**THE STRENGTH OF BITUMINOUS
MIXTURES & THEIR BEHAVIOR
UNDER REPEATED LOADS**

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THE STRENGTH OF BITUMINOUS MIXTURES AND THEIR BEHAVIOR
UNDER REPEATED LOADS, PART II

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INTRODUCTION

At last year's meeting, the authors (1) presented two fundamental, mathematical relationships for sheet-asphalt mixtures tested in the unconfined state. The first expression related the strength of these mixtures to the temperature and the rate of deformation. The second expression related the number of repetitions of applied stress necessary to cause failure as defined by some suitable criterion, the temperature and the rate of deformation.

Since that time the investigation has been continued to include the evaluation of strength and deformation characteristics of a sheet-asphalt mixture subjected to repeated loads and with varying degrees of lateral support. The information from this study was used to further verify the above mentioned relationships. The inclusion of lateral support as a variable made this study more realistic from the standpoint of actual field performance in bituminous pavement where some degree of confinement is known to exist. Lateral support was obtained by use of the triaxial cell.

To establish the fact that the relationship among strength, temperature, and rate of deformation was valid for bituminous-aggregate mixtures other than sheet asphalt, specimens were formed from a bituminous concrete mixture with a maximum aggregate size of 1/2 inch. This comparison was limited to relationships determined from tests performed in the unconfined state.

Finally, since it is known that a severe condition of loading for a flexible pavement or bituminous mixture is a stationary load, a test was

included to evaluate the sheet-asphalt mixture under this condition. Variables of temperature and applied stress were included, and the testing was limited to the sheet-asphalt mixture tested in the unconfined state.

MATERIALS

The mixture chosen for the major portion of this study was a sheet-asphalt mixture designated as Mixture II. This designation is used for continuity with the data presented by the authors in last year's paper (1). In order to check portions of the findings based upon the sheet-asphalt mixture for wider application in the field of bituminous mixtures, specimens were molded from a crushed limestone having a 1/2 inch maximum size. This bituminous-concrete mixture conformed to the specifications for Indiana AH type B Surface Course and is so designated.

A complete description of the aggregate and asphaltic cement used in this study are included in two separate sections. Although the sand, mineral filler and asphalt are the same as those used previously, their description is included here for the convenience of the reader.

Aggregates

The sand used in this study was a local, natural material obtained from a river terrace. The gradation chosen met the requirements of A.S.T.M. D978-54 Standard Specifications for Asphaltic Mixtures, for Sheet Asphalt Pavements, Surface Course, Grading No. 2 (2) and Asphalt Institute 100-XI Sheet Asphalt Surface Course (3). The sieve analysis of the gradation is presented in Table 1 and depicted graphically in Figure 1.

As the terrace sand was deficient in the minus 200 material, this

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Table 1
Sieve Analysis of Sheet-Asphalt and
Indiana AH Type B Surface Course Mixtures
(Percent by Weight)

<u>Sieve</u>		<u>Grading</u>	
Passing	Retained	Sheet-Asphalt	AH Type B
—	1/2 inch	0	0
1/2 inch	3/8 inch	0	9
3/8 inch	No. 4	0	29
No. 4	No. 8	0	20
No. 8	No. 16	7	12
No. 16	No. 50	34	17
No. 50	No. 100	27	6
No. 100	No. 200	15	3
No. 200	—	17	4

GRADATION CURVES FOR MIXTURES USED IN THE STUDY

FIGURE 1

fraction was obtained by adding pulverized limestone.

The bituminous-concrete mixture containing the 1/2-inch maximum size aggregate used crushed limestone obtained from a quarry at Greencastle, Indiana as both the coarse and fine aggregate. The gradation chosen for this mixture meets the Indiana AH type B Surface Course requirements (4). The sieve analysis of this gradation is presented in Table 1 and depicted graphically in Figure 1.

Specific gravity and absorption tests conforming to A.S.T.M. designations C127-42 and C128-42 were conducted on the aggregates. The test results are presented in Table 2.

The control of the gradations was obtained by drying the aggregate and recombining it by weight in the desired proportions.

Asphaltic Cement

Only one asphaltic cement was used throughout this study; it was a No. 65 Paving Cement (A.S.T.M. Penetration Grade 60-70) obtained from the Texas Company, Port Neches, Texas. Several standard A.S.T.M. tests were conducted on the asphaltic cement in the laboratory. The results of these tests are shown in Table 3.

The asphalt content used in the sand-asphalt mixture was obtained by using the Hubbard-Field design procedure (5). The asphalt content for the Indiana AH type B Surface Course gradation was selected from field experience. The asphalt contents of the two gradations are shown in Table 4.

PROCEDURE

The procedures used in this investigation are discussed in two

Table 2
Physical Properties of Aggregates

<u>Aggregate</u>	<u>Bulk Sp. G.</u>	<u>Apparent Sp. G</u>	<u>% Absorption</u>
Greencastle Limestone	2.63	2.71	1.39
Lafayette Sand	2.54	2.67	2.04
Mineral Filler	—	2.73	—

Table 3
Physical Properties of Asphaltic Cement

<u>Test</u>	<u>Value</u>
Penetration (100 gms, 5 sec., 77°F) 1/100 cm.	66
Specific Gravity 77° F/77° F	1.015
Ductility (77° F, 5 cm/min.) cm.	150 †
Solubility in C Cl ₄ , %	99.8 †
Softening Point, °F	125

Table 4

Asphalt Content of Mixtures Used

Asphalt Content, Percent
Based Upon Weight of Aggregates

Sheet-Asphalt Mixture
Indiana AH Type B

9.0
7.0

sections: (a) preparation of test specimens, and (b) methods of testing.

Preparation of Test Specimens

The mixtures used in investigation were those in which the aggregate and asphalt were heated separately and then combined in a mixing operation. The individual aggregate fractions were combined to give the correct gradations. (See Figure 1.) The aggregate was heated in an electric oven to a temperature of about 325°F. The asphalt was heated in a gas oven to a temperature of 300°F.

For the sheet asphalt, the constituents were mixed by hand in a heated porcelain bowl using a metal spoon for a period of two minutes. The coated material was then molded into a specimen two inches in diameter and four inches in height by a double-plunger compaction method which included rodding the material into the mold.

For the bituminous concrete, the constituents were blended in a modified Hobart mixer with a flat-bottom mixing bowl and blade. The mixture was then molded into a specimen three inches in diameter and six inches in height using double plunger compaction with rodding.

The molding procedure consisted of placing the hot bituminous-aggregate mixture into a hot steel mold in three equal lifts. Each lift was tamped thirty times with a heated rod. A hydraulic-compaction device was used to compact the specimen. (See Figure 2.) To control the densities of the specimens, care was taken to introduce the same amount of material into the mold each time. The specimen height was the determining factor for establishing the static axial load which was applied to each end of the specimen. An Ames dial device was used to insure that each specimen was compacted to the proper height. (See Figure 2.) The specimen

Figure 2. Compaction Equipment Showing Ames Dial Device

was left in the compaction device under load for two minutes after which the load was released and the specimen removed immediately from the mold. The specimens were allowed to cure for two days in laboratory air at a temperature of $75 \pm 5^{\circ}\text{F}$. The specimen's height, diameter, and weight were obtained at this time for bulk density calculations. The specimens were then stored in a freezer at a temperature of 20°F . until used in tests.

Methods of Testing

The bituminous-concrete specimens were used to extend the validity of the relationship among maximum compressive stress, temperature of test, and rate of deformation established for mixtures of sheet-asphalt type. Specimens were tested to failure in the unconfined state at three rates of deformation: 0.2, 0.02, and 0.002 in./min. At each of these rates, three temperatures were used: 40° , 100° , and 140°F . These temperatures were maintained during the test by means of a water bath. After reaching room temperature from cold storage, the specimens were placed in the bath for one-half hour before the start of the test.

Specimens molded from the sheet-asphalt mixture were tested with varying degrees of lateral confinement for two reasons: (a) to obtain results which could be used to check the validity of the relationship of temperature, rate of deformation, and maximum compressive stress, previously established for the unconfined condition, for varying degrees of confinement, and (b) to obtain the maximum compressive stress values which were used later for determining the magnitudes of the cycled, applied stresses for the confined, repeated-load test sequence.

Specimens which were tested for the purposes stated above were

tested to failure at two confining pressures: 15 and 30 psi. Three rates of deformation were used: 0.2 in./min., 0.02 in./min., and 0.002 in./min. Three temperatures were used: 40°, 100°, and 140°F. A water bath was used to maintain the test temperatures.

The confined, repeated-load sequence was performed by utilizing a combination mechanical and hydraulic system. (See Figure 3.) The rate of deformation was controlled by the mechanical testing machine. A hydraulic jack was used in the system to obtain the immediate release of load when the desired load on the specimen was reached. The deformation was measured directly from the top of the specimen.

Specimens tested in the confined, repeated-load sequence also were tested at two confining pressures: 15 and 30 psi. Three rates of deformation were used: 0.2, 0.02, and 0.002 in./min. Three temperatures were used: 40°, 100°, and 140°F. For each test condition loads were cycled which were equal to 50 percent and 25 percent of the maximum compressive stress for that particular test condition. Deformation measurements were taken so that the elastic rebound and permanent deformation could be determined. A sufficient period of time was allowed between load applications in order to permit most of the retarded rebound to take place.

The static, unconfined test series was performed at five temperatures: 40°, 55°, 70°, 100°, and 140°F. A consolidation frame was used to apply the static load. (See Figure 4.) The static load was placed on the specimen and the deformation at various time intervals was recorded. The criteria for halting the test was the ability or the inability of the specimen to withstand the applied test load. A specimen withstood the applied test load if the deformation increased only 0.001 inches

Figure 3. General View of Confined, Repeated-Load Apparatus Ready for Test (Shown without water bath)

Figure 4. General View of Static Load Apparatus Ready for Test (Shown without water bath)

per 100 seconds for 400 seconds. A specimen failed to withstand the applied test load when the deformation rate per unit time increased rather than decreased. When the deformation rate per unit time increased, it was noted that complete failure of the test specimen was imminent.

RESULTS

In this investigation, strength-deformation data of bituminous mixtures were obtained by means of conventional compression tests and by means of repeated-load tests. These tests are described in the section dealing with procedure. The aggregate types and gradations are discussed in the materials section.

The type of test, the mixture tested, and the variables studied for each test series are outlined as follows:

1. Compressive Strength Tests

A. Unconfined Compression Tests

Indiana AH type B Surface Course Mixture

Variables: (a) confining pressure
(b) temperature
(c) rate of deformation

B. Confined Compression Tests

Sheet-asphalt Mixture

Variables: (a) confining pressure
(b) temperature
(c) rate of deformation

C. Unconfined Static Load Tests

Sheet-asphalt Mixture

Variables: (a) applied stress

(b) temperature

II. Repeated Load Tests

A. Unconfined, Repeated Load Test

Sheet-Asphalt Mixture

Variables: (a) applied stress

(b) temperature

(c) rate of deformation

B. Confined, Repeated Load Test

Sheet-Asphalt Mixture

Variables: (a) confining pressure

(b) applied stress

(c) temperature

(d) rate of deformation

The results in both tabular and graphical form are presented following the above outline.

Unconfined Compression Tests

In the unconfined compression series of tests, the effect of temperature and rate of deformation upon the maximum unconfined compressive stress of specimens molded from a bituminous-concrete mixture having a one-half inch maximum-sized aggregate was determined. Table 5 shows the results of this study. The results from Table 5 are depicted graphically in Figure 5. In Figure 5 the maximum unconfined compressive stress is plotted versus the rate of deformation for the various temperatures.

In last year's paper (1), a mathematical equation relating maximum

Table 5

Unconfined Compression Test Results for Indiana AH Type B Mixture

Temperature of	Rate of Deformation - in./min.		
	0.002	0.05	0.2
Maximum Compressive Stress (psi)			
40	427 ¹	565 ² 703 ³	1043 ¹
100	72 ² 64 ³	110 ² 96 ³	175 ² 145 ³
140	32 ¹	45 ² 34 ³	70 ¹

¹ Values used in establishing mathematical relationship for Indiana AH Type B Surface Mixture.

² Calculated values.

³ Observed test values taken after the relationship was established.

RELATIONSHIP BETWEEN RATE OF DEFORMATION AND MAXIMUM COMPRESSIVE STRESS AT VARIOUS TEMPERATURES

RATE OF DEFORMATION, IN./MIN. (LOG SCALE)

FIGURE 5

compressive stress, temperature, and rate of deformation are presented as follows:

$$\sigma_c = A \exp \left(B \dot{\epsilon}^C \right) \exp \left(\frac{D}{T} \right) \quad (1)$$

- Where: σ_c = maximum compressive stress, psi
 $\dot{\epsilon}$ = rate of deformation, in./in.
 T = temperature, °F
 $A, B, C,$ and D = constants.

The numerical values of the constants for the model were determined by using a least squares approach (6). For the steel-asphalt mixture tested, this mathematical model showed a high degree of association when tested by use of multiple linear regression analysis (7).

With this close correlation, then, by using the above model, it would be possible to define the relationship among maximum compressive stress, temperature, and rate of deformation for any chosen mix with a limited number of tests. From a limited amount of laboratory test data on specimens loaded from the bituminous-concrete mixture, the parameters of the model were evaluated and the resulting expression was used as a prediction equation to estimate unconfined strength values for various conditions of temperature and rate of deformation. To check the prediction, tests were made to obtain sufficient data to get a comparison between predicted values and observed values. The predicted values and observed values are denoted in Table 3 and Figure 3. Good correlation was observed at all levels between the observed values and the predicted values. This would indicate that the general expression was valid for the unconfined condition for bituminous-concrete mixtures.

Confined Compression Tests

The original model (equation 1) was derived for results obtained

from the unconfined compression test. It was hoped that the original model would have wider applicability than for just the unconfined test condition. Since mixtures are loaded in the field in such a manner that some degree of lateral support is provided, it was decided to check the validity of equation 1 by performing compression tests at various confining pressures.

Compression tests were made at two confining pressures: 15 and 30 psi. At each of the confining pressures and at the extreme values of temperature (40° F. and 140° F.) and rate of deformation (0.002 in./min. and 0.2 in./min.) specimens from the sheet-asphalt mixture were tested to failure. The results from tests at these test conditions were used to evaluate the parameters of the regression equation. The regression equations, once established, were used to predict maximum compressive stresses at the other test conditions (100°F. at 0.002, 0.02, and 0.2 in./min. and 0.02 in./min. at 40° and 140° F.). Specimens were then tested at the above test conditions at both 15 and 30 psi. The predicted values and the observed values for this series of tests are presented in Table 6 along with values for the unconfined compression tests, taken from last year's data (1). It should be noted that there are discrepancies in the unconfined test data for the 40° F. level which are attributed to experimental error.

From observation of the results of tests on sheet-asphalt given in Table 6, it can be seen that the introduction of lateral support increases the maximum compressive strength of the mixture more at the higher temperatures than at lower temperatures. It is at these higher temperatures that the mixture is quite plastic in character. At 40° F. the mixture loses most of its plastic nature and is relatively "stiff".

Table 6

Compression Test Results for Mixture II (Sheet Asphalt)

Temperature F	Lateral Pressure - psi	Rate of Deformation - in./min.		
		0.002	0.02	0.2
Maximum Compressive Stress (psi)				
40	0	420	464	1035
	15	390	609	1080
	30	459	680	1100

100	0	21	46	100
	15	103	114	177
	30	168	195	222

140	0	8	16	26
	15	94	96	104
	30	157	170	173

Therefore, the introduction of lateral pressure at 40° F. resulted only in a small increase in the maximum compressive strength of the mixture. Also, it must be noted that for 40° F. test condition the confining pressures used were a small percentage of the maximum compressive stress. The proportional change of the maximum compressive strength of the mixture with temperature at any one rate of deformation is less pronounced under conditions of confinement than under conditions where no confinement exists. With the inclusion of the results at 100° F. into the regression analysis a much better fitting regression equation could be found than was obtained using limited data from the extreme conditions of temperature and rate of deformation.

Figure 6 shows both the predicted values and the observed values for a confining pressure of 15 psi. Good correlation between observed and predicted values was noted except in the case of tests made at 100°F. For all three rates of deformation at 100° F. the predicted values were higher than the observed values.

Figure 7 shows the predicted values and the observed values for a confining pressure of 30 psi. Again, good correlation between the predicted and observed values was noted except for tests made at the 100° F. temperature. For all three rates of deformation at 100°F., the predicted values were higher than the observed values.

The lack of correlation at the 100° F. level between observed results and those predicted from an equation based upon tests made at the four extremes of rate and temperature, (Figs. 6 and 7) is in contrast to the unconfined test results in the sheet-asphalt mixture(1). This indicates that the introduction of confining pressure changes the relationship between compressive strength and temperature sufficiently that a

RELATIONSHIP BETWEEN RATE OF DEFORMATION AND MAXIMUM COMPRESSIVE STRESS AT VARIOUS TEMPERATURES

RATE OF DEFORMATION, IN./MIN. (LOG SCALE)

RELATIONSHIP BETWEEN RATE OF DEFORMATION AND MAXIMUM COMPRESSIVE STRESS AT VARIOUS TEMPERATURES

RATE OF DEFORMATION IN./MIN. (LOG SCALE)

FIGURE 7

prediction equation based upon tests made at the four extremes of rate and temperature is inaccurate for intermediate temperatures. The addition of an interaction term involving the confining pressure and temperature to the original model might increase its effectiveness for application to the case of tests made under the confined condition.

Unconfined Static Load Tests

The unconfined static load test series was performed to evaluate the ability of a sheet-asphalt specimen to withstand a static load at five temperatures: 40°, 55°, 70°, 100°, and 140° F. Some typical results of these tests are shown graphically in Figures 8 and 9 where the deformation is plotted versus time (log scale) for various applied stresses at one temperature. The maximum static stress the specimen withstood (as explained in the section on Methods of Testing) at various temperatures is presented in Table 7 and graphically depicted in Figure 10 where the maximum unconfined static stress is plotted against the temperature.

The data from the unconfined static load tests show again that temperature had a great influence upon the maximum stress that a specimen could withstand. The change in character of the mixture with temperature is shown quite plainly by comparing the time-deformation curve for 40° F. as shown in Figure 8 with the time-deformation curve for 140° F. as shown in Figure 9. At 140° F. the mixture was quite plastic in character as evidenced by the curve for the applied stress of 20 psi. Between 140 and 200 seconds the amount of deformation increased rapidly from a value of 0.05 inch to a condition where failure was imminent and the load had to be removed immediately in order to obtain a rebound value. At 40° F. the mixture exhibited considerable viscous resistance. The curve for

RELATIONSHIP BETWEEN DEFORMATION AND TIME FOR VARIOUS STATIC LOADS

TIME - SECONDS (LOG SCALE)
FIGURE 8

RELATIONSHIP BETWEEN DEFORMATION AND TIME FOR VARIOUS STATIC LOADS

TIME - SECONDS (LOG SCALE)

FIGURE 9

RELATIONSHIP BETWEEN DEFORMATION AND TIME FOR VARIOUS STATIC LOADS

FIGURE 9

Table 7

Unconfined Static Load Test Results for Mixture II (Sheet Asphalt)

Temperature	Ultimate Static Stress - psi
40	350
55	200
70	100
100	20
140	10

RELATIONSHIP BETWEEN MAXIMUM STATIC STRESS AND TEMPERATURE

FIGURE 10

the applied stress of 375 psi was sloping upward gradually even after a deformation of almost 0.2 inches during a time interval of 2,500 seconds.

Unconfined, Repeated Load Tests

In last year's paper, the authors (1) reported the results of a study in which the number of repetitions of applied stress, temperature, and rate of deformation were related for a sheet-asphalt mixture tested in the unconfined condition. It was found that for each test condition there appeared to be an applied stress that could be cycled a number of times without excessive shear deformation occurring. This stress in each case was labeled as the endurance limit. The results of that particular study are depicted graphically in Figure 11 where the endurance limit stress is shown as a limiting value at the extreme right of the plot.

The family of curves shown in Figure 11 was expressed in a general mathematical model which related the applied stress, number of load applications, temperatures, and rate of deformation. The equation was as follows:

$$x_c = \left[E \cdot 10^{-\alpha(n-1)\beta} + (1-E) \right] x_0$$

- Where
- x_c = applied, cycled, unconfined compressive stress, psi
 - x_0 = maximum unconfined compressive stress for the test condition (fixed rate of deformation and temperature)
 - n = number of load repetitions necessary to cause excessive shear deformations
 - E, α, β = parameters that are dependent upon mixture composition.

**APPLIED STRESS - ENDURANCE LIMIT
RELATIONSHIPS AT VARIOUS TEMPERATURES
AND RATES OF LOADING**

FIGURE II

From this model it can be seen that when $n = 1$, $x_c = x_0$. This is not exactly correct according to the failure criterion developed since this means the specimen could withstand one cycle of the maximum unconfined compressive stress. However, in the interest of a general expression, it was felt that the discrepancy was not a major source of error. It can be seen that as the magnitude of the applied stress is decreased, the number of loading cycles that a specimen will withstand before failure becomes greater. The limiting value for x_c , which was called the endurance limit, is approached as (n) gets large and the term $E \cdot 10^{-(n-1)}$ approaches 0. In this situation, the endurance limit equals $(1 - E)x_0$. For the mixture used in this series of tests, $(1 - E)$ was found to be about 0.25. Regression analysis was used to establish the numerical values of the parameters.

When comparing results of the unconfined repeated load test which are shown in Figure 11 with the results of the unconfined, static load test which are presented in Table 7, it would appear that the unconfined, repeated load test is more severe. For example, the endurance limit for 40° F. and a rate of deformation of 0.002 in./min. (the slowest rate) was 105 psi, while at 40° F. the maximum static stress was 350 psi; for 100° F. and a rate of deformation of 0.002 in./min. the endurance limit was 8 psi, while at 100° F. the maximum static stress was 20 psi; for 140° F. and a rate of deformation of 0.002 in./min. the endurance limit was 2 psi while at 140° F. the maximum compressive stress was 10 psi. The failure criterion which was evolved for the unconfined, repeated load test was more severe in mixture evaluation than was the failure criterion established for the static unconfined load test. Excessive shear deformations were noted in the unconfined, repeated load test before a large amount of aggregate

particles were displaced. Therefore, the cross sectional area of the specimen under test did not enlarge to any extent. In the case of the static load test, some specimen bulging was noted which meant that the cross sectional area of the specimens under test was increasing. This meant that although the applied load remained constant during the test the applied stress was decreasing. This fact was not taken into account in determining the maximum static stress.

Confined, Repeated Load Tests

The confined, repeated-load test series was performed to determine the effect of lateral support upon the relationship among the number of repetitions of applied stress, temperature, and rate of deformation.

Some typical results of these tests are shown graphically in Figures 12 and 13. The permanent deformation is plotted against the number of load applications for different applied stresses at various temperatures and rates of deformation.

It can be noted that the relationship starts out as a straight line when the permanent deformation is plotted against the logarithm of the number of load repetitions. At some stage, dependent upon the stress condition, the plot deviates sharply from the straight line, as is shown in the upper curves of the two figures. What occurs at this point is a matter of conjecture. It is hypothesized that the asphalt film between aggregate particles is being reduced in dimension until some critical thickness is reached. At this point, in order to sustain the load, adjustment in the specimen takes place by reorientation of the aggregate particles themselves. This gives rise to excessive shear deformation which are measured as permanent deformations. The point where excessive

RELATIONSHIP BETWEEN PERMANENT DEFORMATION
AND NUMBER OF LOAD REPETITIONS
FOR VARIOUS APPLIED STRESSES

FIGURE 12

RELATIONSHIP BETWEEN PERMANENT DEFORMATION
AND NUMBER OF LOAD REPETITIONS
FOR VARIOUS APPLIED STRESSES

FIGURE 13

shear deformation occurs was taken as the failure criterion.

Under this hypothesis, the elastic part of the deformation would take place principally in the asphalt film which is bound firmly to the aggregate in a polymolecular layer. As the applied stress decreased, the number of loading cycles necessary to cause deviation from a straight line plot of deformation versus log of load repetitions increased. When the applied stress was 25 percent of the maximum compressive stress, no deviation was observed for the number of load repetitions used in this sequence of observations. This stress in each case was labeled as the endurance limit. At 50 percent of the maximum compressive stress excessive shear deformations were noted in all cases. This indicates that the endurance limit lies between 25 and 50 percent. No attempt was made to determine the endurance limit more closely.

The number of load repetitions necessary to cause failure under various confined test conditions is presented in Table 8 and shown graphically in Figure 14 where the applied stress (log scale) is plotted against the number of load applications necessary to cause failure for the various test conditions. The endurance limit stress is shown as a limiting value on the extreme right of the plot.

From the data of Table 8 it can be seen that for a temperature of 40° F and a rate of deformation of 0.2 in./min., increasing the confining pressure from 0 psi to 15 psi and then to 30 psi increased the endurance limit from 260 psi, to 270 psi, and to 275 psi respectively. Thus, it is shown that the introduction of lateral support at that test level did not affect the endurance limit appreciably. At that temperature and rate of deformation the viscosity of the binder is such that the introduction

Table 8

Confined Repeated Load Test Results for Mixture II (Sheet Asphalt)

Temperature F	Lateral Pressure - psi	% Max. Comp. Stress	Rate of Deformation - in./min.		
			0.002	0.02	0.2
Load Repetitions Necessary to Cause Failure. ¹					
40	15	50	5		5
	15	25	**		**
	30	50	7		5
	30	25	**		**

	15	75		5	
100	15	50		9	
	15	25		**	
	30	75		4	
	30	50		8	
	30	25		**	

140	15	50	6		7
	15	25	**		**
	30	50	5		6
	30	25	**		**

¹ For definition of failure, see text.

**Number of load repetitions used during test did not cause failure.

APPLIED STRESS - ENDURANCE LIMIT
RELATIONSHIPS AT VARIOUS TEMPERATURES
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FIGURE 14

of a confining pressure in the ranges of 0-30 psi had little effect upon the endurance limit. One wouldn't expect the introduction lateral support to affect the endurance limit at 40° F. since there was little increase in the maximum compressive stress between 0 and 30 psi, at that temperature.

At the other extreme of test conditions, a temperature of 140° F. and a rate of deformation of 0.002 in./min., increasing the confining pressure from 0 psi to 15 psi to 30 psi increased the endurance limit from 2 psi to 23 psi to 29 psi. In this case the confining pressure had a marked effect upon the endurance limit. At a temperature of 140° F. and 0.002 in./min., the viscosity of the binder was so low that the introduction of the confining pressure "stiffened" the mix appreciably.

Figures 12 and 13 indicate that an applied stress of 25 percent of the maximum compressive stress for each given test condition (represented by the lower line of each figure) could be cycled a number of times without excessive shear deformations occurring. This value was referred to previously as the endurance limit. Since it has been shown previously that the endurance limit for the unconfined condition was approximately 25 percent of the maximum unconfined compressive stress determined at a given set of test condition, it can be stated that the lateral support applied has little effect upon the endurance limit expressed as a percentage of maximum compressive stress.

This is important since it shows that the addition of lateral support doesn't change the basic behavior of the mixture in any unexpected manner. While it was stated that the endurance limit remained at about 25 percent of the maximum compressive stress, it must be remembered that at the lower rates of deformation and the higher temperatures, introducing lateral

support, materially increased the maximum compressive strength of the mixture. Thus, even though the endurance limit was approximately 25 percent of the maximum compressive stress for both the unconfined and the confined condition, the endurance limit for the confined case was numerically much higher for the high temperatures and low rates of deformation than for the unconfined case. A comparison of Figures 11 and 14 will graphically show this. Such a comparison also shows that the curves for the confined, repeated load tests are quite similar to the curves for the unconfined, repeated load tests when permanent deformation versus the log of the number of load repetitions is plotted.

Summary of Results

Since this study was a continuation of one reported last year in which the additional testing included a wider range of mixture composition and compression tests with lateral support, the conclusions derived from the present study are similar to those reported earlier but are applicable to wider ranges of test conditions and mixture composition.

This study was a laboratory one in which the majority of tests were performed on a sheet-asphalt mixture. While varying amounts of lateral support was used in the compression tests of this study in order to more closely approximate the field condition than was the case for the unconfined tests reported last year, the lateral support provided may not have been of the proper magnitude to simulate possible field conditions.

With these limitations in mind, the following conclusions are presented:

1. The relationship developed among the variables of maximum compressive stress (confined and unconfined), temperature and rate of deformation can be used to obtain information concerning the strength of a bituminous-aggregate mixture under many combinations of test conditions. It appears that this relationship can be established with results obtained under a limited number of test conditions.
2. The general relationship established among maximum compressive stress, temperature, and rate of deformation by means of the unconfined compression test appeared to hold true for the same variables when the test was conducted with varying degrees of lateral support.
3. For the sheet-asphalt mixture, the effect of the confining

pressure upon the maximum compressive stress tends to diminish as the confining pressure is increased.

4. For the confined test condition, there was found to be a combination of applied stress and number of load repetitions that resulted in excessive shear deformations. These excessive shear deformations appear in a plot of deformation versus the logarithm of the number of load repetitions as a deviation from a straight line.

5. Under each test condition, both confined and unconfined, there appeared to be an applied stress that could be cycled without excessive shear deformations occurring. This stress was labeled as the endurance limit.

6. The use of lateral support up to 30 psi increased, markedly, the maximum compressive stress at high temperatures, but this magnitude of lateral support had very little, if any, effect upon the maximum compressive stress at the temperature of 40° F.

7. For the mixtures tested in this study, it was found that the endurance limit was approximately 25 percent of the maximum compressive stress for all test conditions used. This endurance limit appears to be an important mix property.

8. The failure criterion which was evolved for the repeated load test was more severe in mixture evaluation than was the failure criterion established for the static, unconfined load test. This resulted in the conclusion that the static, unconfined load test was a less rigorous test for the bituminous mixtures tested than was the unconfined, repeated load test.

9. It appears that a promising means of evaluating the adequacy

of a bituminous mixture for utilization in the field is to perform the confined, repeated load test on a rational specimen at a temperature of 140° F. and a rate of strain of 0.0005 in./min. The degree of confinement to be introduced can not yet be recommended. From previous work on the strength of bituminous mixtures, it is known that some degree of confinement should be used in order to distinguish those mixtures whose strengths are particularly benefited by lateral support.

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