	REF. JMF.:	_____

MATERIAL SOURCES

COARSE AGG. (SOURCE & LEDGE):

(#2421) Delphi, dolomite #11

(#2421) Delphi, dolomite #12

FINE AGG. (NAT. MAN. & SOURCE):

(#2134) Vulcan, #23 natural sand

(#2421) Delphi, dolomite mfg. sand (QA Fines)

(#2421) Delphi #24, dolomite mfg. sand (QA Stone)

PG BINDER (TYPE & SOURCE)

PG 64-22 Seneca @ Burns Harbor or Lemont IL.

ANTI STRIP. AGENT & DOSAGE RATE:

none required

DESIGN MIX FORMULA / JOB MIX FORMULA

DMF / JMF number		
Material code		
ESAL	2300000	
Mixture type	Fine graded 9.5 mm.	
Maximum particle size	12.5 mm (1/2")	
	MASS	VOLUME
% Pass 1 1/2 in.	100	
% Pass 1 in.	100	
% Pass 3/4 in.	100	
% Pass 1/2 in.	100	
% Pass 3/8 in.	97.4	
% Pass No. 4	80.8	
% Pass No. 8	63.9	
% Pass No. 30	28.5	
% Pass No. 200	9.7	
Gsb	2.654	
Mix temperature min. °F		
Mix temperature max. °F		
RAP % in mixture	0	
RAP binder % extracted	---	

Ignition oven test temp. °F	
Ignition oven calibration factor	
Ignition oven serial number	
Binder % actual (ig. ov.)	
Binder % extracted	
Binder %	6.6
MSG w/ dry back Yes or No	
Gyrations Nini/Ndes/Nmax	7 / 75 / 115
Density, kg/m ³ @Ndes	
Gmb (plot/calculate) @ Nmax	2.46
Gmm (plot/calculate)	2.53
% Air voids @ Ndes	3.9
VMA @ Ndes	14.6
VFA @ Ndes	73.2
Coarse aggregate angularity	100
Fine aggregate angularity	47.2
Sand equivalency	65.2
Dust/calculated effective binder	1.9
Tensile strenght ratio	80.1

HMA PAVEMENT PERFORMANCE AND DURABILITY

QUALITY CONTROL - LABORATORY

SUPERPAVE DESIGN MIX FORMULA B.3**SUPERPAVE DMF/JMF COVERSHEET**

CONTRACTOR:	_____	DATE:	Sep-03
MIX PRODUCER:	_____	CONTRACT:	_____
PLANT LOCATION:	_____	ROAD NO.:	_____
PLANT NO.:	_____	DISTRICT:	_____
MIX DESIGN LAB:	Purdue - Mixture 3	REF. JMF.:	_____

MATERIAL SOURCES**COARSE AGG. (SOURCE & LEDGE):**

(#2421) Delphi, dolomite #8
 (#2421) Delphi, dolomite #11
 (#2421) Delphi, dolomite #12

FINE AGG. (NAT. MAN. & SOURCE):

(#2134) Vulcan, #23 natural sand
 (#2421) Delphi, dolomite mfg. sand (QA Fines)

PG BINDER (TYPE & SOURCE)

PG 64-22 Seneca @ Burns Harbor or Lemont IL.

ANTI STRIP. AGENT & DOSAGE RATE:

none required

DESIGN MIX FORMULA / JOB MIX FORMULA

DMF / JMF number		
Material code		
ESAL	2300000	
Mixture type	Coarse graded 19 mm.	
Maximum particle size	25.4 mm (1")	
	MASS	VOLUME
% Pass 1 1/2 in.	100.0	
% Pass 1 in.	100.0	
% Pass 3/4 in.	96.9	
% Pass 1/2 in.	82.1	
% Pass 3/8 in.	72.9	
% Pass No. 4	49.0	
% Pass No. 8	29.1	
% Pass No. 30	13.0	
% Pass No. 200	4.0	
Gsb	2.685	
Mix temperature min. °F		
Mix temperature max. °F		
RAP % in mixture	0	
RAP binder % extracted	---	

Ignition oven test temp. °F	
Ignition oven calibration factor	
Ignition oven serial number	
Binder % actual (ig. ov.)	
Binder % extracted	
Binder %	5.9
MSG w/ dry back Yes or No	
Gyrations Nini/Ndes/Nmax	7 / 75 / 115
Density, kg/m ³ @Ndes	
Gmb (plot/calculate) @ Nmax	2.46
Gmm (plot/calculate)	2.54
% Air voids @ Ndes	4
VMA @ Ndes	15
VFA @ Ndes	73.6
Coarse aggregate angularity	100
Fine aggregate angularity	47.4
Sand equivalency	75
Dust/calculated effective binder	0.85
Tensile strenght ratio	82.9

QUALITY CONTROL - LABORATORY

SUPERPAVE DESIGN MIX FORMULA B.4

SUPERPAVE DMF/JMF COVERSHEET

CONTRACTOR:	_____	DATE:	Sep-03
MIX PRODUCER:	_____	CONTRACT:	_____
PLANT LOCATION:	_____	ROAD NO.:	_____
PLANT NO.:	_____	DISTRICT:	_____
MIX DESIGN LAB:	Purdue - Mixture 4	REF. JMF.:	_____

MATERIAL SOURCES

COARSE AGG. (SOURCE & LEDGE):

(#2421) Delphi, dolomite #8

(#2421) Delphi, dolomite #12

FINE AGG. (NAT. MAN. & SOURCE):

(#2134) Vulcan, #23 natural sand

(#2421) Delphi, dolomite mfg. sand (QA Fines)

(#2421) Delphi #24, dolomite mfg. sand (QA Stone)

PG BINDER (TYPE & SOURCE)

PG 64-22 Seneca @ Burns Harbor or Lemont IL.

ANTI STRIP. AGENT & DOSAGE RATE:

none required

DESIGN MIX FORMULA / JOB MIX FORMULA

DMF / JMF number		
Material code		
ESAL	2300000	
Mixture type	Fine graded 19 mm.	
Maximum particle size	25.4 mm (1")	
	MASS	VOLUME
% Pass 1 1/2 in.	100.0	
% Pass 1 in.	100.0	
% Pass 3/4 in.	97.5	
% Pass 1/2 in.	85.7	
% Pass 3/8 in.	80.4	
% Pass No. 4	67.5	
% Pass No. 8	48.7	
% Pass No. 30	21.8	
% Pass No. 200	7.5	
Gsb		
Mix temperature min. °F		
Mix temperature max. °F		
RAP % in mixture	0	
RAP binder % extracted	---	

Ignition oven test temp. °F	
Ignition oven calibration factor	
Ignition oven serial number	
Binder % actual (ig. ov.)	
Binder % extracted	
Binder %	5.5
MSG w/ dry back Yes or No	
Gyrations Nini/Ndes/Nmax	7 / 75 / 115
Density, kg/m ³ @Ndes	
Gmb (plot/calculate) @ Nmax	2.476
Gmm (plot/calculate)	2.569
% Air voids @ Ndes	4.3
VMA @ Ndes	12.9
VFA @ Ndes	66.8
Coarse aggregate angularity	100
Fine aggregate angularity	45.37
Sand equivalency	68.2
Dust/calculated effective binder	1.89
Tensile strenght ratio	84.3

Appendix C – Dynamic Modulus Results

TABLE C.1 Mixture 1 Unconditioned Dynamic Modulus (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
4.067	4.12	25	8597	8209	549.07	6.69
4.175			7821			
4.067	4.12	10	6868	6609	365.93	5.54
4.175			6351			
4.067	4.12	5	5667	5467	282.84	5.17
4.175			5267			
4.067	4.12	1	3715	3575	197.99	5.54
4.175			3435			
4.067	4.12	0.5	3060	2948	158.75	5.39
4.175			2836			
4.067	4.12	0.1	2023	1938	120.56	6.22
4.175			1853			
6.067	6.00	25	7527	7530	4.60	0.06
5.942			7533			
6.067	6.00	10	6129	6161	46.32	0.75
5.942			6194			
6.067	6.00	5	5120	5145	36.42	0.71
5.942			5171			
6.067	6.00	1	3405	3440	48.79	1.42
5.942			3474			
6.067	6.00	0.5	2837	2897	84.85	2.93
5.942			2957			
6.067	6.00	0.1	1828	1934	150.97	7.80
5.942			2041			
8.365	7.96	25	6370	6693	456.08	6.81
7.551			7015			
8.365	7.96	10	5418	5555	194.10	3.49
7.551			5693			
8.365	7.96	5	4525	4576	71.42	1.56
7.551			4626			
8.365	7.96	1	2948	3013	91.22	3.03
7.551			3077			
8.365	7.96	0.5	2429	2499	99.35	3.98
7.551			2570			
8.365	7.96	0.1	1616	1642	36.77	2.24
7.551			1668			
9.544	9.83	25	6301	6146	219.20	3.57
10.12			5991			
9.544	9.83	10	5154	5050	147.79	2.93
10.12			4945			
9.544	9.83	5	4305	4198	152.03	3.62
10.12			4090			
9.544	9.83	1	2839	2726	160.51	5.89
10.12			2612			
9.544	9.83	0.5	2337	2245	130.11	5.80
10.12			2153			
9.544	9.83	0.1	1497	1454	61.52	4.23
10.12			1410			

TABLE C.2 Mixture 1 Moisture Conditioned Dynamic Modulus (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
3.771	4.03	25	8412	7963	633.92	7.96
4.292			7515			
3.771	4.03	10	6940	6566	528.56	8.05
4.292			6192			
3.771	4.03	5	5946	5643	429.21	7.61
4.292			5339			
3.771	4.03	1	3792	3727	90.86	2.44
4.292			3663			
3.771	4.03	0.5	3085	3093	11.67	0.38
4.292			3101			
3.771	4.03	0.1	1907	1965	82.02	4.18
4.292			2023			
6.027	6.01	25	6807	6887	113.14	1.64
5.987			6967			
6.027	6.01	10	5375	5478	145.66	2.66
5.987			5581			
6.027	6.01	5	4587	4632	62.93	1.36
5.987			4676			
6.027	6.01	1	3064	3076	16.97	0.55
5.987			3088			
6.027	6.01	0.5	2555	2572	23.33	0.91
5.987			2588			
6.027	6.01	0.1	1582	1610	38.89	2.42
5.987			1637			
7.828	7.97	25	5813	5611	285.32	5.08
8.103			5410			
7.828	7.97	10	4755	4547	293.80	6.46
8.103			4340			
7.828	7.97	5	4022	3878	204.35	5.27
8.103			3733			
7.828	7.97	1	2588	2498	127.99	5.12
8.103			2407			
7.828	7.97	0.5	2130	2053	108.89	5.30
8.103			1976			
7.828	7.97	0.1	1360	1299	85.91	6.61
8.103			1239			
9.14	9.25	25	4571	5151	820.24	15.92
9.350			5731			
9.14	9.25	10	3647	4113	659.02	16.02
9.350			4579			
9.14	9.25	5	3126	3502	532.10	15.19
9.350			3879			
9.14	9.25	1	2049	2246	278.25	12.39
9.350			2443			
9.14	9.25	0.5	1731	1834	146.02	7.96
9.350			1937			
9.14	9.25	0.1	1149	1161	16.97	1.46
9.350			1173			

TABLE C.3 Mixture 1 Unconditioned Dynamic Modulus (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
4.067	4.12	25	2015	1952	89.10	4.56
4.175			1889			
4.067	4.12	10	1430	1389	56.92	4.10
4.175			1349			
4.067	4.12	5	1112	1088	32.88	3.02
4.175			1065			
4.067	4.12	1	744	726	26.16	3.61
4.175			707			
4.067	4.12	0.5	646	628	26.16	4.17
4.175			609			
4.067	4.12	0.1	488	477	14.50	3.04
4.175			467			
6.067	6.00	25	1829	1869	57.63	3.08
5.942			1910			
6.067	6.00	10	1331	1356	35.71	2.63
5.942			1381			
6.067	6.00	5	1040	1078	54.80	5.08
5.942			1117			
6.067	6.00	1	698	723	35.71	4.94
5.942			748			
6.067	6.00	0.5	604	628	33.94	5.40
5.942			652			
6.067	6.00	0.1	460	487	38.18	7.84
5.942			514			
8.365	7.96	25	1341	1479	195.16	13.20
7.551			1617			
8.365	7.96	10	1029	1090	86.27	7.91
7.551			1151			
8.365	7.96	5	867	901	48.44	5.37
7.551			936			
8.365	7.96	1	622	662	55.86	8.44
7.551			701			
8.365	7.96	0.5	544	610	93.34	15.30
7.551			676			
8.365	7.96	0.1	420	526	149.20	28.39
7.551			631			
9.544	9.83	25	1316	1321	7.07	0.54
10.120			1326			
9.544	9.83	10	959	987	38.89	3.94
10.120			1014			
9.544	9.83	5	780	794	19.80	2.49
10.120			808			
9.544	9.83	1	532	539	9.19	1.71
10.120			545			
9.544	9.83	0.5	460	467	9.90	2.12
10.120			474			
9.544	9.83	0.1	352	353	1.41	0.40
10.120			354			

TABLE C.4 Mixture 1 Moisture Conditioned Dynamic Modulus (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
3.771	4.03	25	2147	2251	147.43	6.55
4.292			2355			
3.771	4.03	10	1522	1609	123.04	7.65
4.292			1696			
3.771	4.03	5	1182	1285	144.96	11.29
4.292			1387			
3.771	4.03	1	782	842	84.15	10.00
4.292			901			
3.771	4.03	0.5	677	727	71.06	9.78
4.292			777			
3.771	4.03	0.1	519	555	51.27	9.24
4.292			591			
6.027	6.01	25	1567	1511	79.90	5.29
5.987			1454			
6.027	6.01	10	1133	1124	12.73	1.13
5.987			1115			
6.027	6.01	5	896	922	36.06	3.91
5.987			947			
6.027	6.01	1	606	648	59.40	9.17
5.987			690			
6.027	6.01	0.5	533	572	55.15	9.64
5.987			611			
6.027	6.01	0.1	426	452	36.77	8.13
5.987			478			
7.828	7.97	25	1376	1261	162.63	12.90
8.103			1146			
7.828	7.97	10	1017	935	115.97	12.40
8.103			853			
7.828	7.97	5	792	751	58.69	7.82
8.103			709			
7.828	7.97	1	539	511	39.60	7.75
8.103			483			
7.828	7.97	0.5	469	454	21.92	4.83
8.103			438			
7.828	7.97	0.1	369	357	17.68	4.96
8.103			344			
9.14	9.25	25	1284	1293	12.02	0.93
9.350			1301			
9.14	9.25	10	966	962	6.36	0.66
9.350			957			
9.14	9.25	5	761	767	8.49	1.11
9.350			773			
9.14	9.25	1	523	529	8.49	1.60
9.350			535			
9.14	9.25	0.5	469	479	13.44	2.81
9.350			488			
9.14	9.25	0.1	360	376	22.63	6.02
9.350			392			

TABLE C.5 Mixture 2 Unconditioned Dynamic Modulus (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
3.799	4.14	25	15537	14596	1330.42	9.12
4.486			13655			
3.799	4.14	10	12557	11854	994.19	8.39
4.486			11151			
3.799	4.14	5	10543	10091	638.16	6.32
4.486			9640			
3.799	4.14	1	6848	6733	162.28	2.41
4.486			6618			
3.799	4.14	0.5	5428	5478	70.00	1.28
4.486			5527			
3.799	4.14	0.1	2874	3226	498.16	15.44
4.486			3578			
5.944	5.93	25	9733	10425	978.64	9.39
5.909			11117			
5.944	5.93	10	7698	8303	854.89	10.30
5.909			8907			
5.944	5.93	5	6589	7084	699.33	9.87
5.909			7578			
5.944	5.93	1	4393	4730	476.59	10.08
5.909			5067			
5.944	5.93	0.5	3646	3925	394.57	10.05
5.909			4204			
5.944	5.93	0.1	2296	2468	243.24	9.86
5.909			2640			
7.919	7.88	25	7727	8127	565.69	6.96
7.850			8527			
7.919	7.88	10	6381	6809	605.28	8.89
7.850			7237			
7.919	7.88	5	5451	5820	521.14	8.96
7.850			6188			
7.919	7.88	1	3709	4097	548.71	13.39
7.850			4485			
7.919	7.88	0.5	3181	3519	478.00	13.58
7.850			3857			
7.919	7.88	0.1	2116	2334	308.30	13.21
7.850			2552			
9.896	10.34	25	7749	7273	673.17	9.26
10.789			6797			
9.896	10.34	10	6308	5945	513.36	8.64
10.789			5582			
9.896	10.34	5	5353	5004	494.27	9.88
10.789			4654			
9.896	10.34	1	3678	3437	340.83	9.92
10.789			3196			
9.896	10.34	0.5	3065	2838	321.03	11.31
10.789			2611			
9.896	10.34	0.1	1935	1843	130.81	7.10
10.789			1750			

TABLE C.6 Mixture 2 Moisture Conditioned Dynamic Modulus (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
4.026	4.10	25	12877	11215	2350.42	20.96
4.178			9553			
4.026	4.10	10	10835	9295	2178.60	23.44
4.178			7754			
4.026	4.10	5	9329	8065	1787.57	22.16
4.178			6801			
4.026	4.10	1	6702	5702	1414.92	24.82
4.178			4701			
4.026	4.10	0.5	5648	4775	1234.61	25.86
4.178			3902			
4.026	4.10	0.1	3728	3115	866.91	27.83
4.178			2502			
5.505	6.01	25	10102	8805	1834.94	20.84
6.517			7507			
5.505	6.01	10	7872	7034	1185.82	16.86
6.517			6195			
5.505	6.01	5	6816	6049	1084.70	17.93
6.517			5282			
5.505	6.01	1	4513	4093	593.97	14.51
6.517			3673			
5.505	6.01	0.5	3689	3362	462.45	13.76
6.517			3035			
5.505	6.01	0.1	2307	2102	290.62	13.83
6.517			1896			
7.614	7.93	25	7485	7713	322.44	4.18
8.240			7941			
7.614	7.93	10	6165	6424	365.57	5.69
8.240			6682			
7.614	7.93	5	5164	5369	289.91	5.40
8.240			5574			
7.614	7.93	1	3506	3571	91.92	2.57
8.240			3636			
7.614	7.93	0.5	2888	2940	73.54	2.50
8.240			2992			
7.614	7.93	0.1	1747	1812	91.92	5.07
8.240			1877			
10.045	10.03	25	6599	6902	428.51	6.21
10.009			7205			
10.045	10.03	10	5153	5377	316.78	5.89
10.009			5601			
10.045	10.03	5	4457	4625	236.88	5.12
10.009			4792			
10.045	10.03	1	2969	3043	104.65	3.44
10.009			3117			
10.045	10.03	0.5	2494	2518	33.23	1.32
10.009			2541			
10.045	10.03	0.1	1512	1502	14.14	0.94
10.009			1492			

TABLE C.7 Mixture 2 Unconditioned Dynamic Modulus (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
3.799	4.14	25	2589	2489	140.36	5.64
4.486			2390			
3.799	4.14	10	1816	1778	53.74	3.02
4.486			1740			
3.799	4.14	5	1410	1388	30.76	2.22
4.486			1366			
3.799	4.14	1	874	861	18.03	2.09
4.486			848			
3.799	4.14	0.5	736	723	17.32	2.40
4.486			711			
3.799	4.14	0.1	541	530	15.20	2.87
4.486			519			
5.944	5.93	25	2063	2170	151.32	6.97
5.909			2277			
5.944	5.93	10	1459	1532	103.59	6.76
5.909			1605			
5.944	5.93	5	1120	1176	78.49	6.68
5.909			1231			
5.944	5.93	1	674	714	56.57	7.92
5.909			754			
5.944	5.93	0.5	571	605	49.14	8.12
5.909			640			
5.944	5.93	0.1	405	433	40.66	9.38
5.909			462			
7.919	7.88	25	1543	1537	9.19	0.60
7.850			1530			
7.919	7.88	10	1098	1101	3.89	0.35
7.850			1104			
7.919	7.88	5	870	869	2.12	0.24
7.850			867			
7.919	7.88	1	553	558	7.42	1.33
7.850			564			
7.919	7.88	0.5	480	491	15.56	3.17
7.850			502			
7.919	7.88	0.1	352	372	28.28	7.60
7.850			392			
9.896	10.34	25	1425	1247	251.73	20.19
10.789			1069			
9.896	10.34	10	1045	911	189.50	20.80
10.789			777			
9.896	10.34	5	809	698	156.98	22.49
10.789			587			
9.896	10.34	1	499	429	99.70	23.27
10.789			358			
9.896	10.34	0.5	429	371	82.73	22.33
10.789			312			
9.896	10.34	0.1	312	275	52.33	19.03
10.789			238			

TABLE C.8 Mixture 2 Moisture Conditioned Dynamic Modulus (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
4.026	4.10	25	2105	1954	214.25	10.97
4.178			1802			
4.026	4.10	10	1537	1428	154.15	10.79
4.178			1319			
4.026	4.10	5	1216	1132	119.50	10.56
4.178			1047			
4.026	4.10	1	771	736	49.50	6.73
4.178			701			
4.026	4.10	0.5	654	634	28.99	4.58
4.178			613			
4.026	4.10	0.1	497	491	8.49	1.73
4.178			485			
5.505	6.01	25	1564	1641	108.89	6.64
6.517			1718			
5.505	6.01	10	1153	1206	74.25	6.16
6.517			1258			
5.505	6.01	5	928	968	56.57	5.84
6.517			1008			
5.505	6.01	1	603	635	45.25	7.13
6.517			667			
5.505	6.01	0.5	528	549	29.70	5.41
6.517			570			
5.505	6.01	0.1	408	426	25.46	5.98
6.517			444			
7.614	7.93	25	1287	1385	138.95	10.03
8.240			1484			
7.614	7.93	10	937	988	71.42	7.23
8.240			1038			
7.614	7.93	5	766	784	25.81	3.29
8.240			803			
7.614	7.93	1	515	509	8.13	1.60
8.240			504			
7.614	7.93	0.5	446	443	4.60	1.04
8.240			440			
7.614	7.93	0.1	341	340	1.41	0.42
8.240			339			
10.045	10.03	25	1181	1187	8.49	0.71
10.009			1193			
10.045	10.03	10	865	878	17.68	2.01
10.009			890			
10.045	10.03	5	698	702	5.66	0.81
10.009			706			
10.045	10.03	1	447	459	16.97	3.70
10.009			471			
10.045	10.03	0.5	390	405	21.21	5.24
10.009			420			
10.045	10.03	0.1	282	306	33.23	10.88
10.009			329			

TABLE C.9 Mixture 3 Unconditioned Dynamic Modulus (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of variation (%)
4.266	4.58	25	11968	11382	828.73	7.28
4.897			10796			
4.266	4.58	10	9718	9028	976.51	10.82
4.897			8337			
4.266	4.58	5	8492	7782	1004.09	12.90
4.897			7072			
4.266	4.58	1	5831	5265	800.44	15.20
4.897			4699			
4.266	4.58	0.5	4875	4387	690.84	15.75
4.897			3898			
4.266	4.58	0.1	2976	2718	365.57	13.45
4.897			2459			
5.946	6.03	25	10628	10001	887.42	8.87
6.122			9373			
5.946	6.03	10	8911	8254	929.85	11.27
6.122			7596			
5.946	6.03	5	7738	7089	918.53	12.96
6.122			6439			
5.946	6.03	1	5238	4770	661.85	13.88
6.122			4302			
5.946	6.03	0.5	4364	3956	577.71	14.61
6.122			3547			
5.946	6.03	0.1	2842	2523	451.13	17.88
6.122			2204			
7.440	8.09	25	9023	8511	724.08	8.51
8.735			7999			
7.440	8.09	10	7179	6821	506.29	7.42
8.735			6463			
7.440	8.09	5	6233	5945	407.29	6.85
8.735			5657			
7.440	8.09	1	4219	4086	188.09	4.60
8.735			3953			
7.440	8.09	0.5	3583	3442	199.40	5.79
8.735			3301			
7.440	8.09	0.1	2219	2152	94.75	4.40
8.735			2085			
9.288	9.68	25	9023	6027	344.01	5.71
10.072			7999			
9.288	9.68	10	5452	5161	410.48	7.95
10.072			4871			
9.288	9.68	5	4772	4450	455.02	10.23
10.072			4128			
9.288	9.68	1	3222	2987	332.34	11.13
10.072			2752			
9.288	9.68	0.5	2617	2455	229.10	9.33
10.072			2293			
9.288	9.68	0.1	1737	1582	218.14	13.79
10.072			1428			

TABLE C.10 Mixture 3 Moisture Conditioned Dynamic Modulus (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
4.167	4.24	25	10702	10868	234.05	2.15
4.309			11033			
4.167	4.24	10	8653	8752	140.01	1.60
4.309			8851			
4.167	4.24	5	7337	7450	159.10	2.14
4.309			7562			
4.167	4.24	1	4882	4910	38.89	0.79
4.309			4937			
4.167	4.24	0.5	3964	3985	29.70	0.75
4.309			4006			
4.167	4.24	0.1	2392	2394	2.83	0.12
4.309			2396			
5.682	6.09	25	9866	9724	201.53	2.07
6.497			9581			
5.682	6.09	10	7576	7818	342.24	4.38
6.497			8060			
5.682	6.09	5	6509	6744	332.34	4.93
6.497			6979			
5.682	6.09	1	4285	4479	274.36	6.13
6.497			4673			
5.682	6.09	0.5	3528	3692	231.93	6.28
6.497			3856			
5.682	6.09	0.1	2180	2277	137.18	6.02
6.497			2374			
7.947	7.98	25	10783	9147	2313.65	25.29
8.013			7511			
7.947	7.98	10	8357	7152	1704.83	23.84
8.013			5946			
7.947	7.98	5	7138	6101	1466.54	24.04
8.013			5064			
7.947	7.98	1	4719	4009	1004.09	25.05
8.013			3299			
7.947	7.98	0.5	3878	3248	891.66	27.46
8.013			2617			
7.947	7.98	0.1	2325	1965	509.82	25.95
8.013			1604			
9.199	9.15	25	6131	5708	597.86	10.47
9.106			5286			
9.199	9.15	10	4785	4618	235.82	5.11
9.106			4451			
9.199	9.15	5	3982	3943	55.51	1.41
9.106			3904			
9.199	9.15	1	2761	2685	107.83	4.02
9.106			2609			
9.199	9.15	0.5	2275	2212	89.80	4.06
9.106			2148			
9.199	9.15	0.1	1464	1415	68.59	4.85
9.106			1367			

TABLE C.11 Mixture 3 Unconditioned Dynamic Modulus (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
4.266	4.58	25	2138	2228	126.57	5.68
4.897			2317			
4.266	4.58	10	1478	1562	118.79	7.61
4.897			1646			
4.266	4.58	5	1149	1217	95.46	7.85
4.897			1284			
4.266	4.58	1	722	772	70.00	9.07
4.897			821			
4.266	4.58	0.5	628	677	68.59	10.14
4.897			725			
4.266	4.58	0.1	484	514	41.72	8.12
4.897			543			
5.946	6.03	25	2144	1929	304.06	15.76
6.122			1714			
5.946	6.03	10	1511	1346	233.35	17.34
6.122			1181			
5.946	6.03	5	1171	1020	214.25	21.02
6.122			868			
5.946	6.03	1	764	638	178.90	28.06
6.122			511			
5.946	6.03	0.5	653	544	154.86	28.49
6.122			434			
5.946	6.03	0.1	494	408	121.62	29.81
6.122			322			
7.440	8.09	25	1674	1701	38.18	2.24
8.735			1728			
7.440	8.09	10	1181	1192	15.56	1.31
8.735			1203			
7.440	8.09	5	954	939	21.21	2.26
8.735			924			
7.440	8.09	1	631	620	16.26	2.63
8.735			608			
7.440	8.09	0.5	545	533	16.97	3.11
8.735			521			
7.440	8.09	0.1	425	406	26.87	6.62
8.735			387			
9.288	9.68	25	1274	1352	110.31	8.16
10.072			1430			
9.288	9.68	10	896	969	102.53	10.59
10.072			1041			
9.288	9.68	5	666	752	120.92	16.09
10.072			837			
9.288	9.68	1	413	497	118.79	23.90
10.072			581			
9.288	9.68	0.5	368	449	114.55	25.51
10.072			530			
9.288	9.68	0.1	271	358	122.33	34.22
10.072			444			

TABLE C.12 Mixture 3 Moisture Conditioned Dynamic Modulus (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
4.167	4.24	25	1850	1929	111.37	5.77
4.309			2008			
4.167	4.24	10	1296	1387	128.69	9.28
4.309			1478			
4.167	4.24	5	1002	1076	103.94	9.66
4.309			1149			
4.167	4.24	1	620	693	102.53	14.81
4.309			765			
4.167	4.24	0.5	520	603	117.38	19.47
4.309			686			
4.167	4.24	0.1	375	466	128.69	27.62
4.309			557			
5.682	6.09	25	1682	1576	150.61	9.56
6.497			1469			
5.682	6.09	10	1191	1114	108.89	9.78
6.497			1037			
5.682	6.09	5	940	876	91.22	10.42
6.497			811			
5.682	6.09	1	633	568	92.63	16.32
6.497			502			
5.682	6.09	0.5	565	502	89.10	17.75
6.497			439			
5.682	6.09	0.1	467	409	82.73	20.25
6.497			350			
7.947	7.98	25	1367	1432	92.98	6.49
8.013			1498			
7.947	7.98	10	964	1017	75.31	7.41
8.013			1070			
7.947	7.98	5	764	805	58.34	7.25
8.013			846			
7.947	7.98	1	495	528	46.67	8.84
8.013			561			
7.947	7.98	0.5	440	469	41.37	8.82
8.013			498			
7.947	7.98	0.1	351	380	40.31	10.62
8.013			408			
9.199	9.15	25	1251	1305	76.37	5.85
9.106			1359			
9.199	9.15	10	912	953	57.28	6.01
9.106			993			
9.199	9.15	5	715	758	60.81	8.02
9.106			801			
9.199	9.15	1	479	513	48.08	9.37
9.106			547			
9.199	9.15	0.5	426	451	35.36	7.84
9.106			476			
9.199	9.15	0.1	331	357	36.77	10.30
9.106			383			

TABLE C.13 Mixture 4 Unconditioned Dynamic Modulus (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
3.74	4.21	25	14058	12376	2378.71	19.22
4.68			10694			
3.74	4.21	10	12241	10574	2358.20	22.30
4.68			8906			
3.74	4.21	5	10563	9192	1939.59	21.10
4.68			7820			
3.74	4.21	1	7557	6521	1465.83	22.48
4.68			5484			
3.74	4.21	0.5	6401	5518	1249.46	22.65
4.68			4634			
3.74	4.21	0.1	4221	3587	896.61	25.00
4.68			2953			
5.825	6.13	25	10910	11398	690.14	6.05
6.435			11886			
5.825	6.13	10	9172	9731	790.55	8.12
6.435			10290			
5.825	6.13	5	8130	8742	864.79	9.89
6.435			9353			
5.825	6.13	1	5795	6329	754.48	11.92
6.435			6862			
5.825	6.13	0.5	4995	5492	702.86	12.80
6.435			5989			
5.825	6.13	0.1	3341	3640	422.85	11.62
6.435			3939			
7.680	7.87	25	9006	9531	742.46	7.79
8.053			10056			
7.680	7.87	10	7125	7729	853.48	11.04
8.053			8332			
7.680	7.87	5	6225	6776	779.23	11.50
8.053			7327			
7.680	7.87	1	4373	4739	517.60	10.92
8.053			5105			
7.680	7.87	0.5	3638	3964	461.39	11.64
8.053			4291			
7.680	7.87	0.1	2329	2552	315.72	12.37
8.053			2776			
10.402	9.96	25	7653	8650	1411.03	16.31
9.524			9648			
10.402	9.96	10	6536	7317	1103.79	15.09
9.524			8097			
10.402	9.96	5	5878	6460	824.13	12.76
9.524			7043			
10.402	9.96	1	4176	4593	589.02	12.83
9.524			5009			
10.402	9.96	0.5	3562	3903	483.31	12.38
9.524			4245			
10.402	9.96	0.1	2293	2539	347.19	13.68
9.524			2784			

TABLE C.14 Mixture 4 Moisture Conditioned Dynamic Modulus (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation	Coefficient of Variation (%)
3.804	4.22	25	15884	13526	3334.72	24.65
4.629			11168			
3.804	4.22	10	12467	10692	2510.23	23.48
4.629			8917			
3.804	4.22	5	10840	9169	2363.15	25.77
4.629			7498			
3.804	4.22	1	7318	6220	1553.51	24.98
4.629			5121			
3.804	4.22	0.5	6066	5138	1313.10	25.56
4.629			4209			
3.804	4.22	0.1	3819	3251	803.27	24.71
4.629			2683			
6.233	5.90	25	10349	12148	2544.17	20.94
5.571			13947			
6.233	5.90	10	8527	9755	1736.65	17.80
5.571			10983			
6.233	5.90	5	7572	8499	1310.27	15.42
5.571			9425			
6.233	5.90	1	5359	5969	861.96	14.44
5.571			6578			
6.233	5.90	0.5	4568	5035	659.73	13.10
5.571			5501			
6.233	5.90	0.1	2998	3352	500.63	14.94
5.571			3706			
8.554	7.84	25	7389	8875	2100.81	23.67
7.124			10360			
8.554	7.84	10	6004	7069	1506.14	21.31
7.124			8134			
8.554	7.84	5	5293	6143	1202.08	19.57
7.124			6993			
8.554	7.84	1	3711	4225	726.91	17.20
7.124			4739			
8.554	7.84	0.5	3146	3587	623.67	17.39
7.124			4028			
8.554	7.84	0.1	2070	2352	398.10	16.93
7.124			2633			
9.041	9.44	25	6753	7173	593.26	8.27
9.847			7592			
9.041	9.44	10	5682	6015	470.23	7.82
9.847			6347			
9.041	9.44	5	4966	5280	444.06	8.41
9.847			5594			
9.041	9.44	1	3495	3673	251.73	6.85
9.847			3851			
9.041	9.44	0.5	2940	3093	216.37	7.00
9.847			3246			
9.041	9.44	0.1	1845	1979	189.50	9.58
9.847			2113			

TABLE C.15 Mixture 4 Unconditioned Dynamic Modulus (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
3.74	4.21	25	4089	3526	796.91	22.60
4.68			2962			
3.74	4.21	10	2921	2519	568.51	22.57
4.68			2117			
3.74	4.21	5	2297	1955	483.66	24.74
4.68			1613			
3.74	4.21	1	1361	1174	265.17	22.60
4.68			986			
3.74	4.21	0.5	1131	982	211.42	21.54
4.68			832			
3.74	4.21	0.1	802	710	130.81	18.44
4.68			617			
5.825	6.13	25	2540	2857	447.60	15.67
6.435			3173			
5.825	6.13	10	1839	2065	318.91	15.45
6.435			2290			
5.825	6.13	5	1391	1604	300.52	18.74
6.435			1816			
5.825	6.13	1	853	1035	256.68	24.81
6.435			1216			
5.825	6.13	0.5	715	829	161.22	19.45
6.435			943			
5.825	6.13	0.1	512	570	82.02	14.39
6.435			628			
7.680	7.87	25	2055	2122	94.75	4.47
8.053			2189			
7.680	7.87	10	1721	1644	108.89	6.62
8.053			1567			
7.680	7.87	5	1389	1310	112.43	8.59
8.053			1230			
7.680	7.87	1	908	849	83.44	9.83
8.053			790			
7.680	7.87	0.5	780	733	67.18	9.17
8.053			685			
7.680	7.87	0.1	584	552	45.96	8.33
8.053			519			
10.402	9.96	25	2182	2094	125.16	5.98
9.524			2005			
10.402	9.96	10	1547	1488	83.44	5.61
9.524			1429			
10.402	9.96	5	1249	1189	84.85	7.14
9.524			1129			
10.402	9.96	1	843	767	107.48	14.01
9.524			691			
10.402	9.96	0.5	740	658	115.61	17.56
9.524			577			
10.402	9.96	0.1	565	485	113.84	23.50
9.524			404			

TABLE C.16 Mixture 4 Moisture Conditioned Dynamic Modulus (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	E* (MPa)	E* Average (MPa)	E* Standard Deviation (MPa)	Coefficient of Variation (%)
3.804	4.22	25	3343	2891	639.22	22.11
4.629			2439			
3.804	4.22	10	2361	2031	466.69	22.98
4.629			1701			
3.804	4.22	5	1815	1558	363.45	23.33
4.629			1301			
3.804	4.22	1	1158	985	245.37	24.92
4.629			811			
3.804	4.22	0.5	997	845	215.67	25.54
4.629			692			
3.804	4.22	0.1	769	650	168.29	25.89
4.629			531			
6.233	5.90	25	2151	2350	280.72	11.95
5.571			2548			
6.233	5.90	10	1588	1711	173.59	10.15
5.571			1834			
6.233	5.90	5	1249	1322	102.88	7.78
5.571			1395			
6.233	5.90	1	815	842	38.18	4.53
5.571			869			
6.233	5.90	0.5	723	734	14.85	2.02
5.571			744			
6.233	5.90	0.1	554	554	0.71	0.13
5.571			553			
8.554	7.84	25	1773	2401	887.42	36.97
7.124			3028			
8.554	7.84	10	1268	1701	612.35	36.00
7.124			2134			
8.554	7.84	5	976	1295	450.43	34.80
7.124			1613			
8.554	7.84	1	588	771	258.80	33.57
7.124			954			
8.554	7.84	0.5	518	649	184.55	28.46
7.124			779			
8.554	7.84	0.1	384	470	121.62	25.88
7.124			556			
9.041	9.44	25	1233	1570	475.88	30.32
9.847			1906			
9.041	9.44	10	909	1170	369.11	31.55
9.847			1431			
9.041	9.44	5	706	909	286.38	31.52
9.847			1111			
9.041	9.44	1	458	587	181.73	30.98
9.847			715			
9.041	9.44	0.5	406	515	154.15	29.93
9.847			624			
9.041	9.44	0.1	310	391	114.55	29.30
9.847			472

FIGURE C.1 Mixture 2 Unconditioned Dynamic Modulus (20C)

FIGURE C.2 Mixture 2 Moisture Conditioned Dynamic Modulus (20C)

FIGURE C.3 Mixture 2 Unconditioned Dynamic Modulus (40C)

FIGURE C.4 Mixture 2 Moisture Conditioned Dynamic Modulus (40C)

FIGURE C.5 Mixture 3 Unconditioned Dynamic Modulus (20C)

FIGURE C.6 Mixture 3 Moisture Conditioned Dynamic Modulus (20C)

FIGURE C.7 Mixture 3 Unconditioned Dynamic Modulus (40C)

FIGURE C.8 Mixture 3 Moisture Conditioned Dynamic Modulus (40C)

FIGURE C.9 Mixture 4 Unconditioned Dynamic Modulus (20C)

FIGURE C.10 Mixture 4 Moisture Conditioned Dynamic Modulus (20C)

FIGURE C.11 Mixture 4 Unconditioned Dynamic Modulus (40C)

FIGURE C.12 Mixture 4 Moisture Conditioned Dynamic Modulus (40C)

FIGURE C.13 Mixture 1 Unconditioned Dynamic Modulus (20C)

FIGURE C.14 Mixture 1 Moisture Conditioned Dynamic Modulus (20C)

FIGURE C.15 Mixture 1 Unconditioned Dynamic Modulus (40C)

FIGURE C.16 Mixture 1 Moisture Conditioned Dynamic Modulus (40C)

FIGURE C.17 Mixture 2 Unconditioned Dynamic Modulus (20C)

FIGURE C.18 Mixture 2 Moisture Conditioned Dynamic Modulus (20C)

FIGURE C.19 Mixture 2 Unconditioned Dynamic Modulus (40C)

FIGURE C.20 Mixture 2 Moisture Conditioned Dynamic Modulus (40C)

FIGURE C.21 Mixture 3 Unconditioned Dynamic Modulus (20C)

FIGURE C.22 Mixture 3 Moisture Conditioned Dynamic Modulus (20C)

FIGURE C.23 Mixture 3 Unconditioned Dynamic Modulus (40C)

FIGURE C.24 Mixture 3 Moisture Conditioned Dynamic Modulus (40C)

FIGURE C.25 Mixture 4 Unconditioned Dynamic Modulus (20C)

FIGURE C.26 Mixture 4 Moisture Conditioned Dynamic Modulus (20C)

FIGURE C.27 Mixture 4 Unconditioned Dynamic Modulus (40C)

FIGURE C.28 Mixture 4 Moisture Conditioned Dynamic Modulus (40C)

FIGURES C.29, C.30, C.31, and C.32 Mixture 1 Dynamic Modulus at 4, 6, 8, and 10% Air Voids Contents (20C)

FIGURES C.33, C.34, C.35, and C.36 Unconditioned Dynamic Modulus at 4, 6, 8, and 10% Air Voids Contents (20C)

FIGURES C.37, C.38, C.39, and C.40 Unconditioned Dynamic Modulus at 4, 6, 8, and 10% Air Voids Contents (40C)

FIGURES C.41, C.42, C.43, and C.44 Moisture Conditioned Dynamic Modulus at 4, 6, 8, and 10% Air Voids Contents (20C)

FIGURES C.45, C.46, C.47, and C.48 Moisture Conditioned Dynamic Modulus at 4, 6, 8, and 10% Air Voids Contents (40C)

TABLE C.17 Mixture 1 Unconditioned Phase Angle (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
4.067	4.12	25	23.4	22.1	1.83	8.28
4.175			20.8			
4.067	4.12	10	25.6	24.0	2.20	9.16
4.175			22.5			
4.067	4.12	5	26.5	25.4	1.51	5.92
4.175			24.4			
4.067	4.12	1	29.5	28.6	1.23	4.29
4.175			27.7			
4.067	4.12	0.5	30.0	29.2	1.05	3.61
4.175			28.5			
4.067	4.12	0.1	29.6	29.2	0.69	2.36
4.175			28.7			
6.067	6.00	25	21.5	21.6	0.27	1.23
5.942			21.8			
6.067	6.00	10	23.3	23.2	0.06	0.27
5.942			23.2			
6.067	6.00	5	25.1	24.7	0.56	2.25
5.942			24.3			
6.067	6.00	1	28.6	28.3	0.34	1.19
5.942			28.1			
6.067	6.00	0.5	29.5	29.2	0.40	1.38
5.942			29.0			
6.067	6.00	0.1	29.9	29.7	0.27	0.92
5.942			29.5			
8.365	7.96	25	22.2	22.2	0.06	0.26
7.551			22.1			
8.365	7.96	10	25.2	24.4	1.08	4.44
7.551			23.6			
8.365	7.96	5	26.2	24.6	2.32	9.42
7.551			23.0			
8.365	7.96	1	29.3	29.0	0.50	1.73
7.551			28.6			
8.365	7.96	0.5	29.8	29.4	0.56	1.91
7.551			29.0			
8.365	7.96	0.1	30.2	29.3	1.18	4.01
7.551			28.5			
9.544	9.83	25	23.6	23.2	0.64	2.75
10.120			22.7			
9.544	9.83	10	25.6	25.1	0.66	2.64
10.120			24.7			
9.544	9.83	5	26.9	26.6	0.49	1.84
10.120			26.2			
9.544	9.83	1	30.1	30.4	0.40	1.30
10.120			30.7			
9.544	9.83	0.5	30.7	31.0	0.40	1.30
10.120			31.3			
9.544	9.83	0.1	31.0	30.7	0.33	1.06
10.120			30.5			

TABLE C.18 Mixture 1 Moisture Conditioned Phase Angle (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation	Coefficient of Variation (%)
3.771	4.03	25	22.5	21.8	1.09	4.98
4.292			21.0			
3.771	4.03	10	31.3	28.6	3.78	13.21
4.292			25.9			
3.771	4.03	5	30.6	28.4	3.13	11.02
4.292			26.2			
3.771	4.03	1	34.3	31.4	3.96	12.60
4.292			28.6			
3.771	4.03	0.5	36.1	32.7	4.79	14.66
4.292			29.3			
3.771	4.03	0.1	37.4	33.6	5.24	15.58
4.292			29.9			
6.027	6.01	25	20.0	19.5	0.80	4.10
5.987			18.9			
6.027	6.01	10	26.8	26.8	0.09	0.34
5.987			26.7			
6.027	6.01	5	26.9	26.1	1.06	4.06
5.987			25.4			
6.027	6.01	1	29.2	29.1	0.09	0.32
5.987			29.0			
6.027	6.01	0.5	29.5	30.0	0.69	2.31
5.987			30.5			
6.027	6.01	0.1	29.3	30.5	1.82	5.95
5.987			31.8			
7.828	7.97	25	18.2	21.0	4.02	19.14
8.103			23.8			
7.828	7.97	10	26.9	29.1	3.19	10.94
8.103			31.4			
7.828	7.97	5	28.0	29.2	1.70	5.83
8.103			30.4			
7.828	7.97	1	30.3	31.1	1.10	3.55
8.103			31.9			
7.828	7.97	0.5	30.4	31.2	1.22	3.92
8.103			32.1			
7.828	7.97	0.1	29.6	30.6	1.41	4.63
8.103			31.6			
9.14	9.25	25	16.9	17.1	0.32	1.88
9.350			17.3			
9.14	9.25	10	18.8	20.4	2.28	11.20
9.350			22.0			
9.14	9.25	5	29.6	28.9	1.01	3.51
9.350			28.2			
9.14	9.25	1	28.9	29.6	1.07	3.63
9.350			30.4			
9.14	9.25	0.5	29.1	31.2	2.93	9.39
9.350			33.3			
9.14	9.25	0.1	28.1	31.6	4.84	15.34
9.350			35.0			

TABLE C.19 Mixture 1 Unconditioned Phase Angle (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
4.067	4.12	25	31.3	29.9	1.91	6.37
4.175			28.6			
4.067	4.12	10	29.6	28.5	1.53	5.38
4.175			27.4			
4.067	4.12	5	28.8	28.1	1.01	3.59
4.175			27.3			
4.067	4.12	1	26.8	25.9	1.32	5.10
4.175			24.9			
4.067	4.12	0.5	25.6	24.3	1.75	7.19
4.175			23.1			
4.067	4.12	0.1	23.0	21.2	2.59	12.23
4.175			19.4			
6.067	6.00	25	25.1	31.0	8.38	27.05
5.942			36.9			
6.067	6.00	10	24.5	29.8	7.56	25.36
5.942			35.1			
6.067	6.00	5	24.0	28.4	6.30	22.16
5.942			32.9			
6.067	6.00	1	22.9	24.3	1.94	8.00
5.942			25.7			
6.067	6.00	0.5	21.3	22.2	1.34	6.01
5.942			23.2			
6.067	6.00	0.1	18.4	18.8	0.56	2.99
5.942			19.2			
8.365	7.96	25	31.8	34.3	3.42	9.99
7.551			36.7			
8.365	7.96	10	30.9	31.6	1.04	3.28
7.551			32.3			
8.365	7.96	5	28.7	28.7	0.10	0.33
7.551			28.8			
8.365	7.96	1	22.7	23.9	1.77	7.42
7.551			25.2			
8.365	7.96	0.5	20.7	22.5	2.49	11.10
7.551			24.2			
8.365	7.96	0.1	17.9	20.2	3.30	16.32
7.551			22.5			
9.544	9.83	25	30.2	31.9	2.44	7.65
10.120			33.6			
9.544	9.83	10	29.7	31.4	2.40	7.66
10.120			33.1			
9.544	9.83	5	28.0	29.5	2.12	7.19
10.120			31.0			
9.544	9.83	1	26.7	26.3	0.55	2.10
10.120			25.9			
9.544	9.83	0.5	25.9	25.1	1.19	4.73
10.120			24.3			
9.544	9.83	0.1	24.2	23.1	1.63	7.04
10.120			21.9			

TABLE C.20 Mixture 1 Moisture Conditioned Phase Angle (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
3.771	4.03	25	30.4	29.1	1.82	6.26
4.292			27.8			
3.771	4.03	10	29.4	28.4	1.42	5.01
4.292			27.4			
3.771	4.03	5	29.8	28.5	1.87	6.57
4.292			27.2			
3.771	4.03	1	26.4	25.8	0.92	3.58
4.292			25.1			
3.771	4.03	0.5	24.7	24.1	0.88	3.67
4.292			23.4			
3.771	4.03	0.1	20.5	20.0	0.59	2.95
4.292			19.6			
6.027	6.01	25	29.2	28.8	0.45	1.54
5.987			28.5			
6.027	6.01	10	28.2	27.4	1.20	4.39
5.987			26.5			
6.027	6.01	5	28.1	26.9	1.74	6.48
5.987			25.6			
6.027	6.01	1	25.6	23.9	2.33	9.76
5.987			22.3			
6.027	6.01	0.5	24.1	22.6	2.10	9.29
5.987			21.1			
6.027	6.01	0.1	20.4	19.6	1.17	5.99
5.987			18.8			
7.828	7.97	25	29.9	30.1	0.25	0.82
8.103			30.2			
7.828	7.97	10	28.8	28.6	0.16	0.57
8.103			28.5			
7.828	7.97	5	29.7	28.1	2.35	8.36
8.103			26.4			
7.828	7.97	1	27.3	25.6	2.41	9.42
8.103			23.9			
7.828	7.97	0.5	25.6	23.8	2.55	10.71
8.103			22.0			
7.828	7.97	0.1	23.6	21.7	2.69	12.39
8.103			19.8			
9.14	9.25	25	27.5	27.1	0.54	2.01
9.350			26.7			
9.14	9.25	10	23.8	24.0	0.30	1.24
9.350			24.2			
9.14	9.25	5	21.9	22.5	0.90	3.99
9.350			23.1			
9.14	9.25	1	22.4	21.5	1.14	5.28
9.350			20.7			
9.14	9.25	0.5	21.1	20.1	1.41	7.02
9.350			19.1			
9.14	9.25	0.1	19.6	18.7	1.27	6.78
9.350			17.8			

TABLE C.21 Mixture 2 Unconditioned Phase Angle (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
3.799	4.14	25	21.3	19.5	2.62	13.47
4.486			17.6			
3.799	4.14	10	22.6	22.4	0.37	1.66
4.486			22.1			
3.799	4.14	5	24.3	23.4	1.27	5.43
4.486			22.5			
3.799	4.14	1	28.1	27.5	0.86	3.13
4.486			26.9			
3.799	4.14	0.5	29.4	29.0	0.53	1.83
4.486			28.7			
3.799	4.14	0.1	27.3	29.9	3.61	12.09
4.486			32.4			
5.944	5.93	25	21.3	21.6	0.48	2.23
5.909			21.9			
5.944	5.93	10	24.5	25.1	0.86	3.40
5.909			25.7			
5.944	5.93	5	25.8	25.5	0.45	1.78
5.909			25.2			
5.944	5.93	1	29.3	28.6	0.98	3.42
5.909			27.9			
5.944	5.93	0.5	30.5	29.5	1.40	4.75
5.909			28.5			
5.944	5.93	0.1	31.2	30.2	1.42	4.71
5.909			29.2			
7.919	7.88	25	20.3	20.6	0.38	1.85
7.850			20.9			
7.919	7.88	10	22.1	22.3	0.26	1.17
7.850			22.5			
7.919	7.88	5	23.5	23.5	0.08	0.36
7.850			23.4			
7.919	7.88	1	28.0	27.2	1.10	4.03
7.850			26.4			
7.919	7.88	0.5	29.4	28.4	1.33	4.68
7.850			27.5			
7.919	7.88	0.1	32.0	31.1	1.37	4.42
7.850			30.1			
9.896	10.34	25	19.0	19.6	0.74	3.76
10.789			20.1			
9.896	10.34	10	24.2	24.1	0.16	0.65
10.789			24.0			
9.896	10.34	5	23.7	24.6	1.36	5.51
10.789			25.6			
9.896	10.34	1	27.3	28.6	1.75	6.14
10.789			29.8			
9.896	10.34	0.5	28.6	30.0	2.06	6.86
10.789			31.5			
9.896	10.34	0.1	30.5	32.8	3.20	9.76
10.789			35.0			

TABLE C.22 Mixture 2 Moisture Conditioned Phase Angle (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
4.026	4.10	25	17.0	17.0	0.01	0.08
4.178			17.0			
4.026	4.10	10	21.7	21.1	0.83	3.96
4.178			20.5			
4.026	4.10	5	23.0	22.8	0.28	1.21
4.178			22.6			
4.026	4.10	1	25.8	27.0	1.75	6.49
4.178			28.2			
4.026	4.10	0.5	26.7	28.5	2.52	8.86
4.178			30.3			
4.026	4.10	0.1	28.1	30.8	3.79	12.33
4.178			33.4			
5.505	6.01	25	17.0	16.7	0.42	2.55
6.517			16.4			
5.505	6.01	10	20.5	21.4	1.25	5.86
6.517			22.2			
5.505	6.01	5	22.6	23.0	0.63	2.73
6.517			23.5			
5.505	6.01	1	28.2	28.0	0.40	1.42
6.517			27.7			
5.505	6.01	0.5	30.3	29.4	1.24	4.23
6.517			28.5			
5.505	6.01	0.1	33.4	32.1	1.92	5.97
6.517			30.7			
7.614	7.93	25	16.9	17.9	1.42	7.95
8.240			18.9			
7.614	7.93	10	22.1	21.8	0.52	2.40
8.240			21.4			
7.614	7.93	5	23.3	23.9	0.85	3.55
8.240			24.5			
7.614	7.93	1	29.1	29.8	1.08	3.62
8.240			30.6			
7.614	7.93	0.5	30.8	31.7	1.24	3.92
8.240			32.6			
7.614	7.93	0.1	34.3	34.3	0.06	0.19
8.240			34.4			
10.045	10.03	25	18.5	17.5	1.34	7.62
10.009			16.6			
10.045	10.03	10	22.9	21.4	2.11	9.84
10.009			19.9			
10.045	10.03	5	25.8	25.8	0.08	0.33
10.009			25.9			
10.045	10.03	1	28.0	29.3	1.80	6.13
10.009			30.6			
10.045	10.03	0.5	29.1	31.0	2.69	8.69
10.009			32.9			
10.045	10.03	0.1	31.8	33.3	2.21	6.64
10.009			34.9			

TABLE C.23 Mixture 2 Unconditioned Phase Angle (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
3.799	4.14	25	30.5	29.2	1.74	5.96
4.486			28.0			
3.799	4.14	10	29.9	28.6	1.95	6.82
4.486			27.2			
3.799	4.14	5	30.5	29.0	2.03	7.01
4.486			27.6			
3.799	4.14	1	27.0	28.1	1.51	5.37
4.486			29.2			
3.799	4.14	0.5	24.8	26.0	1.73	6.63
4.486			27.3			
3.799	4.14	0.1	20.1	21.8	2.32	10.64
4.486			23.4			
5.944	5.93	25	32.9	31.7	1.71	5.41
5.909			30.5			
5.944	5.93	10	31.5	30.4	1.59	5.22
5.909			29.3			
5.944	5.93	5	30.3	30.6	0.31	1.02
5.909			30.8			
5.944	5.93	1	28.6	29.1	0.66	2.26
5.909			29.6			
5.944	5.93	0.5	26.6	27.2	0.84	3.08
5.909			27.8			
5.944	5.93	0.1	21.5	22.4	1.37	6.10
5.909			23.4			
7.919	7.88	25	30.4	29.5	1.17	3.95
7.850			28.7			
7.919	7.88	10	29.0	28.1	1.21	4.30
7.850			27.3			
7.919	7.88	5	28.9	27.9	1.48	5.33
7.850			26.8			
7.919	7.88	1	27.9	26.5	2.01	7.58
7.850			25.1			
7.919	7.88	0.5	26.6	24.9	2.33	9.34
7.850			23.3			
7.919	7.88	0.1	23.7	21.5	3.08	14.32
7.850			19.3			
9.896	10.34	25	30.2	31.3	1.60	5.11
10.789			32.4			
9.896	10.34	10	28.3	28.3	0.07	0.25
10.789			28.4			
9.896	10.34	5	28.9	29.3	0.62	2.10
10.789			29.8			
9.896	10.34	1	28.7	28.3	0.62	2.17
10.789			27.9			
9.896	10.34	0.5	26.9	26.0	1.22	4.68
10.789			25.2			
9.896	10.34	0.1	24.0	23.0	1.37	5.96
10.789			22.0			

TABLE C.24 Mixture 2 Moisture Conditioned Phase Angle (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
4.026	4.10	25	29.0	29.1	0.11	0.36
4.178			29.2			
4.026	4.10	10	28.4	27.8	0.90	3.23
4.178			27.1			
4.026	4.10	5	30.5	29.2	1.78	6.10
4.178			27.9			
4.026	4.10	1	27.7	26.2	2.04	7.79
4.178			24.8			
4.026	4.10	0.5	25.8	24.5	1.77	7.20
4.178			23.3			
4.026	4.10	0.1	21.8	20.8	1.43	6.88
4.178			19.8			
5.505	6.01	25	28.0	28.0	0.03	0.10
6.517			28.0			
5.505	6.01	10	27.0	27.4	0.50	1.83
6.517			27.7			
5.505	6.01	5	28.4	27.9	0.69	2.48
6.517			27.4			
5.505	6.01	1	27.5	26.2	1.87	7.16
6.517			24.8			
5.505	6.01	0.5	26.1	24.6	2.04	8.27
6.517			23.2			
5.505	6.01	0.1	23.5	21.6	2.58	11.93
6.517			19.8			
7.614	7.93	25	28.8	29.8	1.35	4.54
8.240			30.7			
7.614	7.93	10	26.4	27.8	2.04	7.35
8.240			29.2			
7.614	7.93	5	25.6	26.7	1.45	5.45
8.240			27.7			
7.614	7.93	1	24.8	25.4	0.89	3.52
8.240			26.0			
7.614	7.93	0.5	22.8	23.7	1.27	5.34
8.240			24.6			
7.614	7.93	0.1	21.8	21.7	0.25	1.16
8.240			21.5			
10.045	10.03	25	30.0	28.6	1.95	6.82
10.009			27.2			
10.045	10.03	10	29.2	26.8	3.33	12.42
10.009			24.5			
10.045	10.03	5	28.0	25.7	3.20	12.45
10.009			23.5			
10.045	10.03	1	27.8	25.2	3.65	14.46
10.009			22.7			
10.045	10.03	0.5	26.0	23.5	3.51	14.98
10.009			21.0			
10.045	10.03	0.1	24.2	20.9	4.65	22.22
10.009			17.6			

TABLE C.25 Mixture 3 Unconditioned Phase Angle (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
4.266	4.58	25	19.4	19.7	0.40	2.02
4.897			19.9			
4.266	4.58	10	22.3	23.0	0.91	3.94
4.897			23.6			
4.266	4.58	5	24.1	24.3	0.29	1.19
4.897			24.5			
4.266	4.58	1	28.3	28.3	0.01	0.05
4.897			28.3			
4.266	4.58	0.5	29.9	29.6	0.35	1.17
4.897			29.4			
4.266	4.58	0.1	32.0	30.9	1.59	5.15
4.897			29.8			
5.946	6.03	25	22.7	21.2	2.17	10.24
6.122			19.7			
5.946	6.03	10	27.0	25.1	2.72	10.82
6.122			23.2			
5.946	6.03	5	27.3	26.3	1.41	5.38
6.122			25.3			
5.946	6.03	1	30.2	29.3	1.24	4.22
6.122			28.4			
5.946	6.03	0.5	31.1	30.3	1.09	3.59
6.122			29.6			
5.946	6.03	0.1	31.9	31.1	1.07	3.43
6.122			30.4			
7.440	8.09	25	21.37	19.62	2.47	12.61
8.735			17.87			
7.440	8.09	10	26.34	24.75	2.25	9.09
8.735			23.16			
7.440	8.09	5	27.5	25.34	3.05	12.05
8.735			23.18			
7.440	8.09	1	31.16	29.255	2.69	9.21
8.735			27.35			
7.440	8.09	0.5	32.58	30.85	2.45	7.93
8.735			29.12			
7.440	8.09	0.1	33.61	32.71	1.27	3.89
8.735			31.81			
9.288	9.68	25	20.6	19.4	1.63	8.40
10.072			18.3			
9.288	9.68	10	26.5	25.6	1.22	4.74
10.072			24.8			
9.288	9.68	5	26.2	26.5	0.35	1.31
10.072			26.7			
9.288	9.68	1	30.8	30.5	0.41	1.36
10.072			30.2			
9.288	9.68	0.5	32.4	31.6	1.07	3.39
10.072			30.9			
9.288	9.68	0.1	35.4	34.1	1.85	5.41
10.072			32.8			

TABLE C.26 Mixture 3 Moisture Conditioned Phase Angle (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
4.167	4.24	25	19.4	19.2	0.18	0.92
4.309			19.1			
4.167	4.24	10	28.2	26.3	2.64	10.03
4.309			24.4			
4.167	4.24	5	24.8	24.8	0.11	0.43
4.309			24.7			
4.167	4.24	1	28.8	29.6	1.07	3.61
4.309			30.3			
4.167	4.24	0.5	29.6	30.4	1.11	3.65
4.309			31.2			
4.167	4.24	0.1	30.4	30.9	0.65	2.11
4.309			31.4			
5.682	6.09	25	18.3	18.5	0.28	1.53
6.497			18.7			
5.682	6.09	10	23.2	24.2	1.39	5.73
6.497			25.2			
5.682	6.09	5	25.7	25.1	0.90	3.58
6.497			24.5			
5.682	6.09	1	30.7	30.1	0.94	3.13
6.497			29.4			
5.682	6.09	0.5	32.4	31.9	0.71	2.24
6.497			31.4			
5.682	6.09	0.1	33.2	34.2	1.43	4.18
6.497			35.2			
7.947	7.98	25	18.7	18.4	0.43	2.35
8.013			18.1			
7.947	7.98	10	23.6	22.4	1.76	7.87
8.013			21.1			
7.947	7.98	5	25.8	26.2	0.60	2.29
8.013			26.6			
7.947	7.98	1	31.3	30.4	1.32	4.32
8.013			29.5			
7.947	7.98	0.5	33.1	31.9	1.72	5.39
8.013			30.7			
7.947	7.98	0.1	35.4	33.6	2.55	7.61
8.013			31.8			
9.199	9.15	25	16.5	18.0	2.11	11.68
9.106			19.5			
9.199	9.15	10	20.5	22.3	2.54	11.37
9.106			24.1			
9.199	9.15	5	24.2	25.6	1.87	7.31
9.106			26.9			
9.199	9.15	1	27.5	28.6	1.55	5.43
9.106			29.7			
9.199	9.15	0.5	28.6	29.7	1.56	5.25
9.106			30.8			
9.199	9.15	0.1	30.4	31.2	1.21	3.86
9.106			32.1			

TABLE C.27 Mixture 3 Unconditioned Phase Angle (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
4.266	4.58	25	31.2	30.0	1.65	5.49
4.897			28.8			
4.266	4.58	10	29.2	28.3	1.22	4.30
4.897			27.5			
4.266	4.58	5	29.2	28.1	1.56	5.56
4.897			27.0			
4.266	4.58	1	26.7	26.6	0.16	0.61
4.897			26.5			
4.266	4.58	0.5	24.5	24.4	0.06	0.26
4.897			24.4			
4.266	4.58	0.1	20.0	20.0	0.00	0.00
4.897			20.0			
5.946	6.03	25	30.7	31.6	1.17	3.72
6.122			32.4			
5.946	6.03	10	29.9	30.6	1.03	3.37
6.122			31.4			
5.946	6.03	5	28.4	29.6	1.73	5.83
6.122			30.8			
5.946	6.03	1	25.7	27.6	2.79	10.09
6.122			29.6			
5.946	6.03	0.5	23.3	25.2	2.66	10.55
6.122			27.1			
5.946	6.03	0.1	19.5	21.1	2.16	10.28
6.122			22.6			
7.440	8.09	25	31.5	29.7	2.51	8.44
8.735			28.0			
7.440	8.09	10	28.2	28.3	0.09	0.33
8.735			28.3			
7.440	8.09	5	27.3	29.4	2.96	10.06
8.735			31.5			
7.440	8.09	1	25.6	27.1	2.21	8.16
8.735			28.7			
7.440	8.09	0.5	24.3	25.8	2.08	8.06
8.735			27.3			
7.440	8.09	0.1	21.4	23.4	2.83	12.10
8.735			25.4			
9.288	9.68	25	35.0	31.9	4.39	13.75
10.072			28.8			
9.288	9.68	10	33.5	30.0	4.99	16.66
10.072			26.4			
9.288	9.68	5	32.6	29.3	4.72	16.09
10.072			26.0			
9.288	9.68	1	29.9	26.6	4.67	17.60
10.072			23.3			
9.288	9.68	0.5	28.6	25.1	4.93	19.62
10.072			21.6			
9.288	9.68	0.1	27.0	24.2	3.94	16.29
10.072			21.4			

TABLE C.28 Mixture 3 Moisture Conditioned Phase Angle (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
4.167	4.24	25	33.1	30.3	3.99	13.17
4.309			27.5			
4.167	4.24	10	31.3	28.5	3.92	13.75
4.309			25.7			
4.167	4.24	5	30.9	28.9	2.81	9.74
4.309			26.9			
4.167	4.24	1	28.4	27.5	1.28	4.65
4.309			26.6			
4.167	4.24	0.5	25.7	25.3	0.65	2.57
4.309			24.8			
4.167	4.24	0.1	22.9	22.5	0.57	2.52
4.309			22.1			
5.682	6.09	25	31.6	31.1	0.76	2.46
6.497			30.5			
5.682	6.09	10	28.9	28.6	0.40	1.41
6.497			28.4			
5.682	6.09	5	28.7	28.5	0.17	0.59
6.497			28.4			
5.682	6.09	1	24.9	25.9	1.41	5.46
6.497			26.9			
5.682	6.09	0.5	24.2	24.7	0.63	2.55
6.497			25.1			
5.682	6.09	0.1	20.6	21.0	0.66	3.16
6.497			21.5			
7.947	7.98	25	27.9	29.9	2.91	9.74
8.013			32.0			
7.947	7.98	10	25.6	28.2	3.62	12.85
8.013			30.8			
7.947	7.98	5	26.2	27.8	2.29	8.22
8.013			29.4			
7.947	7.98	1	24.0	24.8	1.12	4.54
8.013			25.6			
7.947	7.98	0.5	22.2	23.3	1.46	6.29
8.013			24.3			
7.947	7.98	0.1	19.3	20.8	2.12	10.20
8.013			22.3			
9.199	9.15	25	30.1	29.6	0.74	2.51
9.106			29.1			
9.199	9.15	10	28.1	28.1	0.06	0.23
9.106			28.1			
9.199	9.15	5	27.9	27.0	1.33	4.93
9.106			26.0			
9.199	9.15	1	24.7	23.5	1.75	7.44
9.106			22.2			
9.199	9.15	0.5	23.6	22.3	1.85	8.27
9.106			21.0			
9.199	9.15	0.1	23.4	21.5	2.61	12.11
9.106			19.7			

TABLE C.29 Mixture 4 Unconditioned Phase Angle (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
3.74	4.21	25	18.0	18.2	0.40	2.17
4.68			18.5			
3.74	4.21	10	20.1	21.9	2.57	11.72
4.68			23.7			
3.74	4.21	5	22.2	22.7	0.71	3.15
4.68			23.2			
3.74	4.21	1	26.3	26.8	0.63	2.35
4.68			27.2			
3.74	4.21	0.5	27.8	28.1	0.40	1.43
4.68			28.4			
3.74	4.21	0.1	30.7	30.5	0.25	0.83
4.68			30.3			
5.825	6.13	25	17.6	16.0	2.14	13.31
6.435			14.5			
5.825	6.13	10	20.4	20.4	0.03	0.14
6.435			20.4			
5.825	6.13	5	22.4	20.4	2.82	13.84
6.435			18.4			
5.825	6.13	1	25.2	24.5	1.05	4.30
6.435			23.7			
5.825	6.13	0.5	26.7	26.4	0.39	1.47
6.435			26.2			
5.825	6.13	0.1	29.9	30.5	0.80	2.62
6.435			31.0			
7.680	7.87	25	19.5	18.8	0.95	5.06
8.053			18.1			
7.680	7.87	10	22.8	21.6	1.69	7.85
8.053			20.4			
7.680	7.87	5	23.6	23.3	0.37	1.61
8.053			23.0			
7.680	7.87	1	27.7	27.5	0.38	1.39
8.053			27.2			
7.680	7.87	0.5	28.9	28.8	0.12	0.41
8.053			28.7			
7.680	7.87	0.1	30.9	31.8	1.22	3.84
8.053			32.6			
10.402	9.96	25	20.0	19.2	1.03	5.35
9.524			18.5			
10.402	9.96	10	23.1	22.2	1.32	5.95
9.524			21.3			
10.402	9.96	5	25.8	24.4	1.99	8.17
9.524			23.0			
10.402	9.96	1	28.7	27.6	1.61	5.85
9.524			26.4			
10.402	9.96	0.5	30.1	29.1	1.48	5.09
9.524			28.0			
10.402	9.96	0.1	33.1	31.6	2.07	6.54
9.524			30.1			

TABLE C.30 Mixture 4 Moisture Conditioned Phase Angle (20C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
3.804	4.22	25	18.8	18.5	0.36	1.95
4.629			18.3			
3.804	4.22	10	21.5	21.8	0.36	1.65
4.629			22.1			
3.804	4.22	5	24.5	23.9	0.82	3.44
4.629			23.3			
3.804	4.22	1	28.2	27.6	0.73	2.64
4.629			27.1			
3.804	4.22	0.5	29.1	28.7	0.59	2.07
4.629			28.2			
3.804	4.22	0.1	30.3	30.0	0.45	1.49
4.629			29.7			
6.233	5.90	25	16.7	17.4	1.04	5.98
5.571			18.1			
6.233	5.90	10	23.2	22.6	0.76	3.38
5.571			22.1			
6.233	5.90	5	21.3	22.5	1.72	7.64
5.571			23.7			
6.233	5.90	1	24.9	26.6	2.38	8.93
5.571			28.3			
6.233	5.90	0.5	26.2	27.9	2.45	8.78
5.571			29.6			
6.233	5.90	0.1	28.1	29.8	2.34	7.87
5.571			31.4			
8.554	7.84	25	17.7	18.8	1.48	7.88
7.124			19.8			
8.554	7.84	10	21.9	23.6	2.48	10.51
7.124			25.4			
8.554	7.84	5	22.8	25.3	3.54	14.01
7.124			27.8			
8.554	7.84	1	27.5	29.3	2.56	8.75
7.124			31.1			
8.554	7.84	0.5	28.7	30.3	2.28	7.51
7.124			31.9			
8.554	7.84	0.1	30.7	32.1	1.90	5.91
7.124			33.4			
9.041	9.44	25	17.0	18.0	1.32	7.36
9.847			18.9			
9.041	9.44	10	23.1	22.5	0.75	3.33
9.847			22.0			
9.041	9.44	5	23.0	23.1	0.21	0.89
9.847			23.3			
9.041	9.44	1	27.3	26.7	0.81	3.02
9.847			26.1			
9.041	9.44	0.5	28.7	27.8	1.29	4.65
9.847			26.9			
9.041	9.44	0.1	31.6	30.0	2.21	7.38
9.847			28.4			

TABLE C.31 Mixture 4 Unconditioned Phase Angle (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
3.74	4.21	25	29.7	29.8	0.11	0.36
4.68			29.9			
3.74	4.21	10	30.0	29.6	0.53	1.79
4.68			29.3			
3.74	4.21	5	33.4	31.7	2.43	7.66
4.68			29.9			
3.74	4.21	1	33.1	30.7	3.44	11.22
4.68			28.3			
3.74	4.21	0.5	31.0	28.3	3.80	13.42
4.68			25.7			
3.74	4.21	0.1	26.9	23.5	4.85	20.66
4.68			20.1			
5.825	6.13	25	29.7	29.4	0.33	1.11
6.435			29.2			
5.825	6.13	10	29.7	29.5	0.35	1.18
6.435			29.2			
5.825	6.13	5	29.7	30.5	1.10	3.62
6.435			31.3			
5.825	6.13	1	29.5	29.0	0.71	2.44
6.435			28.5			
5.825	6.13	0.5	27.4	27.7	0.40	1.46
6.435			28.0			
5.825	6.13	0.1	23.7	22.3	1.89	8.45
6.435			21.0			
7.680	7.87	25	31.1	29.8	1.80	6.03
8.053			28.5			
7.680	7.87	10	29.2	28.1	1.62	5.77
8.053			26.9			
7.680	7.87	5	32.8	30.2	3.79	12.57
8.053			27.5			
7.680	7.87	1	27.4	26.8	0.87	3.25
8.053			26.2			
7.680	7.87	0.5	25.4	24.5	1.27	5.18
8.053			23.6			
7.680	7.87	0.1	21.4	20.4	1.34	6.59
8.053			19.5			
10.402	9.96	25	31.7	31.8	0.06	0.19
9.524			31.8			
10.402	9.96	10	29.7	30.4	1.00	3.30
9.524			31.1			
10.402	9.96	5	29.1	30.2	1.61	5.34
9.524			31.3			
10.402	9.96	1	27.8	28.9	1.58	5.47
9.524			30.0			
10.402	9.96	0.5	26.5	27.3	1.17	4.29
9.524			28.1			
10.402	9.96	0.1	23.3	23.8	0.71	2.97
9.524			24.3			

TABLE C.32 Mixture 4 Moisture Conditioned Phase Angle (40C)

Air Voids (%)	Air Voids Average (%)	Frequency (Hz.)	Phase Angle (deg.)	Phase Angle Average (deg)	Phase Angle Standard Deviation (deg)	Coefficient of Variation (%)
3.804	4.22	25	29.4	29.1	0.36	1.24
4.629			28.9			
3.804	4.22	10	28.3	27.6	1.05	3.80
4.629			26.8			
3.804	4.22	5	30.3	28.5	2.60	9.14
4.629			26.6			
3.804	4.22	1	26.5	26.1	0.56	2.14
4.629			25.7			
3.804	4.22	0.5	24.0	23.9	0.16	0.68
4.629			23.8			
3.804	4.22	0.1	18.6	19.3	1.02	5.27
4.629			20.0			
6.233	5.90	25	28.0	28.4	0.62	2.17
5.571			28.8			
6.233	5.90	10	26.0	26.7	1.00	3.75
5.571			27.4			
6.233	5.90	5	25.5	26.9	1.94	7.24
5.571			28.2			
6.233	5.90	1	25.7	26.0	0.51	1.96
5.571			26.4			
6.233	5.90	0.5	24.4	24.3	0.07	0.31
5.571			24.3			
6.233	5.90	0.1	20.6	20.1	0.72	3.60
5.571			19.6			
8.554	7.84	25	28.5	27.7	1.10	3.95
7.124			27.0			
8.554	7.84	10	26.7	26.8	0.20	0.74
7.124			26.9			
8.554	7.84	5	25.5	27.9	3.45	12.35
7.124			30.4			
8.554	7.84	1	27.1	29.0	2.74	9.43
7.124			30.9			
8.554	7.84	0.5	24.8	28.3	4.93	17.40
7.124			31.8			
8.554	7.84	0.1	20.2	24.6	6.14	24.99
7.124			28.9			
9.041	9.44	25	28.7	28.4	0.42	1.49
9.847			28.1			
9.041	9.44	10	25.3	25.7	0.64	2.50
9.847			26.2			
9.041	9.44	5	24.0	24.9	1.36	5.47
9.847			25.9			
9.041	9.44	1	24.6	24.8	0.25	1.00
9.847			24.9			
9.041	9.44	0.5	23.5	23.7	0.18	0.78
9.847			23.8			
9.041	9.44	0.1	21.0	20.8	0.25	1.19
9.847			20.6

FIGURE C.49 Mixture 2 Unconditioned Phase Angle (20C)

FIGURE C.50 Mixture 2 Moisture Conditioned Phase Angle (20C)

FIGURE C.51 Mixture 2 Unconditioned Phase Angle (40C)

FIGURE C.52 Mixture 2 Moisture Conditioned Phase Angle (40C)

FIGURE C.53 Mixture 3 Unconditioned Phase Angle (20C)

FIGURE C.54 Mixture 3 Moisture Conditioned Phase Angle (20C)

FIGURE C.55 Mixture 3 Unconditioned Phase Angle (40C)

FIGURE C.56 Mixture 3 Moisture Conditioned Phase Angle (40C)

FIGURE C.57 Mixture 4 Unconditioned Phase Angle (20C)

FIGURE C.58 Mixture 4 Moisture Conditioned Phase Angle (20C)

FIGURE C.59 Mixture 4 Unconditioned Phase Angle (40C)

FIGURE C.60 Mixture 4 Moisture Conditioned Phase Angle (40C)

FIGURES C.61, C.62, C.63, and C.64 Unconditioned Phase Angle at 4, 6, 8, and 10% Air Voids Contents (20C)

FIGURES C.65, C.66, C.67, and C.68 Unconditioned Phase Angle at 4, 6, 8, and 10% Air Voids Contents (40C)

FIGURES C.69, C.70, C.71, and C.72 Moisture Conditioned Phase Angle at 4, 6, 8, and 10% Air Voids Contents (20C)

FIGURES C.73, C.74, C.75, and C.76 Moisture Conditioned Phase Angle at 4, 6, 8, and 10% Air Voids Contents (40C)

Appendix D – Beam Fatigue Results

TABLE D.1 Mixture 1 Beam Fatigue Results

Air Voids (%)	Air Voids Average (%)	Conditioning Method	S ₀ (MPa)	S ₀ Average (MPa)	Phase Angle	Phase Angle Average (deg)	Initial Dissipated Energy (MPa)	Initial Dissipated Energy Average (MPa)	Cumulated Dissipated Energy (MPa)	Cumulated Dissipated Energy Average (MPa)	Nf	Nf Average (MPa)
2.91	3.8	Air	6477	6044	26.6	26.9	0.619	0.60	59.761	60.11	140740	149205
4.79		Air	5611		27.2		0.59		60.462		157670	
5.47	6.1	Air	5543	5258	25.1	25.3	0.513	0.51	31.909	33.08	82740	89830
6.67		Air	4972		25.5		0.505		34.243		96920	
7.16	7.6	Air	5907	5407	23.8	25.0	0.514	0.51	42.621	43.60	120140	123705
8.03		Air	4906		26.1		0.503		44.578		127270	
9.85	10.5	Air	6257	5178	21.3	21.3	0.652	0.53	13.637	20.45	36220	70610
11.24		Air	4099		21.2		0.404		27.265		105000	
4.07	4.4	Uncond.	3663	3899	31.6	30.2	0.428	0.46	97.288	70.77	360980	244997
4.15		Uncond.	4248		29.4		0.504		73.763		229760	
4.99		Uncond.	3786		29.5		0.453		41.263		144250	
5.77	6.3	Uncond.	4322	3887	29	29.6	0.484	0.45	69.588	65.77	200270	215745
6.80		Uncond.	3451		30.1		0.414		61.942		231220	
7.71	7.9	Uncond.	3124	3236	29.4	29.1	0.391	0.40	55.759	44.59	227510	177750
8.16		Uncond.	3347		28.7		0.406		33.422		127990	
9.84	9.9	Uncond.	3166	2709	27.5	29.6	0.393	0.35	55.858	42.56	221100	185590
9.96		Uncond.	2251		31.6		0.301		29.252		150080	
3.94	4.2	Moisture	4812	4467	27.6	27.3	0.313	0.43	23.889	31.60	68820	94957
4.38		Moisture	4168		25		0.464		24.12		75050	
4.41		Moisture	4420		29.2		0.512		46.781		141000	
5.01	5.9	Moisture	4149	3799	28.5	28.5	0.47	0.45	31.12	32.96	99610	120705
6.83		Moisture	3449		28.5		0.422		34.796		141800	
7.69	7.8	Moisture	3587	3399	27.5	27.7	0.43	0.41	31.974	20.22	116720	74210
7.82		Moisture	3210		27.8		0.387		8.475		31700	
9.06	9.4	Moisture	3265	3266	30	29.1	0.368	0.36	14.296	11.64	54170	45930
9.65		Moisture	3267		28.2		0.346		8.993		37690	

TABLE D.2 Mixture 2 Beam Fatigue Results

Air Voids (%)	Air Voids Average (%)	Conditioning Methid	S _o (MPa)	S _o Average (MPa)	Phase Angle	Phase Angle Average (deg)	Initial Dissipated Energy	Initial Dissipated Energy Average (MPa)	Cumulated Dissipated Energy	Cumulated Dissipated Energy Average (MPa)	Nf	Nf Average (MPa)
4.05	4.4	Air	7391	7125	25	23.8	0.651	0.603	52.332	57.153	120480	133783
4.55		Air	7149		23.2		0.596		49.73		110750	
4.74		Air	6836		23.3		0.561		69.396		170120	
5.61	5.7	Air	7426	7343	22	20.8	0.539	0.553	62.657	56.214	154880	135080
5.78		Air	7259		19.6		0.566		49.771		115280	
7.53	8.0	Air	6270	6705	24	21.9	0.557	0.525	40.21	47.790	98900	126710
8.41		Air	7140		19.8		0.492		55.37		154520	
9.18	9.6	Air	6271	6334	20.9	21.4	0.486	0.483	38.257	45.168	107040	122555
10.07		Air	6396		21.8		0.48		52.078		138070	
3.99	4.3	Uncond.	7114	6451	24.5	25.1	0.621	0.589	92.647	85.873	219630	214477
4.00		Uncond.	5838		27.2		0.57		72.269		190670	
4.97		Uncond.	6401		23.7		0.577		92.702		233130	
5.68	5.7	Uncond.	5564	5822	26.1	26.0	0.558	0.564	58.526	61.844	157630	163090
5.77		Uncond.	6080		25.9		0.569		65.162		168550	
7.08	7.6	Uncond.	4681	4894	26.7	25.7	0.494	0.496	51.282	50.153	160250	155230
7.76		Uncond.	5063		25.5		0.518		44.701		138430	
7.84		Uncond.	4937		24.8		0.475		54.476		167010	
9.02	9.9	Uncond.	5421	4592	25.5	25.7	0.514	0.453	56.232	59.844	149420	193377
9.08		Uncond.	4251		27.1		0.448		71.063		236790	
11.64		Uncond.	4105		24.5		0.397		52.238		193920	
3.49	3.9	Moisture	5097	5223	25.4	25.2	0.507	0.517	7.158	8.760	23560	25057
3.75		Moisture	4783		26.3		0.501		8.265		22900	
4.55		Moisture	5789		24		0.5428		10.858		28710	
5.48	5.8	Moisture	4700	4671	26.6	25.9	0.49	0.472	9.944	7.767	27160	23210
5.86		Moisture	3968		26.7		0.439		4.028		13220	
6.01		Moisture	5344		24.4		0.486		9.33		29250	
8.10	8.3	Moisture	4336	4234	25.3	26.0	0.427	0.421	5.376	5.311	17310	18015
8.46		Moisture	4132		26.6		0.415		5.246		18720	
9.27	9.8	Moisture	3462	3357	25.9	25.5	0.376	0.377	4.537	4.794	17560	18060
10.27		Moisture	3252		25.1		0.378		5.051		18560	

TABLE D.3 Mixture 3 Beam Fatigue Results

Air Voids (%)	Air Voids Average (%)	Conditioning Method	S _o (MPa)	S _o Average (MPa)	Phase Angle	Phase Angle Average (deg)	Initial Dissipated Energy	Initial Dissipated Energy Average (MPa)	Cumulated Dissipated Energy	Cumulated Dissipated Energy Average (MPa)	Nf	Nf Average (MPa)
3.77	4.4	Air	6647	6216	25.5	24.3	0.602	0.558	27.945	25.083	68510	59915
4.97		Air	5784		23		0.514		22.22		51320	
5.42	5.9	Air	6557	6602	24.6	24.0	0.556	0.562	15.116	18.289	38560	46300
6.43		Air	6647		23.3		0.568		21.462		54040	
7.44	7.7	Air	6361	5652	23.6	24.4	0.541	0.503	9.68	9.046	25890	26345
7.98		Air	4942		25.2		0.464		8.412		26800	
9.11	9.7	Air	5200	4934	21.2	22.9	0.415	0.413	13.975	11.842	49840	41485
10.22		Air	4667		24.6		0.41		9.709		33130	
4.15	4.5	Uncond.	6210	5684	28.1	27.3	0.569	0.537	23.854	28.703	63640	81265
4.85		Uncond.	5157		26.4		0.505		33.552		98890	
5.21	6.1	Uncond.	5415	4768	25.9	26.1	0.436	0.432	21.98	23.410	57880	76675
6.98		Uncond.	4120		26.3		0.427		24.84		95470	
8.07	8.3	Uncond.	4376	4240	27.1	27.2	0.485	0.465	13.921	20.809	44600	69405
8.49		Uncond.	4103		27.2		0.445		27.697		94210	
9.44	9.6	Uncond.	3342	3509	27.7	27.3	0.365	0.380	15.174	18.919	60450	71825
9.84		Uncond.	3676		26.8		0.395		22.664		83200	
3.15	3.8	Moisture	4360	4749	29	27.5	0.449	0.485	4.575	5.481	16440	16970
4.37		Moisture	5137		26		0.521		6.387		17500	
6.39	6.4	Moisture	3451	3901	26.8	27.2	0.392	0.420	3.279	3.823	12660	14575
6.47		Moisture	4351		27.5		0.448		4.367		16490	
7.11	7.2	Moisture	3356	3448	26.8	27.6	0.351	0.363	2.551	3.163	12110	14175
7.31		Moisture	3539		28.3		0.374		3.775		16240	
9.49	9.5	Moisture	2882	2942	27.6	27.6	0.356	0.361	3.596	2.763	14610	11340
9.60		Moisture	3002		27.5		0.365		1.93		8070	

TABLE D.4 Mixture 4 Beam Fatigue Results

Air Voids (%)	Air Voids Average (%)	Conditioning Method	S ₀ (MPa)	S ₀ Average (MPa)	Phase Angle	Phase Angle Average (deg)	Initial Dissipated Energy	Initial Dissipated Energy Average (MPa)	Cumulated Dissipated Energy	Cumulated Dissipated Energy Average (MPa)	Nf	Nf Average (MPa)
4.06	4.4	Air	8098	8464	26.1	23.6	0.732	0.687	24.556	21.069	51550	43893
4.58		Air	8670		22.7		0.674		15.499		31560	
4.69		Air	8624		22		0.654		23.153		48570	
5.89	6.5	Air	8924	8051	21.1	22.1	0.641	0.614	8.3501	15.031	16610	34253
6.63		Air	7891		23.9		0.616		22.218		51200	
6.89		Air	7337		21.4		0.586		14.524		34950	
8.55	8.7	Air	7650	6972	19.8	21.4	0.526	0.527	14.477	11.585	38540	30613
8.71		Air	7649		20.4		0.552		12.443		31710	
8.88		Air	5618		24.1		0.504		7.836		21590	
10.02	10.2	Air	5420	5696	22	23.1	0.473	0.496	9.545	10.460	25090	28690
10.46		Air	5972		24.1		0.518		11.374		32290	
3.60		Uncond.	7281		26.2		0.663		31.06		64920	
4.61	4.1	Uncond.	6585	6933	27.2	26.7	0.64	0.652	26.636	28.848	59790	62355
5.93		Uncond.	5618		26.8		0.56		33.983		99390	
6.27		Uncond.	6144		25.7		0.568		21.879		53460	
7.10	7.2	Uncond.	5831	5753	25.2	25.7	0.542	0.549	15.39	19.657	41910	52250
7.25		Uncond.	5674		26.2		0.555		23.924		62590	
9.10		Uncond.	4983		26.3		0.508		14.517		41620	
9.30	9.2	Uncond.	5080	5032	25.4	25.9	0.504	0.506	24.417	19.467	70910	56265
4.59		Moisture	5559		25.6		0.555		4.162		11880	
4.89		Moisture	5827		26.1		0.567		2.529		6800	
6.22	6.3	Moisture	4517	4490	26.4	26.7	0.486	0.481	3.388	3.539	10480	11175
6.45		Moisture	4462		27		0.476		3.69		11870	
8.68		Moisture	3689		25.4		0.415		2.478		9120	
8.72	8.7	Moisture	3764	3727	26	25.7	0.423	0.419	2.416	2.447	8290	8705
9.77		Moisture	3026		26.2		0.315		0.682		2830	
10.20		Moisture	3594		27.6		0.405		1.664		5610	
	10.0			3310		26.9		0.360		1.173		4220

(a)

(b)

(c)

FIGURES D.1 (a) Unconditioned, (b) Oven-Aged, and (c) Moisture Conditioned Initial Stiffness

(a)

(b)

FIGURE D.2 Initial Flexural Stiffness Comparison of (a) Unconditioned and Oven-Aged; and (b) Unconditioned and Moisture Conditioned