ABRIDGMENTS OF REPORTS RESULTING FROM STUDIES OF PROJECT, "ROAD TEST ON HOT-MIX ASPHALTIC CONCRETE"

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Road (and Laboratory) Tests on Hot-Mix Asphaltic Concrete
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Abridgments of Reports Resulting from Studies of Project, "Road Test on Hot-Mix Asphaltic Concrete"

This report presents in condensed version the results of six studies that evolved from an investigation performed to study factors influencing the design and performance of asphalt paving mixtures in Texas. The complete reports have been submitted to the Texas Highway Department and some of these appear in the Proceedings of the Highway Research Board or the Association of Asphalt Paving Technologists.

CONTENTS

SUMMARY AND CONCLUSIONS

I. The relationship between Hveem stability and specimen height was of a simple linear character and different mixtures produced graphs of nearly identical slopes. This behavior suggests a relatively simple means for determining height-adjusted stabilities from testing specimens of one height. The Texas gyratory-shear compaction method automatically adjusts the compactive efforts for molding different mixtures and quantity of mixture. This effect facilitated the compaction of specimens of different heights but of nearly identical densities.

II. Variations in mixing viscosity for producing asphaltic concrete affected the density and theoretical maximum specific gravity of the material. As the mixing temperature increased the unit weight of specimens increased and the vacuum-saturation specific gravity of the loose mixture increased; however, the resulting amounts of void also increased. Maximum Hveem stability was associated with Saybolt Furol viscosities between 75 and 100 seconds; cohesiometer values increased as mixing temperature increased. The absolute viscosity of recovered asphalt increased as mixing temperature increased.

III. The evaluation of asphaltic concrete by use of the deflectometer showed that the apparatus responded to specimen variables known to affect performance of asphaltic pavements. Test results from the deflectometer showed the following:

1. An optimum asphalt content was associated with maximum fatigue life.

2. The resistance to repeated loads can be maximized by use of (1) rough surface texture aggregate, (2) dense graded aggregate, (3) high viscosity asphalt, and (4) increase of pavement thickness which can reduce the magnitude of stress from an imposed load.

3. Factors that increased fatigue life generally reduced flexibility.

4. Molding of large (18-inch diameter) specimens required that compactive forces impart three dimensional movement to the aggregates.

IV. The study on operator and procedure variables of molding asphaltic concrete indicated the following conclusions:

1. There was no apparent correlation between Hveem stability and compaction method nor with specimen density for the mixtures investigated. However, for these asphaltic concrete mixtures the coefficient of variation for stability was approximately 10 percent.

2. Specimen density variability was reduced for a mixture by using a compaction procedure consisting of a fixed number of gyrations and a constant foot and leveling pressure.

3. Variations in number of gyrations and foot pressure for the molding procedure showed that an optimum compactive effort existed for maximum cohesiometer value. It appears that increased compactive effort over the standard manual THD procedure produces fines that fill the asphalt to give it greater tensile strength; however, excessive compaction effort will further degrade the aggregate with a resultant loss of cohesiometer value.

4. When differences in operator stamina and physical strength are apparent, the standard manual THD molding procedure may produce specimens with the most uniform stability values. This would appear to follow from the procedure's requirement that an "end point" be reached in the compaction operation.

V. The effects of oven curing at 140°F of loose and compacted asphaltic concrete specimens were examined for mixtures containing aggregates with three degrees of absorption capacity. The data showed the following:

1. Oven curing of both loose and molded asphaltic aggregate mixtures for time intervals up to 30 hours did not materially affect the Hveem stability value.

2. The Hveem cohesion values were generally increased with increased curing time. However, the maximum cohesiometer value was obtained at different curing times depending upon the aggregate and grade of asphalt used.

3. Data on the consistency of the recovered asphalt from cured mixtures revealed an expected general increase with increase of curing time.

4. Oven curing of the loose mixture for periods up to 30 hours did not appear to affect densification of the asphalt-aggregate blends.

VI. Evaluation of laboratory mixture design and physical characteristics of road cores warrant the following conclusions:

1. The State's specifications for aggregate gradation on Types C and D generally result in yielding dense graded aggregate blends. However, it is possible to meet specification requirements with an overly gap-graded blend. It is recommended that gradation be expressed in "total percent passing."

2. The sand equivalent test is recommended for use in controlling the cleanliness of aggregates for hot-mix asphaltic concrete. A minimum sand equivalent value of 45 is suggested since the data showed that immersion-compression test requirements were met for such mixtures.

3. The centrifuge kerosene equivalent test was used to establish the design-amount of asphalt for the aggregates evaluated. The method is entirely satisfactory.

4. The vacuum-saturation specific gravity of the loose asphalt-aggregate mixture is recommended as the basis for computation of the void content. The use of this specific gravity value is logical since it allows for absorption of asphalt by the aggregate and the data have shown that this value was not exceeded by pavement densities.

5. Laboratory design of asphaltic concrete mixtures should include some type of durability test. The immersion-compression test was not investigated for this purpose and at this time not enough information is available to verify the present requirement of 75 percent retained strength.

6. Variabilities in the manufacture of and construction with asphaltic concrete precluded establishing a correlation between laboratory aging of asphalt with performance of pavements. The approximate upper limit of asphalt hardening in a pavement was found to be reached at about two years of service.

7. Final voids in an asphaltic concrete mixture have a critical effect on the rate of hardening taking place in the binder. Rate of hardening of the binder is also directly related to temperature and exposure during mixing, transporting and placing of a mix. Every effort should therefore be made to minimize the mixing temperature, the mix cycle, the handling time, and the delay between the laydown operation and compaction.

8. Field density measurement should be required. It is recommended that field density should be not less than 96 percent of laboratory density based on laboratory samples made from material of the same batch on which field density checks are made. Randomized samples should be taken.

9. It is recommended that a minimum cohesiometer value of 100 be specified in the design for asphaltic concrete to be used in the higher type pavements. A maximum cohesiometer value should also be specified but as yet data are not available to be specific; however, it is felt that the maximum cohesiometer value should not exceed 300 to 350.

I. A STUDY OF HVEEM STABILITY VS. SPECIMEN HEIGHT

In the determination of Hveem stabilities for different mixtures, it has been noted that variations in strength values existed for seemingly identical specimens. Some variation in stability was expected to be normal, however, the source of this variation was not known. Differences in test values could be due to (1) molding of specimens, (2) test procedures, or (3) the method used for correcting stability for height of specimen. In order to isolate or define the above sources of stability variations, the following procedure was used:

1. One operator molded all specimens.

2. Adherence to testing procedure was emphasized.

3. Six different asphaltic mixtures were used to prepare test specimens of five different heights with nearly identical density for a set from each mixture.

Specimen Preparation and Testing

All test specimens were molded according to the Texas Highway Department manual procedure. A phase of the work showed that specimens of different heights could be molded to nearly identical densities for a given mixture. This finding facilitated the elimination of effect of density on stability.

Evaluation for stability was performed with the Hveem stabilometer and under the Texas procedure. From this work a method was established for determining the stability for specimens of "unmeasurable" strength as determined by the limitations of the Hveem stabilometer. Specimens of unmeasurable stability are those that during testing show a transmitted pressure of 200 psi at a vertical load less than 5,000 lb. These specimens can be given a standard stability value by plotting computed stabilities vs. vertical load obtained from the transmitted pressures and corresponding applied pressures during a test. The points are plotted on regular coordinates and the curve established is extrapolated to the proper vertical pressure (400 psi) to obtain the standard stability of the specimen.

Discussion of Results

As mentioned previously the Texas gyratory-shear method of compaction is convenient for molding specimens of equal densities but of various heights. However, the resistance of the specimen being molded to the load indicating an end point must be primarily due to aggregate friction rather than from direct bearing. For this reason the mixtures used in this study had a limited amount of 5/8 to 1/2 inch aggregate so that proper densification of specimens 1-1/2 inch high could be obtained. Contrary to common belief, extreme physical effort was not required in this molding procedure. Great physical exertion is evidence of improper molding technique and is an indication for the operator to check his procedure.

The data on measured stability showed that reproducibility of this value was good; for stabilities above 20 the coefficient of variation expressed in percent ranged from 2.0 to 14.0 and averaged 6.5. For specimens of measured stability less than 20 the coefficient of variation was generally above 10, but for all the specimens tested the standard deviation on stability averaged 2.4.

A primary objective of the study was to examine the effect of specimen height on the measured stability and following this to develop a means by which the measured stability of a specimen could be corrected to that of a selected standard specimen height. Figure 1 shows the relationship between measured stability and specimen height for two of the mixtures used; also shown are the height-corrected stability values obtained by use of the actual specimen height and the effective height. The effective height is the height of specimen less the amount (3/16 in.) which bears against a steel diaphragm clamp in the stabilometer. The measured stabilities were corrected for height by making use of existing curves. The figure shows that the present method for height correction was not adequate for specimens below 1.95 inches in height. There was a linear relationship between stability and height of specimen and the direction of both lines appear to be similar. The slopes for seven mixtures had correlation coefficients (r) ranging from 0.90 to 1.00 and except for one mixture ($r = 1.00$) their differences from an average weighted slope (-20.1) were not significant. Thus, the relationship between measured stability (S) and specimen height (H) could be defined by the following equation

$$S = -20.1H + B$$

which defines a family of curves of various intercepts, B. From this

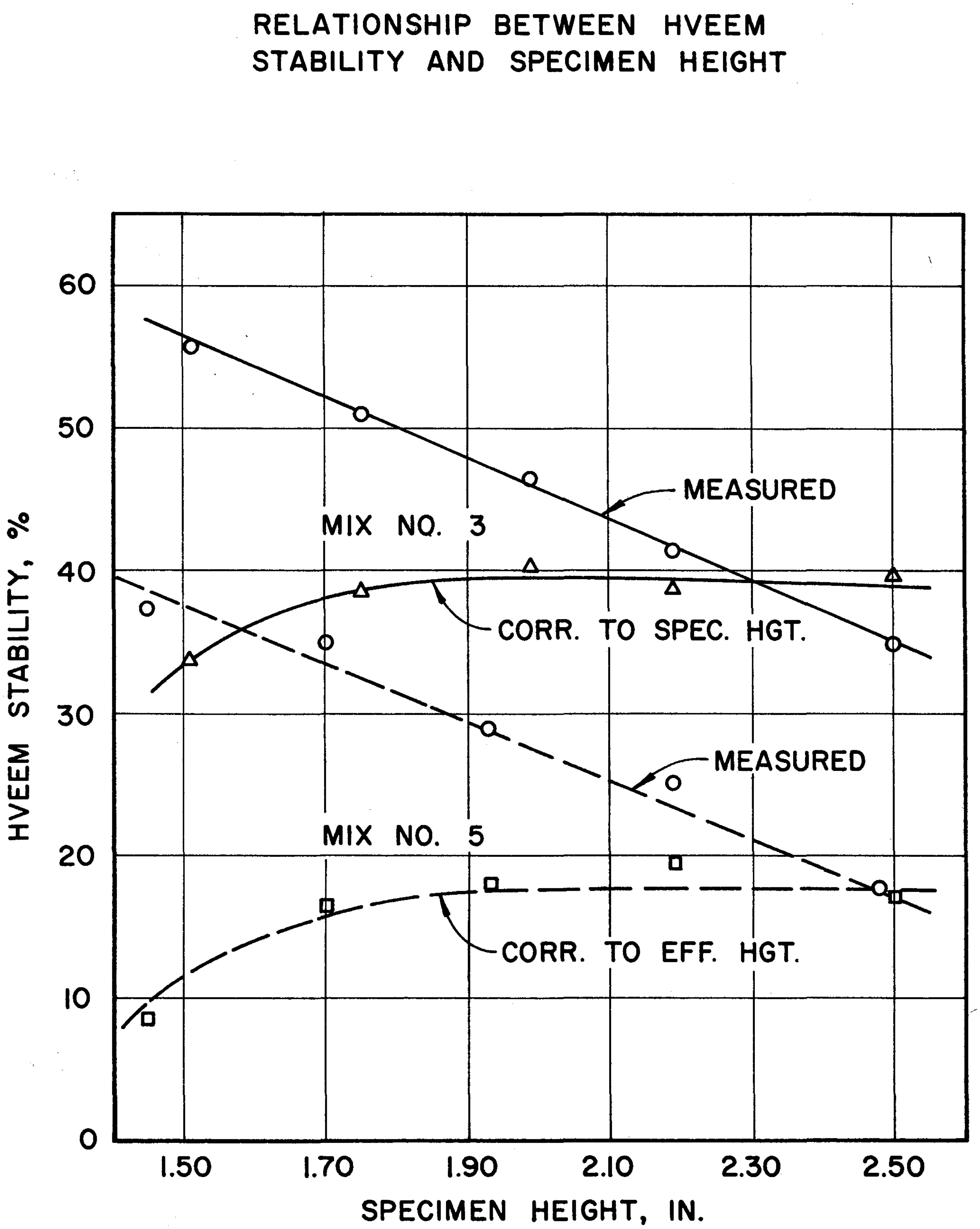

RELATIONSHIP BETWEEN HVEEM
STABILITY AND SPECIMEN HEIGHT
HVEEM STABILITY, %
SPECIMEN HEIGHT, IN.
0
10
20
30
40
50
60
1.50
1.70
1.90
2.10
2.30
2.50
MIX NO. 3
MEASURED
CORR. TO SPEC. HGT.
MIX NO. 5
MEASURED
CORR. TO EFF. HGT.

Figure 1

expression a height-correction or in a more general term height-adjusted equation for stability can be written in the following manner.

$$S_A = S_M - 20.1\ (H_D - H_M)$$

where

S_A = adjusted stability

S_M = measured stability

H_D = desired height

H_M = measured height

To facilitate the determination of an adjusted stability the chart of Figure 2 has been prepared. As explained in the figure, the measured values of S and H are entered from the left ordinate and the abscissa, this point is then extended parallel to the guide lines to intersect the desired H line; the adjusted stability is found on the right ordinate by projecting the second point horizontally.

<u>Conclusions</u>

The following conclusions are warranted for the study.

1. The Texas method for compacting asphaltic concrete specimens eliminated variabilities between specimen density and specimen height. This factor is considered an advantage over other compaction methods that employ a constant compactive effort, regardless of mixture or specimen height. The reproducibility in density of specimens compacted by one operator was extremely good.

2. The strength of specimens which cannot be tested normally, that is, of "unmeasurable" stability can be approximated by the method suggested. Also as is suggested from the height adjusted stability equation developed it is possible that a specimen of lesser height than the standard can be tested and then its stability can be adjusted to obtain the strength of a standard height specimen.

3. The relationship between measured Hveem stability and specimen height is linear and with a slope equal to -20.1.

CHART FOR HEIGHT–ADJUSTED STABILITY

Example: S=42.5% and H=2.02. Locate this point "A", then follow diagonally to vertical of desired height, then project horizontally for adjusted stability. S_A for H of 1.75 in. is 48.0% and S_A for H of 2.50 in. is 32.7%.

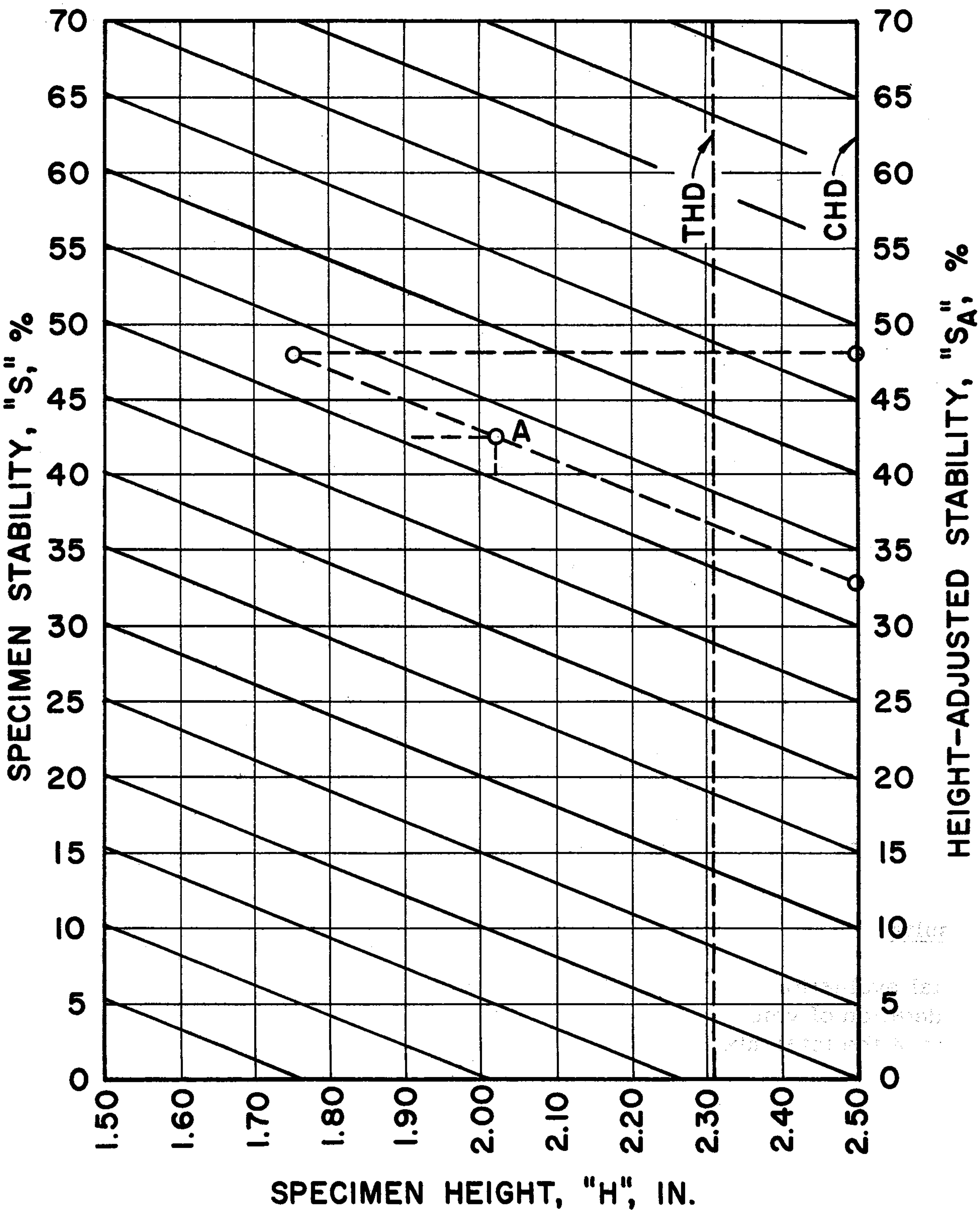


Figure 2

II. A STUDY OF THE MIXING VISCOSITY OF ASPHALT IN HOT-MIX PRODUCTION

This study on mixing viscosity of asphalt used in producing hot-mix asphaltic concrete was conducted to determine the effects of mixing temperature on physical properties of both the mixture and asphalt. An optimum asphalt content was established to meet Texas' specifications for asphaltic concrete and then aggregate blends containing this one amount of asphalt were mixed and molded at temperatures ranging from 250° to 410°F.

Specimen Preparation and Testing

All specimens were made from one aggregate blend and one asphalt of 85-100 penetration. The aggregate and asphalt were heated separately to the desired temperature and then mixed in a Hobart C-10 mixer. The asphalt content was 5.6 percent by total weight. The asphalt-aggregate blends were kept in a 140°F oven for a period of 15 hours. Proper sample sizes were then taken for molding and for determination of vacuum-saturation specific gravity of the loose mixture.

Molding of the specimens was achieved by the Texas manual gyratory-shear compaction method on mixtures brought to their corresponding mixing temperature. Density values were obtained for the molded specimens by weighing in air and then in water. Void content was determined on the basis of the vacuum-saturation specific gravity.

Hveem stability and cohesiometer tests were performed according to the Texas Highway Department procedure. Specimens molded at the different temperatures were evaluated for strength and then were used for the recovery of the asphalt. The recovered asphalt was tested for penetration, thin film viscosity and aging index. The Hallikainen viscometer was utilized for the thin film viscosity determinations.

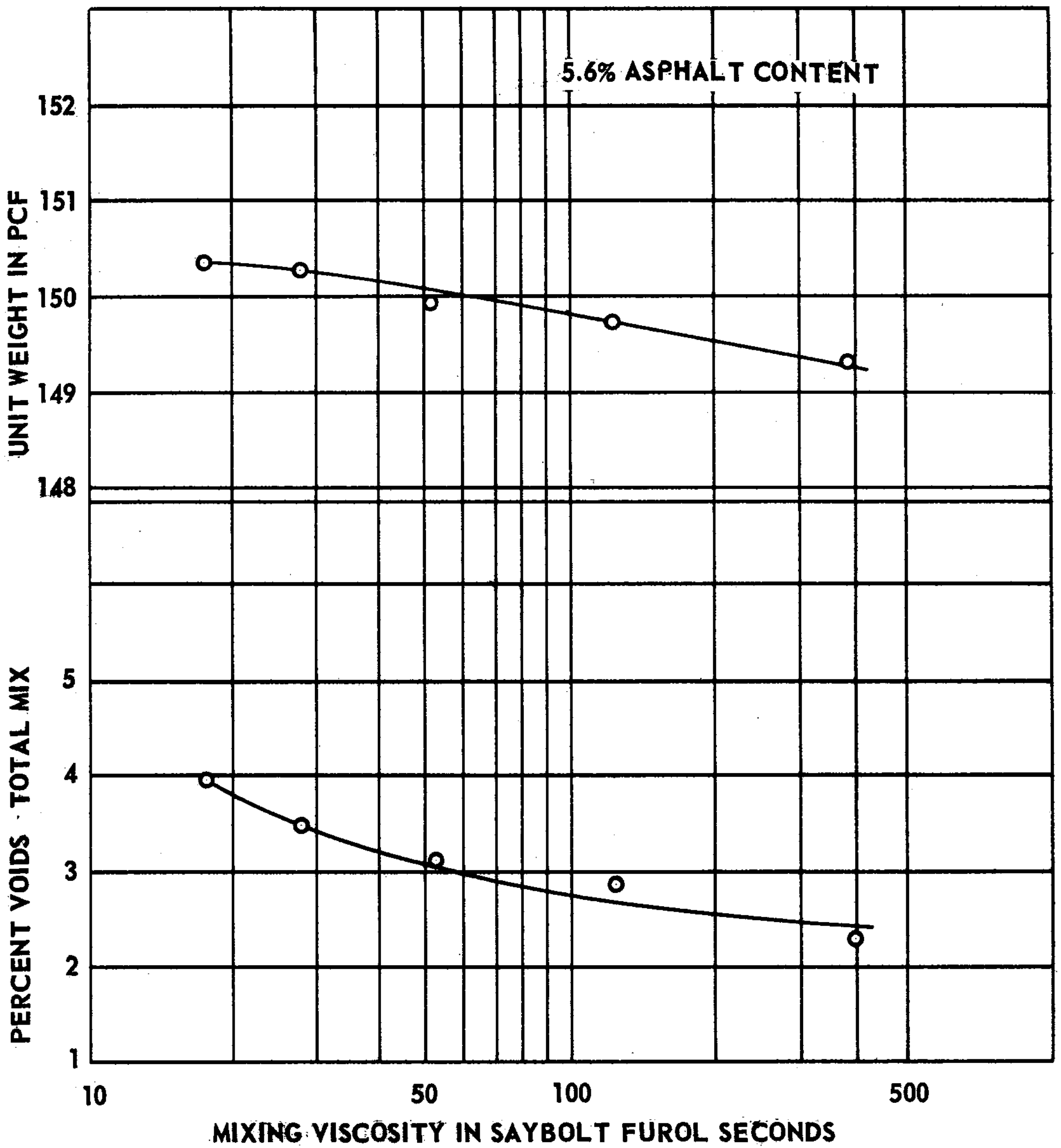
Test Results

Initial evaluation of various asphalt-aggregate blends indicated that, in consideration of voids, the optimum asphalt content was 5.6 percent by weight of the total mixture. The effects of mixing temperature or in a more general sense mixing viscosity on unit weight and void content are shown in Figure 3. The upper portion of the figure shows that more densification of a specimen was obtained at the lower mixing viscosity (higher temperature). This finding is in accord with present thinking since aggregate friction is reduced by low asphalt viscosity. The lower portion of the figure may appear to be slightly confusing to those that base amount of voids on a theoretical specific gravity of the mixture which does not directly account for absorption of the asphalt by the aggregate. (The aggregate blend utilized had water absorption values of 1.23 percent for the + No. 4 sieve size and 2.10 percent for the - No. 4 sieve size.) To these persons as the unit weight of the specimens decreases the amount of voids should decrease for a specific mixture but the lower portion of the figure shows an opposite trend. The decrease in void content as mixing viscosity increases is explained as follows. First, it must be remembered that the theoretical maximum specific gravity was determined by measurements of the loose blends mixed at the different temperatures. Since the asphalt had different viscosities at these temperatures it had varying capability of penetrating the aggregate pores. That is, at high mixing viscosity (low temperature) less penetration of asphalt into the pores occurred and thus resulted in lower theoretical maximum density for the mixture. For example, the vacuum-saturation specific gravity obtained for a mixing temperature of 250°F was 2.449 and that for 410°F was 2.509 which resulted in void contents of 2.29 and 3.95 percent respectively for the compacted specimens.

The effects of mixing viscosity on the strength of the test specimens are illustrated in Figure 4. The graph for Hveem stability shows a minimum value at a Saybolt Furol viscosity of approximately 100 seconds and higher stabilities above or below this viscosity. Presently, the shape of this curve cannot be explained. The shape of the curve showing the effect of mixing temperature on the cohesiometer value is considered to be influenced by the greater hardening of the asphalt and greater specimen density resulting from the increase of mixing temperatures.

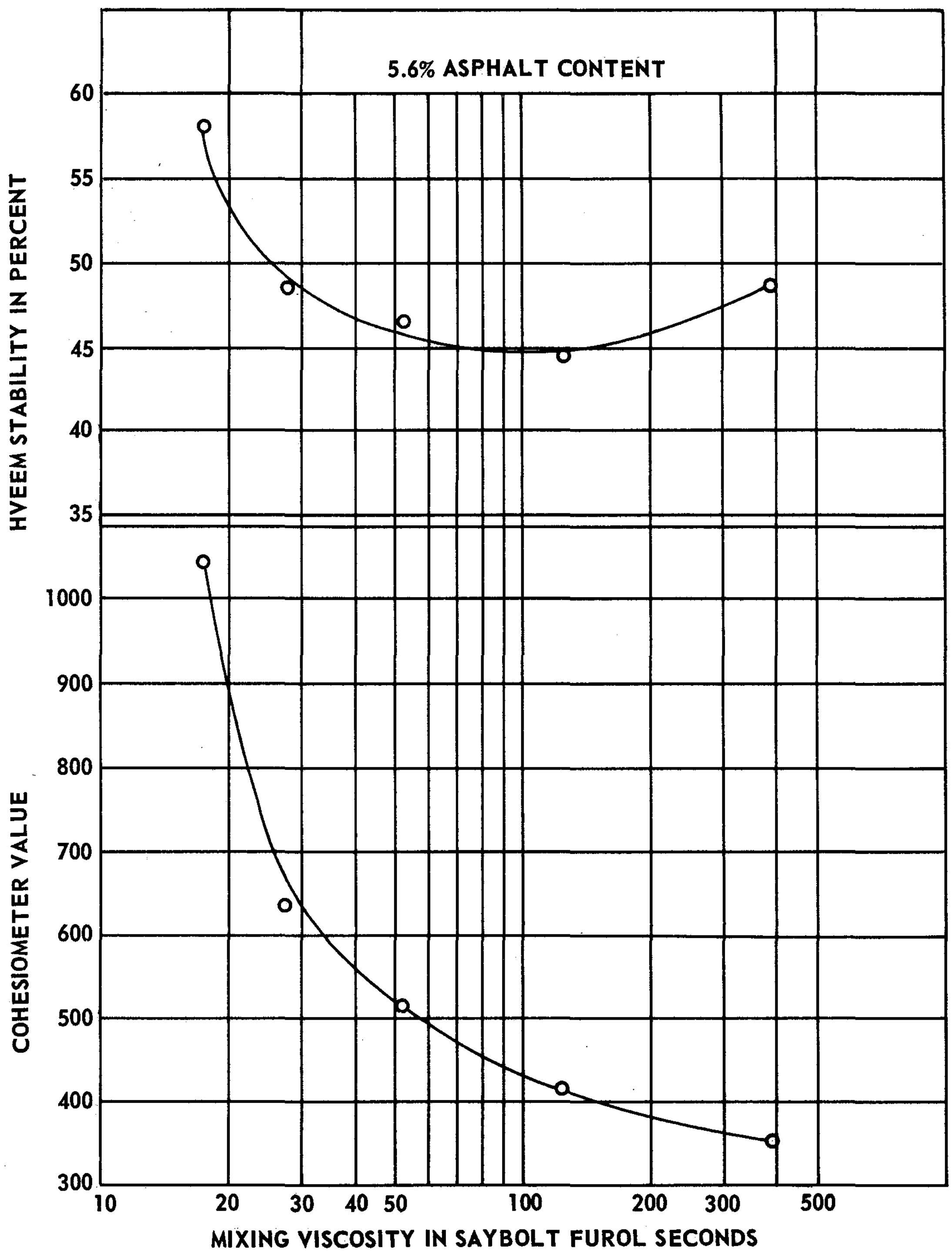
Table 1 shows the change in penetration value of the asphalt recovered from specimens mixed and molded at the various temperatures.

A more effective means of showing the great changes in consistency of the asphalt caused by variations in mixing temperatures is presented in Figure 5. This figure shows that by increasing the mixing temperature from about 290°F to 350°F the absolute viscosity of the asphalt was increased by more than 200 percent. Also the curves illustrate that laboratory aging did not show as great an effect on the asphalt that had been



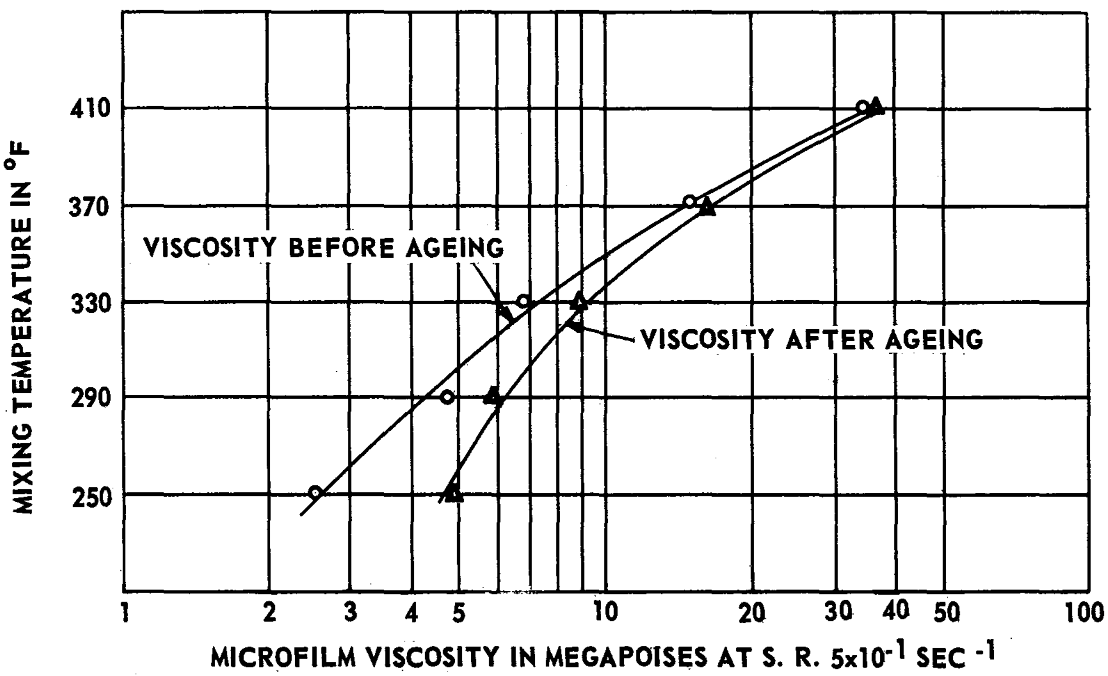
Effect of Mixing Viscosity on Unit Weight and Void Content

Figure 3



Effect of Mixing Viscosity on Hveem Stability and Cohesiometer Value

Figure 4



Effect of Mixing Temperature on Microfilm Viscosity of Recovered Asphalt

Figure 5

heated to the higher mixing temperature. This behavior is presented by the upper portion of Figure 6 which shows the Aging Index approaching a value of one at the higher temperatures. The lower portion of Figure 6 indicates that use of the higher mixing temperatures resulted in an asphalt diverging from Newtonian flow properties.

TABLE 1

Standard Penetration of Recovered Asphalt From Test Specimens

		Mixing Temperature °F				
	Original	250	290	330	370	410
Penetration Value	92	66	53	44	33	18

Conclusions

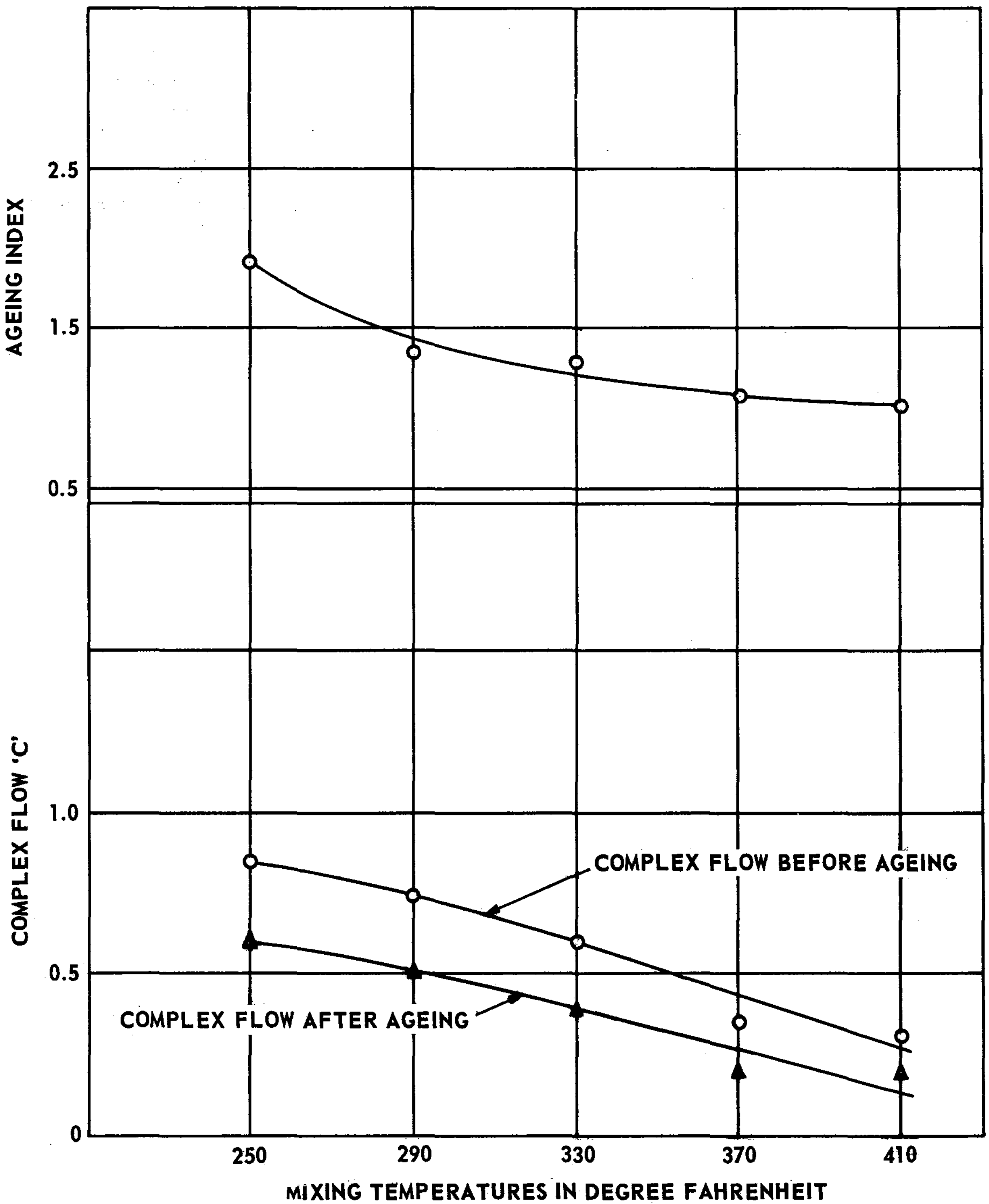
The results of work done on this study have shown the following to be warranted conclusions.

1. A change of asphalt viscosity at the time of mixing with aggregates will affect the density of the molded specimen and will show a change on the vacuum-saturation specific gravity of the loose mixture.

2. Minimum Hveem stability value will be obtained for mixing viscosities between about 75 to 150 Saybolt Furol seconds.

3. Low mixing Saybolt Furol viscosities result in high cohesiometer values.

4. Increasing the mixing temperature of asphalt results in hardening and decreases the Aging Index of asphalts.



Effect of Mixing Temperature on Aging Index and Complex Flow

of Recovered Asphalt

Figure 6

III. AN APPARATUS FOR LABORATORY INVESTIGATIONS OF ASPHALTIC CONCRETE UNDER REPEATED FLEXURAL DEFORMATIONS

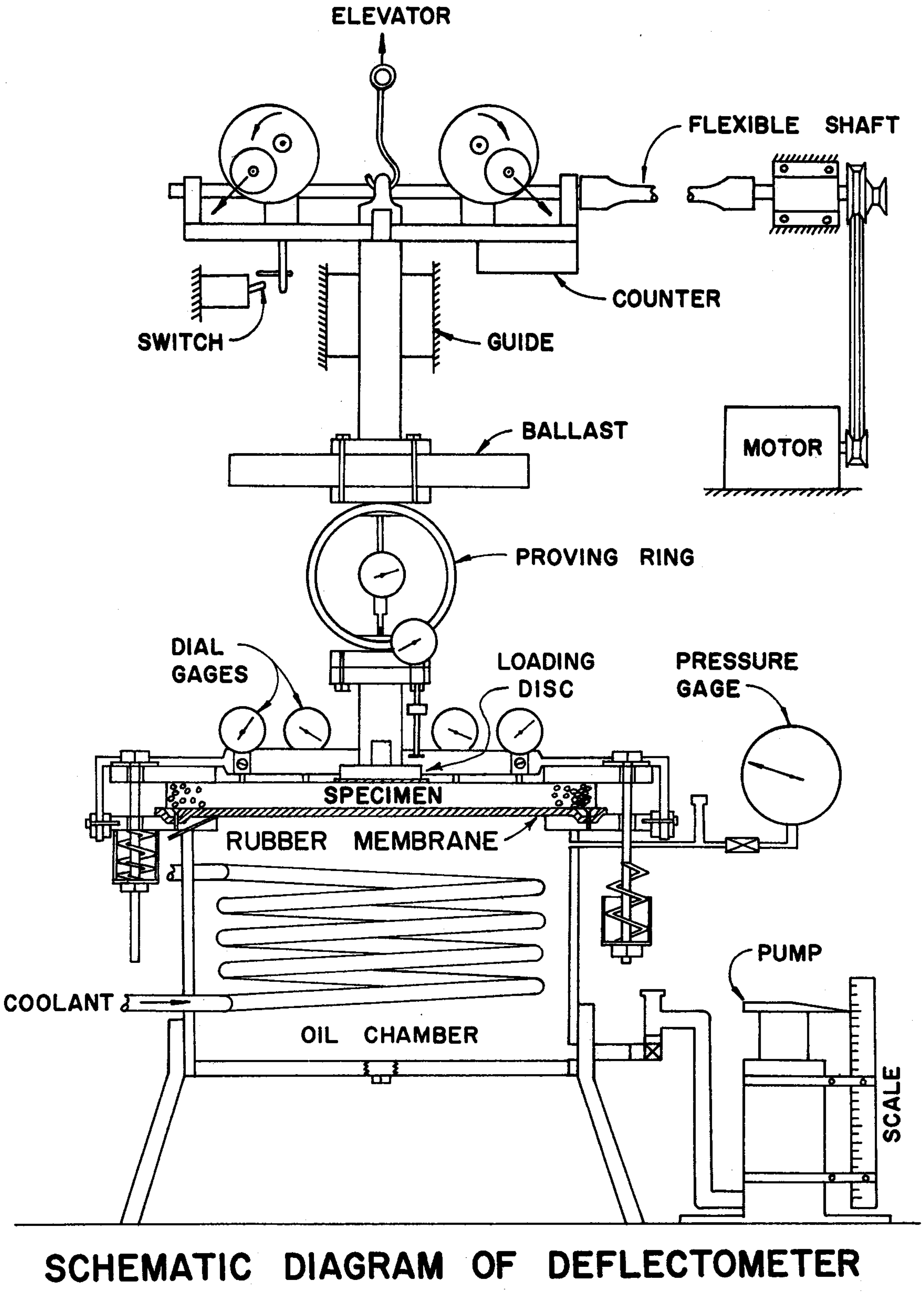
In order to study the response of asphaltic concrete to repeated loads, a device was built to evaluate the effects of several variables in these mixtures on so called fatigue properties. The evaluation of different mixtures tested in the apparatus (deflectometer) showed that gradation, aggregate surface texture, asphalt content, and asphalt viscosity had definite effects on resistance to repetitive loads. The factors that improved resistance to repeated loads generally decreased the flexibility of the specimen. Stress equations derived for elastic materials were found suitable for showing a relationship between magnitude of applied stress and fatigue life of asphaltic concrete.

Deflectometer

A schematic diagram of the testing apparatus is shown in Figure 7. The deflectometer is made up of two basic components which are (1) the loading system and (2) the reaction unit. The loading system imparts the test load by means of two eccentric masses which rotate in opposite directions so that the net force has a vertical direction. The forces due to the rotation of the eccentrics have magnitudes that vary sinusoidally with time and the maximum value is less than the dead load so that there is no impact (collision) on the test specimen. The loading system is free to move vertically and follow the deformation of a specimen so that the same loads are applied throughout the duration of a test.

The reaction unit is a cylindrical oil chamber sealed at the top with a thin rubber membrane and to which is connected an oil pump. A specimen is clamped onto the oil chamber by means of a ring and an assembly of bolts, sleeves and springs. The reaction unit was designed to afford and indicate various supporting pressures to the test specimen. The test specimen is approximately 17-1/2 inches in diameter; however, under testing conditions the effective diameter is 14 inches.

The molding of test specimens was accomplished by use of the loading system to furnish the compactive effort. Proper particle orientation and degree of compaction was obtained by tilting the compaction head and oscillating it during the period of vibration. Efficient compactive effort was achieved by making the live load greater than the dead



SCHEMATIC DIAGRAM OF DEFLECTOMETER

NO SCALE

Figure 7

load so that impact resulted. Kneading compaction producing proper densification was furnished to a mixture by the three directional motion given to aggregate particles. The basic method of compaction used was suitable for producing 4 and 17-1/2 inch diameter specimens of comparable physical characteristics so that standard strength or stability values could be obtained for the larger specimens.

Materials

Two different aggregate mixtures were used to make coarse sheet asphalt specimens; however, the gradations for the two aggregate blends were identical. One aggregate blend considered to be rough textured was obtained by combining a wet-bottom boiler slag with crushed limestone screenings; the second combination representing a smooth textured aggregate was made by combining concrete sand with the limestone screenings. The gradation common to both aggregate blends is shown in Table 2.

Specimens were made from asphalts of one source but having standard penetration values of 60, 90, and 122. Mixture design and the majority of the testing with the deflectometer were performed on specimens containing the 90 penetration asphalt.

A standardized procedure was used for the batching and mixing of aggregate and asphalt. The loose asphaltic mixtures were stored in oven at 140°F for a period of 15 hours in order to allow absorption of asphalt by the aggregate prior to compaction. The vacuum-saturation specific gravity was determined for the "cured" mixture and served as a basis for the computation of void content.

Mixture design curves for the two aggregate blends compacted by the Texas gyratory-shear method are shown in Figure 8.

Test Conditions and Results

Of the different load conditions possible with the deflectometer, the following was chosen for a standard.

1. Load frequency of 11 cycles per second.

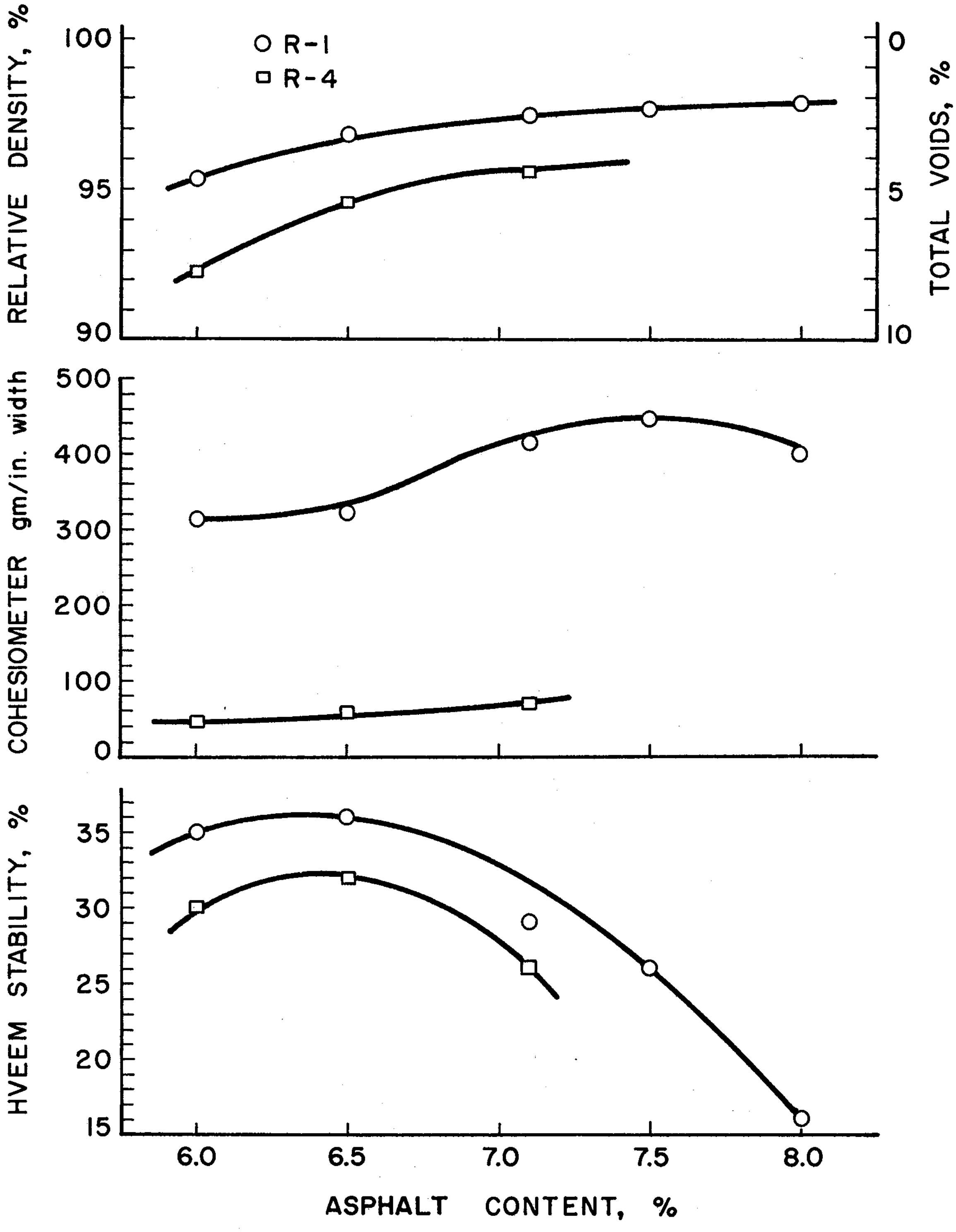
2. Dead load of 139 pounds.

TABLE 2

Gradation of Coarse Sheet Asphalt

Sieve Number	Total Percent Passing
4	100
8	90
16	55
30	30
50	20
100	15
200	10
Surface Area,* sq. ft./lb.	45.2

* From California Highway Department surface area factors.



DESIGN CURVES FOR R-1-90 AND R-4-90

FIGURE 8

3. Live load due to rotation of eccentrics, 104 pounds.

4. Load contact area of 5.0 square inches.

5. Initial support to specimen of 1 psi.

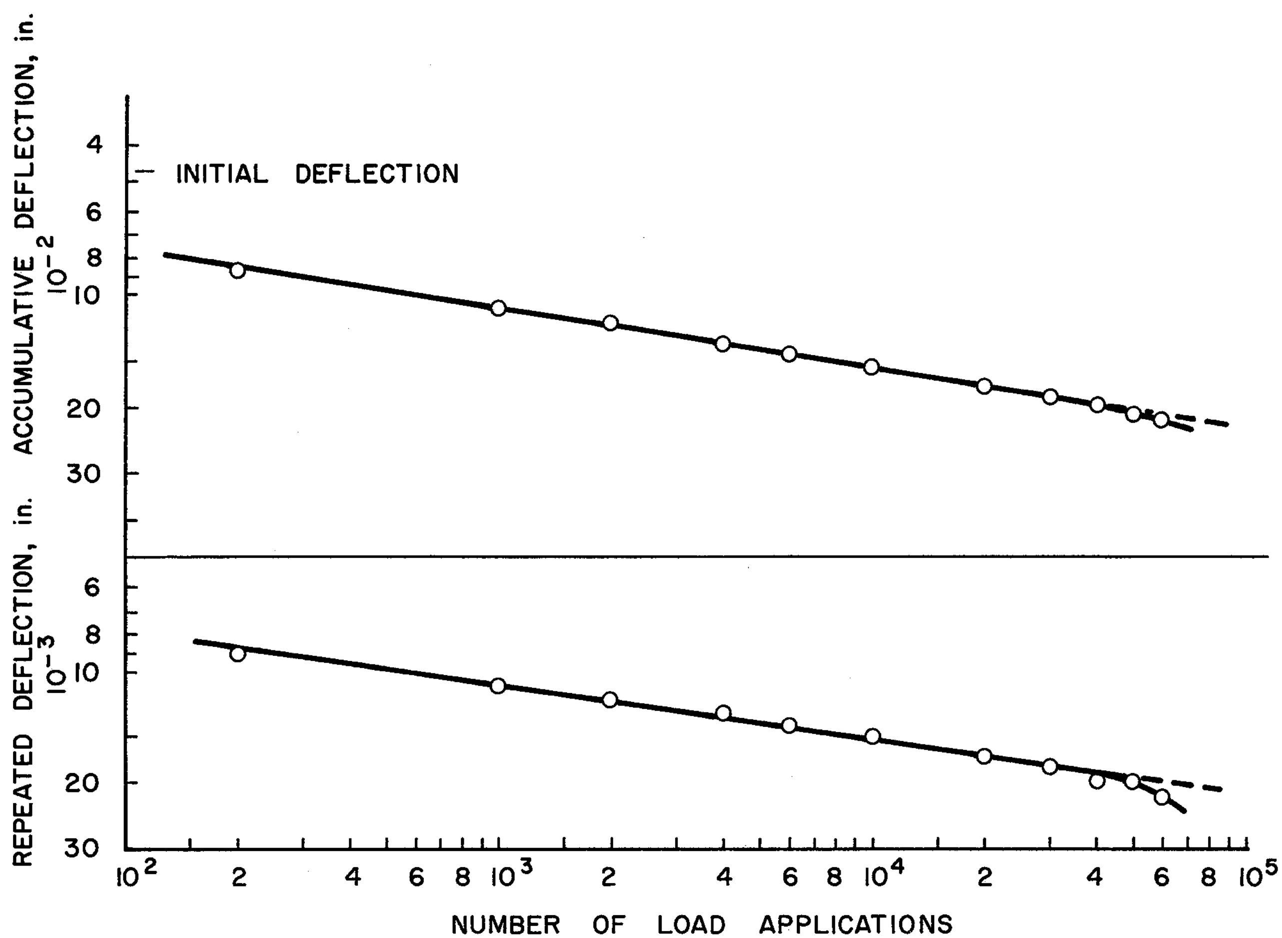
All tests were performed at a temperature of 75 $\pm$ 1°F.

The indication of failure for a specimen undergoing repeated flexures was determined from a running logarithmic plot of load disc deflection versus number of load application. Such a plot was initially a straight line which eventually deviated into a curve as illustrated in Figure 9. The point of tangency between the straight line and curve represented the number of load applications resulting in failure of the specimen. Loading was continued on a specimen until at least three points were off the line established by earlier readings, and in most cases, the number of total load applications was greater than twice that representing failure.

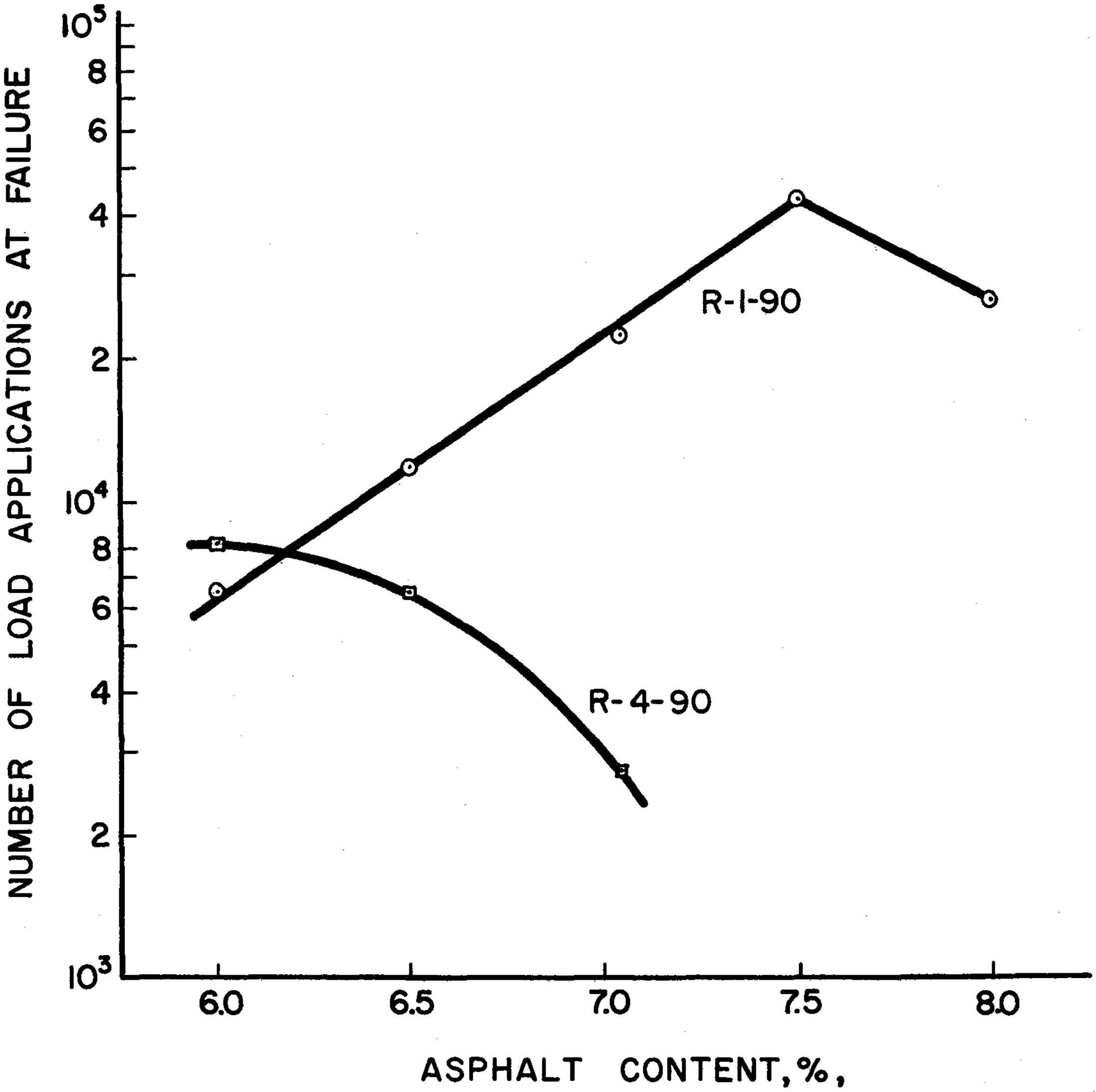
An achievement of this work was the development of a method for obtaining proper compaction of the large 17-1/2 inch diameter specimens. The compaction of the test specimens was accomplished with the loading system of the deflectometer to furnish the compactive effort, however, in order to obtain adequate density and proper particle orientation it was necessary to tilt the compaction head and oscillate it during the period of vibratory loading. This method of vibratory-kneading compaction was capable of producing 4-inch diameter specimens with physical properties and strength identical to those of the larger deflectometer specimens.

Asphalt Content

The effects of asphalt content on the resistance to repeated loading for two aggregate mixtures are shown in Figure 10. The curve labeled R-1-90 represents the rough textured aggregate mixed with 85-100 penetration asphalt (OA-90) and the R-4-90 curve is for the smooth textured aggregate with the same asphalt. It is of interest to note that these curves indicate the existence of an optimum asphalt content for maximum fatigue life. These curves also show differences between the two aggregate blends with regards to resistance to repetitive loads which are due primarily to differences in aggregate surface texture. In particular the rough textured aggregate mixture showed better resistance to the loading. The optimum asphalt content of 7.5 percent in consideration of fatigue for the R-1 aggre-



LOAD-DISC DEFLECTION VS. NUMBER OF LOAD APPLICATIONS
R-1-7.5-90 STANDARD
FIGURE 9



ASPHALT CONTENT VS. NUMBER OF LOAD APPLICATIONS AT FAILURE. STANDARD

FIGURE 10

gate happens to be that amount associated with actual paving mixtures made with this material.

The photographs of Figure 11 show typical crack patterns produced on the bottom surfaces of R-1 specimens. The upper picture shows a pattern similar to "alligatoring" found in asphaltic concrete surfacings. The lower picture shows radial cracks which may indicate that the asphalt film thickness was excessive since these are comparable to disconnected cracks found often in asphaltic surface treatments.

Specimen Thickness

As expected the number of load applications to result in failure increased as thickness of specimens increased. However, as shown by Figure 12 this relationship was of an exponential nature, that is, a straight line was determined with logarithmic coordinates.

Initial Support

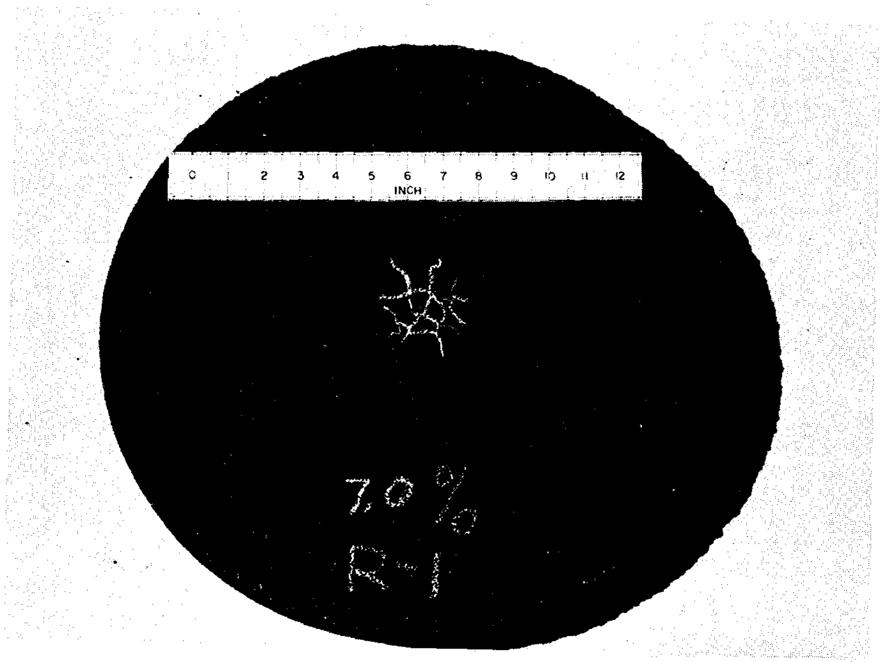
Figure 13 shows that the number of load repetitions to cause failure had a simple linear relationship with and directly proportional to the amount of initial support given to a test specimen.

Asphalt Viscosity

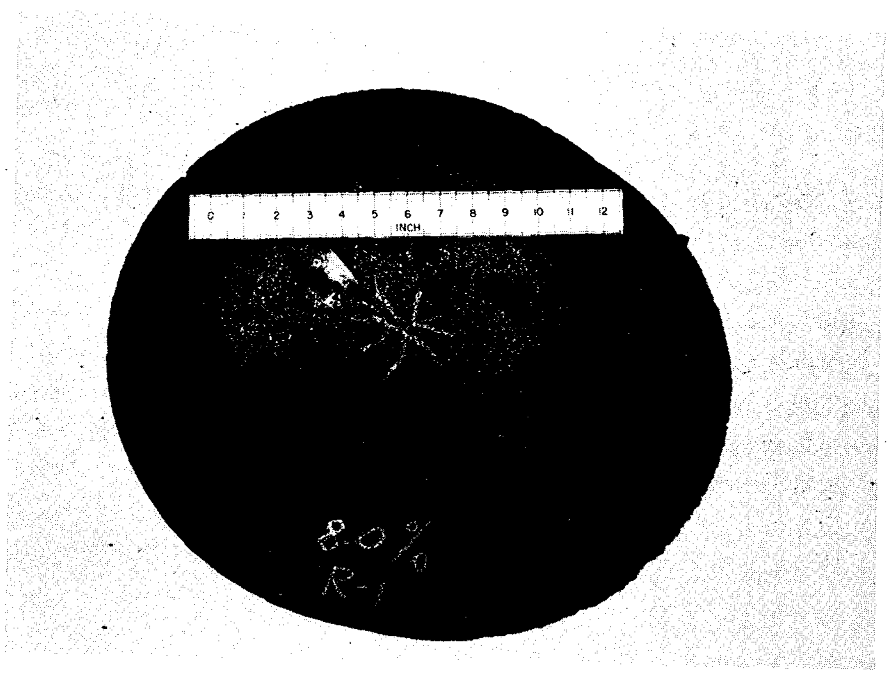
The effect of asphalt viscosity on fatigue life is illustrated by the graphs of Figure 14. It should be pointed out that the specimens containing the hardest asphalts were the stiffest and consequently the total load applied was of least value. This was so because the force due to translation of the loading system was the smallest. This difference was small and would not change the direction of the sloped lines in Figure 14 but only the magnitude of the slopes should a comparison be made on equal stress or strain; however, it does not appear necessary to make the comparison on this basis but rather as shown.

Stress Computations

The conditions of loading in the deflectometer are such that analytical equations are available for the computations of stress or strain. These



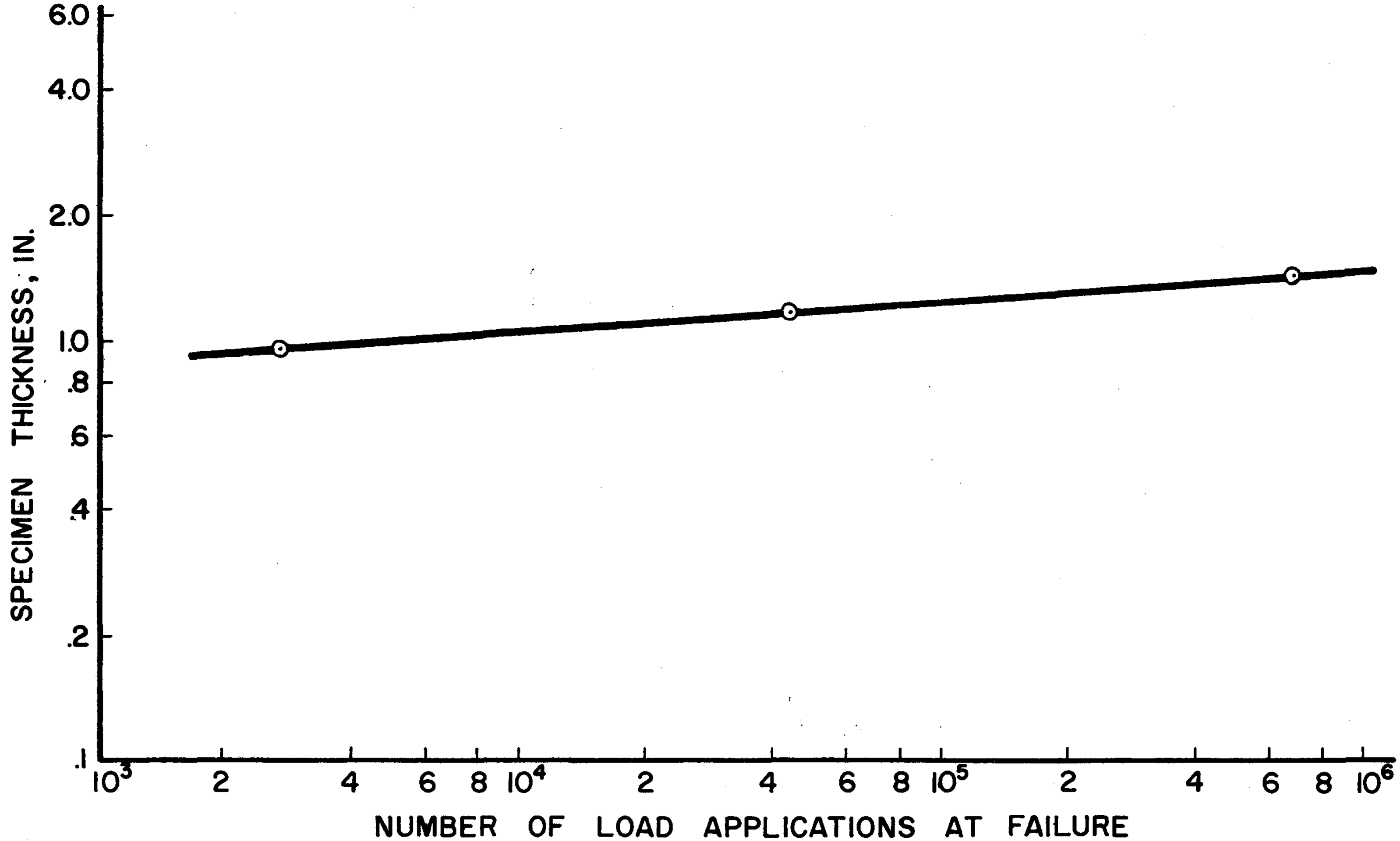
(a)



(b)

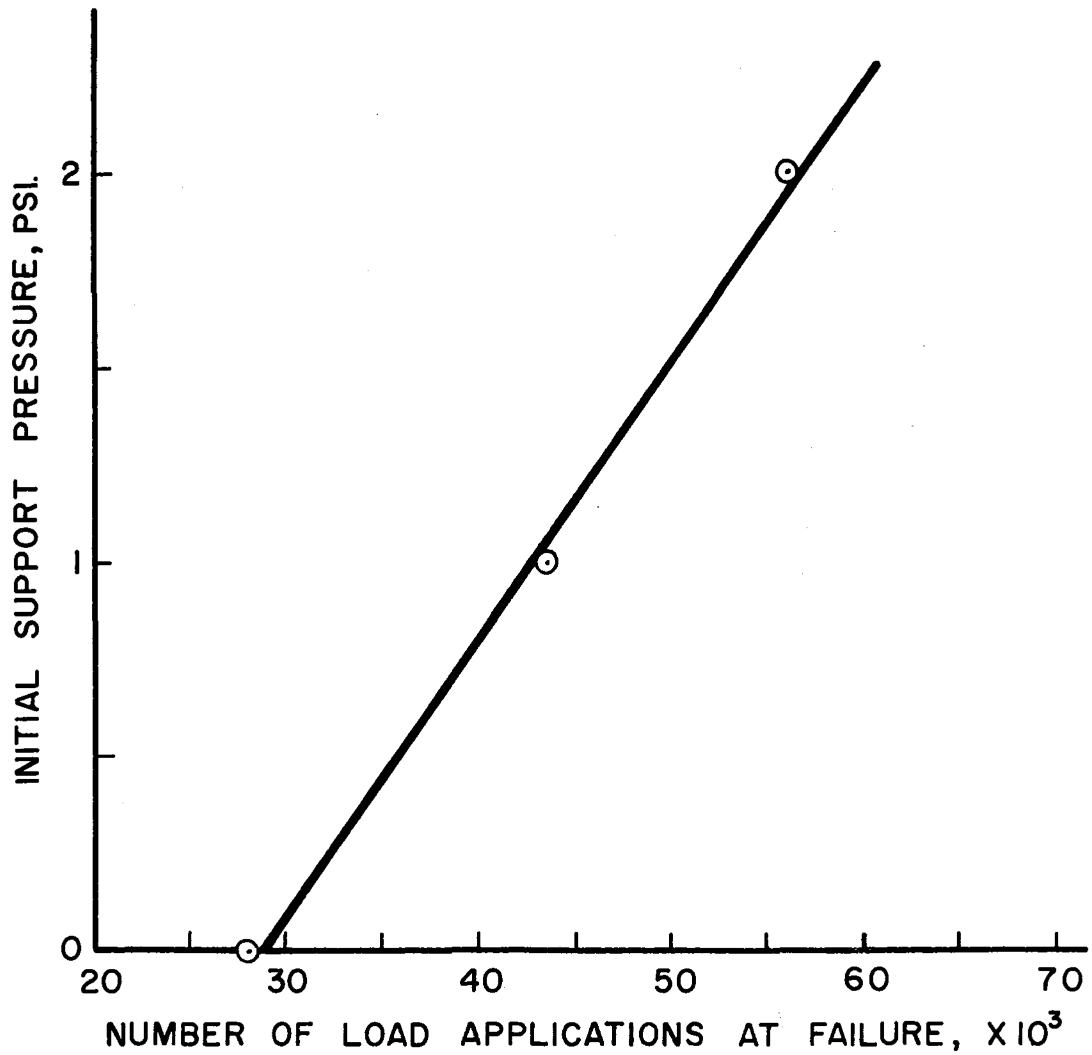
Crack Patterns

FIGURE 11



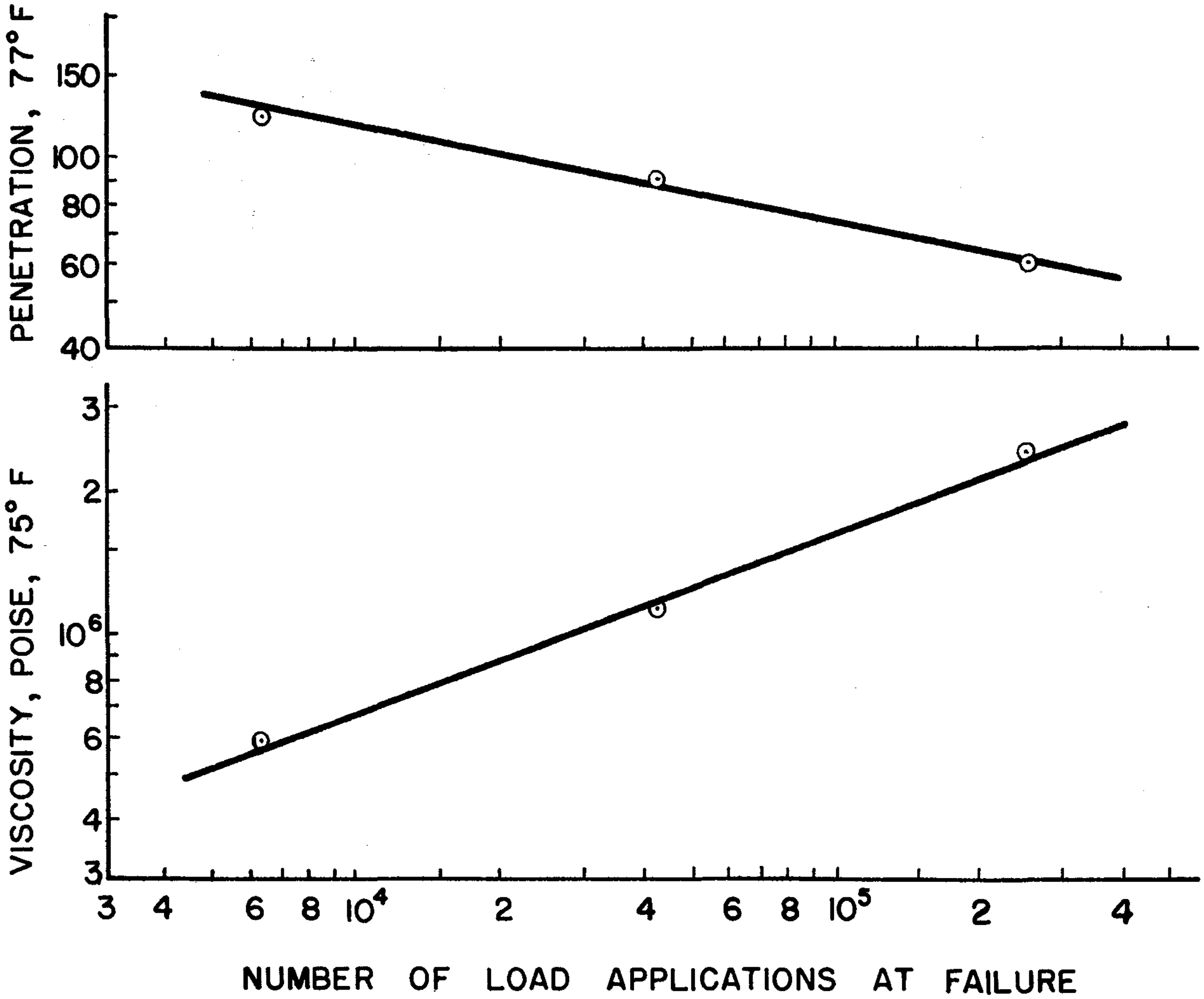
SPECIMEN THICKNESS VS. LOAD APPLICATIONS AT FAILURE. R-1-7.5-90 STANDARD

FIGURE 12



INITIAL SUPPORT VS. NUMBER OF LOAD APPLICATIONS AT FAILURE
R-1-7.5-90 5.00 SQ. IN. DISC

FIGURE 13



ASPHALT VISCOSITY AND PENETRATION VS. NUMBER OF LOAD APPLICATIONS AT FAILURE. R-1-7.5 STANDARD

FIGURE 14

equations were derived by Grashof in consideration of an elastic material and use of the Bernoulli-Euler theory of bending.

For the purpose of this study the maximum radial stress located at the surface center was expressed as follows:

$$S_x = \frac{3\ (m+1)\ W}{2\ \pi\ mt^2}\ \left(\ln \frac{r}{r_o} + \frac{r_o{}^2}{4r^2}\right) - \frac{3\ (m+1)\ r^2}{8\ mt^2}\ p \qquad (1)$$

and the modulus of elasticity as

$$E = \frac{3\ (m^2-1)}{4\ \delta\ m^2 t^3}\ \left(\frac{Wr^2}{\pi} - \frac{(r^2-x^2)^2}{4}\ p\right) \qquad (2)$$

where m = reciprocal of Poisson's ratio

W = central load, pound

t = specimen thickness, inch

r = effective specimen radius, inch

r_o = radius of loaded area, inch

p = support pressure, pounds per square inch

δ = deflection of specimen at x, inch

x = radial distance from center, inch

The value of Poisson's ratio for the mixtures was assumed to be 0.2 ($m = 5$). The central load, W, for the computation of radial stress was the maximum load applied; for the determination of modulus of elasticity it was the difference between the maximum and minimum central load. All calculations were made for the condition of p equal to 1.5 psi.

The equation for radial stress at the center was simplified by omitting the term $r_o{}^2/4r^2$ since this value was relatively small. With the substitution of the constant used in testing with a 5.00 square inch load-disc, equation 1 simplified to

$$S_x = \frac{201 + 0.97\ F_t}{t^2} \tag{3}$$

where F_t was the inertial force due to translation of the loading system.

The modulus of elasticity was in effect a secant modulus since the deflection $\underline{\delta}$ utilized for its determination was the repeated deflection observed and will be called Dynamic Modulus of Elasticity. The simplified equation for this modulus computed from central deflection was

$$E_D = \frac{11.2}{t^3}\ (150 + 2\ F_t) \tag{4}$$

Testing of and computations for a series of specimens compacted to various densities showed that a linear relationship existed between the logarithm of E_D and the values of density as shown in Figure 15.

As might be deduced from Figure 12 the relationship between central radial stress and number of load applications to cause failure is of a linear characteristic when plotted on logarithmic coordinates; such an S-N curve is illustrated in Figure 16.

Conclusions

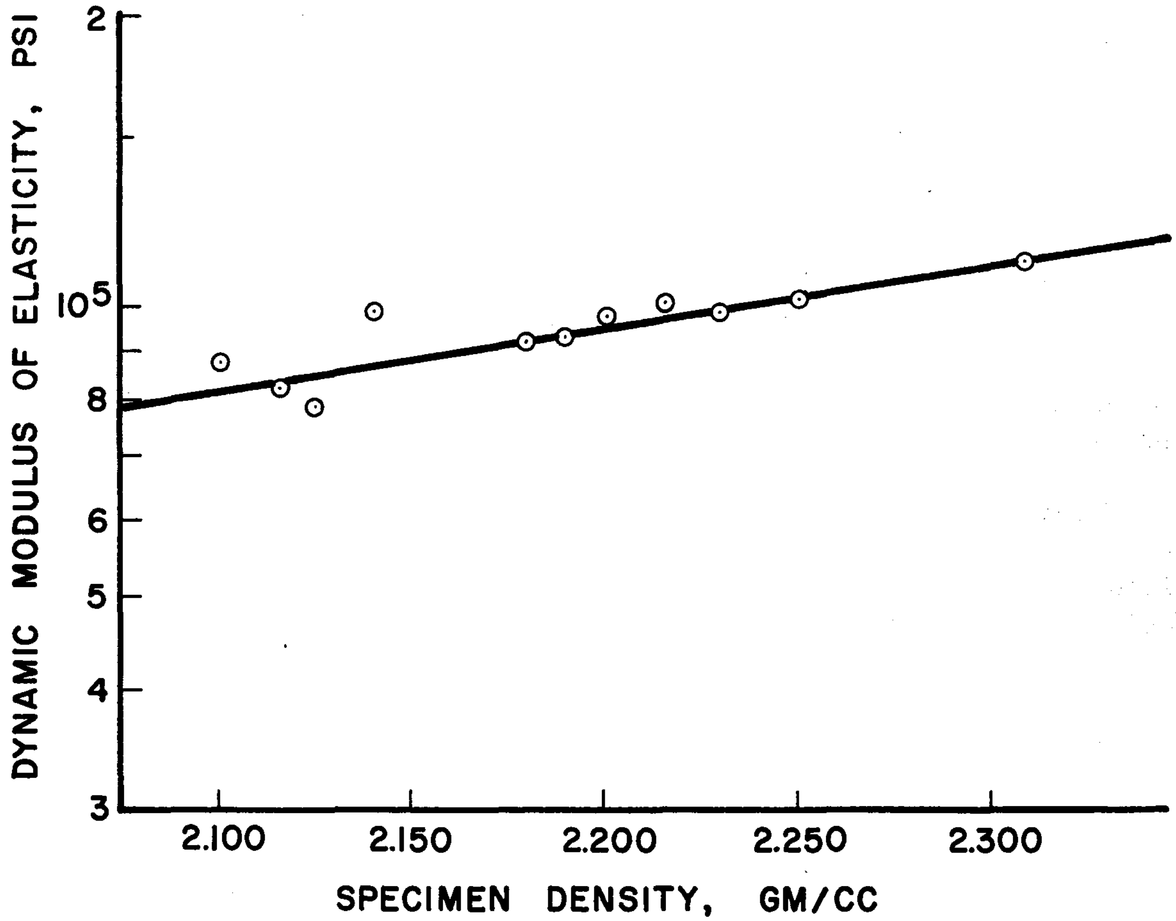
The results of the study warrant the following conclusions:

1. A most significant factor for densifying large specimens of asphaltic concrete is the application of horizontal forces during dynamic compaction.

2. The deflectometer was found to respond to mixture variables which are known from experience to affect the flexibility and resistance to repeated loads of asphaltic concrete.

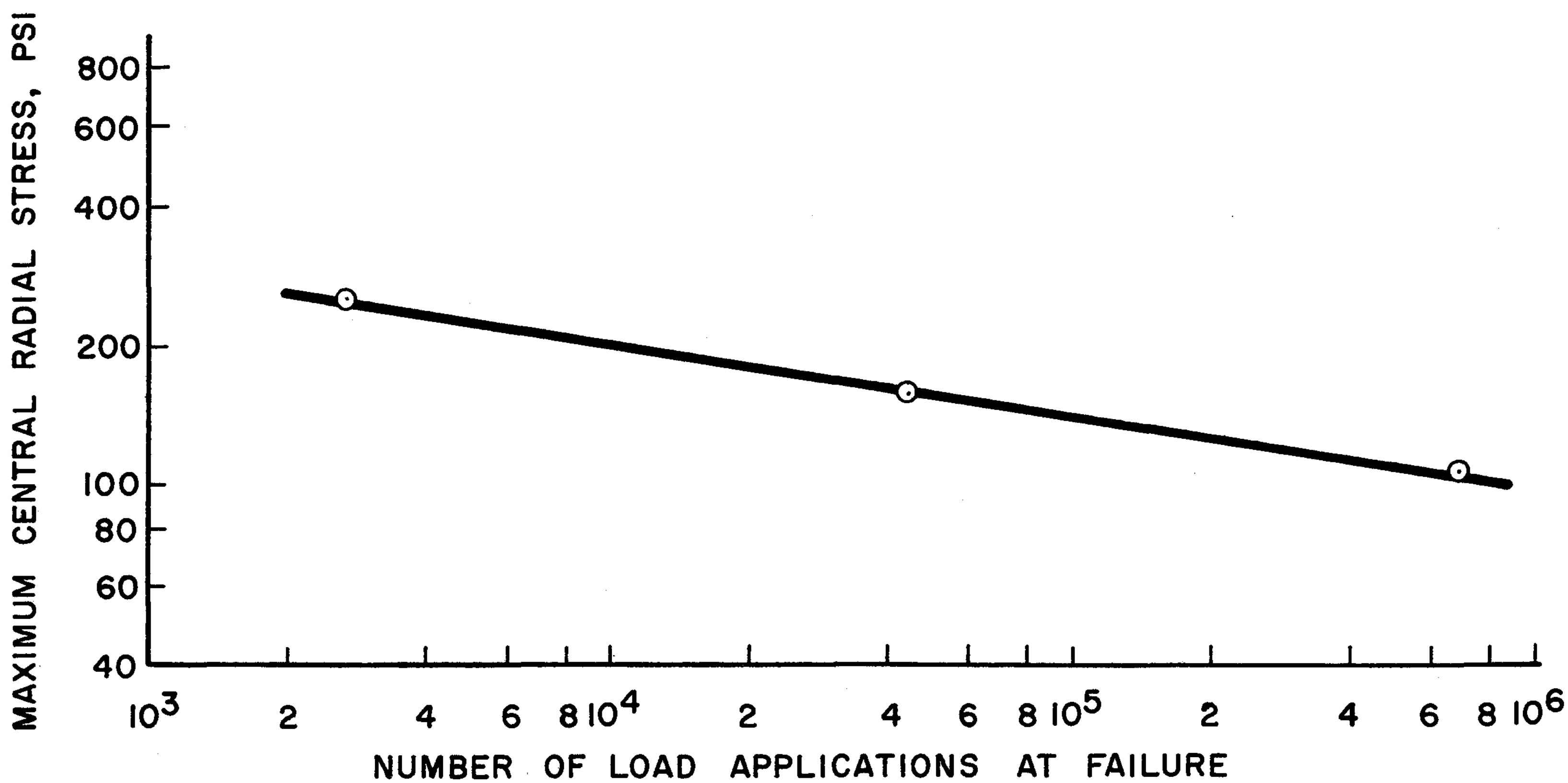
3. An optimum asphalt content was associated with maximum resistance to repeated loads for the specimens tested.

4. The resistance to repeated loads of a pavement sample can be maximized by the use of (1) coarse-textured aggregates and (2) by the use of high viscosity asphalt. Increase in thickness of sample improves fatigue life due to a reduction of imposed stress.



DYNAMIC MODULUS OF ELASTICITY
VS. SPECIMEN DENSITY
R-1-7.5-90

FIGURE 15



MAXIMUM STRESS VS. NUMBER OF LOAD APPLICATIONS AT FAILURE

FIGURE 16

5. Factors that increased the fatigue life of a mixture generally resulted in a loss of flexibility.

6. Grashof's equations were suitable for the evaluation and comparison of specimens tested in the deflectometer.

IV. A LABORATORY STUDY OF THE OPERATOR VARIABLE ON MOLDING PROCEDURES AND MIX DESIGN VARIATIONS IN HOT-MIX ASPHALTIC CONCRETE

This study was conducted in an effort to measure the effect of differences in the amount and intensity of laboratory compactive effort on the densification of selected but distinctly different asphaltic concrete mixtures. The program also included research on operator repeatability and reproducibility between operators who molded numerous test specimens at different levels of compaction energy.

The compaction apparatus used in the study is shown in Figure 17. This schematic represents the standard Texas Highway Department gyratory shear compactor which has been modified to permit application of selected constant ram pressures for the different compaction energy levels studied. Ram pressure is regulated with compressed air by use of an air pressure regulator through an oil reservoir.

A number of different operators performed in the program and a statistical analysis was conducted on the data from selected operators. Graphical comparisons are shown in the bar graph of Figure 18. It is of interest to note from Figure 18 that for operator J.M., low densities are associated with high Hveem stabilities for the four modified methods of compaction. Operator J. M. also had lower coefficients of variation. The major observed difference in these two operators was physical strength and stamina. Operator R.W. was stronger and more robust than J.M.

In general the program of study was concerned with the following:

(1) To determine how well a given operator of limited training repeated test specimen densities for given designs and materials;

(2) To determine whether or not the physical characteristics of asphaltic concrete made from widely different types of materials affected an operator's ability to repeat test specimen densities;

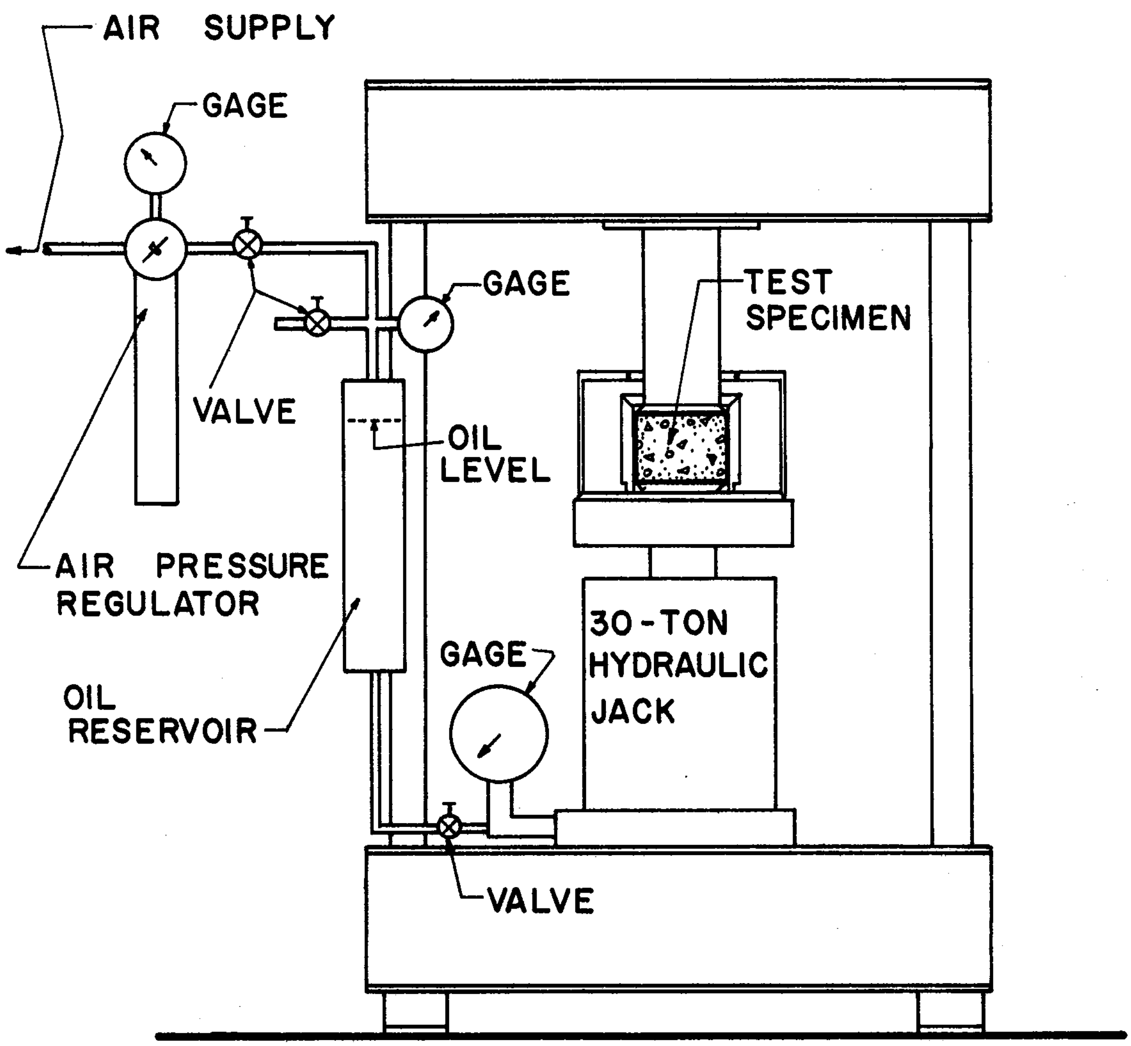
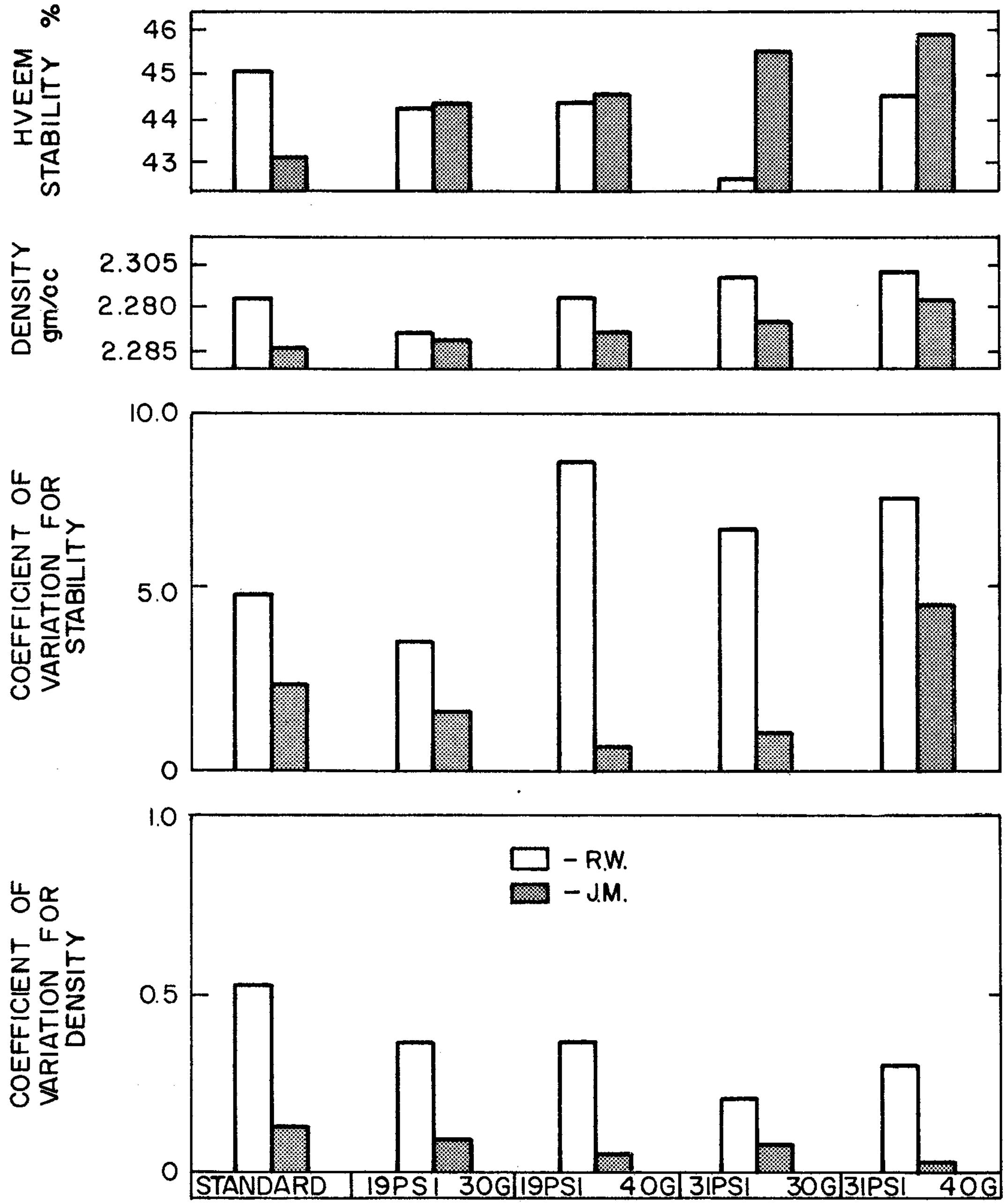

AIR SUPPLY
GAGE
GAGE
TEST
SPECIMEN
VALVE
OIL
LEVEL
AIR PRESSURE
REGULATOR
30-TON
HYDRAULIC
JACK
GAGE
OIL
RESERVOIR
VALVE

FIGURE 17



EFFECTS OF MOLDING METHODS ON VARIATIONS OF SPECIMEN DENSITY AND STABILITY ON MIXTURE 1774

FIGURE 18

(3) To determine how well different operators reproduce the test specimen density results of other operators working with the same materials and equipment; and

(4) To determine, in general, the effect of changing Texas' standard molding and testing procedures on the results of the Hveem stabilometer and cohesiometer values.

Conclusions

The following conclusions appear to be generally justified based on the materials, designs, operators and equipment used in this program:

1. For an asphaltic concrete made completely of rounded particles and a low penetration asphalt cement the THD procedure of molding produced higher Hveem stabilities and lower bulk densities than those obtained by other methods of densification. Highest densities and highest cohesiometer values were obtained at 40 gyrations applied at a constant foot pressure of 31 psi.* Intraparticle attrition and better nesting of aggregates may account for this apparent improvement of the cohesiometer values.

2. In phase II of the program nine operators were used and not only were the foot pressure and number of gyrations varied but also the leveling pressure was changed. The sandstone aggregates used in Phase II had a high abrasion loss and were degraded materially during molding. The data show that the highest bulk densities were obtained from specimens molded by Standard THD Procedures. Apparently higher levels of compaction energy produced greater voids by degradation of the aggregates. At a fixed leveling pressure of 1590 psi and variable gyrations from 20 to 50 the Hveem stability and cohesion presented no pattern within operator variability even though stability ranged from 41 to 63 and cohesion from 178 to 522.

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* This foot pressure of 31 psi is a calculated value based on a hydraulic ram pressure of 50 psi and assumes an even distribution of pressure at the interface between the upper ram and the specimen.

However, for a fixed foot pressure and fixed number of gyrations and variable leveling pressure, there was a definite peaking in the cohesiometer values obtained. The peak occurred at 2750 psi leveling pressure, and 30 gyrations at a foot pressure of 31 psi. Bulk densities of the molded specimens did not correlate with energy of compaction.

3. The aggregate combination used in Phase III of the study contained 85 percent rounded material and 15 percent crushed stone with a medium high absorption value. If those specimens molded by THD procedures are omitted the bulk specific gravity is seen to vary directly with increased energy of compaction. By comparing results of the cohesiometer values listed in Tables 3 and 4 it appears that the effect of operator variability is more pronounced than is variation in energy of compaction for this mix design.

4. Operator reproducibility is often affected by the nature of the materials and design of an asphaltic concrete mixture. The aggregates used in Phase IV were dense and rounded except for 16 percent which was a crushed sandstone of high absorption. Both the density and the Hveem stability are apparently unaffected by differences in compactive effort and operator technique. As was the case with other mixes studied the cohesiometer values increased with compactive effort. It is suggested that a mix of this type might be improved in stability by added compaction if the Marshall method of design were used, since Hveem cohesion and Marshall stability correlate reasonably well.

5. A gap graded mix molded by two different operators showed excellent reproducibility and repeatability in test values. For a variation of compaction energy of more than three fold in the five levels used there was a remarkably small variation in Hveem stability. For sixty specimens the range was from 38 to 43. This would indicate a limiting stability exists for the materials and mix design studied. It further appears that where differences in laboratory compaction energy produce maximum values in both Hveem cohesion and stability there are separate and distinct levels of compaction energy producing maximum stability in one case and maximum cohesion in the other.

6. One possible explanation for an increase in cohesion with increasing energy of compaction is the production of an asphalt mastic on the aggregate surface by intraparticle attrition. For the

TABLE 3

Laboratory Results of Modified
Molding Procedures THD Type D Hot-Mix, River
Gravel, Crushed Limestone and Field Sand - Leveling Pressure 1590 psi

	THD Standard				19 psi 30 Gyrations				19 psi 40 Gyrations			
Oper.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.
E. H.	1.97	2.400	44	390	1.97	2.385	46	276	1.95	2.399	44	282
E. H.	1.97	2.400	48	315	1.99	2.383	42	201	1.97	2.392	44	279
R. W.	2.00	2.376	45	271	1.99	2.365	36	144	1.95	2.392	42	258
R. W.	2.00	2.371	47	266	2.02	2.342	--	161	1.96	2.390	44	332
W. S.	1.97	2.393	48	306	1.97	2.383	39	194	1.98	2.388	37	233
W. S.	1.98	2.413	49	355	1.95	2.395	44	276	1.96	2.392	41	269
J. M.	2.03	2.335	44	220	1.99	2.379	44	296	1.99	2.383	45	312
J. M.	1.99	2.371	45	223	1.99	2.384	41	262	1.97	2.392	37	366
J. M.	1.99	2.385	47	273	1.99	2.379	43	276	1.98	2.388	42	285
Average Values	1.99	2.383	46	291	1.98	2.377	42	232	1.97	2.391	42	291

	31 psi 30 Gyrations				31 psi 40 Gyrations			
Oper.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.
E. H.	1.95	2.406	43	310	1.97	2.407	52	427
E. H.	1.94	2.412	52	330	1.97	2.400	44	357
R. W.	1.96	2.397	41	331	1.97	2.408	47	378
R. W.	1.95	2.419	41	318	1.97	2.403	38	403
W. S.	1.96	2.404	39	308	1.95	2.411	45	383
W. S.	1.95	2.397	43	297	1.97	2.405	40	362
J. M.	1.98	2.396	42	398	1.98	2.401	42	407
J. M.	1.98	2.394	39	381	1.96	2.408	42	410
J. M.	1.98	2.397	42	316	1.96	2.405	37	354
Average Values	1.96	2.402	41	339	1.97	2.405	43	387

TABLE 4

Laboratory Results of Modified
Molding Procedures THD Type D Hot-Mix, River
Gravel, Crushed Limestone and Field Sand - Leveling Pressure 1590 psi

	THD Standard				19 psi 30 Gyrations				19 psi 40 Gyrations			
		Bulk	Hveem			Bulk	Hveem			Bulk	Hveem	
Oper.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.
R. W.	1.99	2.382	38.5	242	1.97	2.402	43	373	1.97	2.405	43	322
R. W.	1.99	2.390	43	252	1.97	2.389	53	388	1.96	2.414	46	394
R. W.	1.98	2.389	41.5	232	1.99	2.389	40.5	316	1.98	2.402	42.5	415
R. W.	1.98	2.389	47	303	1.97	2.396	51	399	1.95	2.408	40	364
R. W.	1.98	2.396	42	266	2.00	2.376	44	337	1.99	2.403	41.5	266
R. W.	1.97	2.395	50.5	264	1.98	2.389	42	355	1.97	2.403	46.5	411
Average Values	1.98	2.390	44	260	1.98	2.390	46	361	1.97	2.406	43	362

	31 psi 30 Gyrations				31 psi 40 Gyrations			
		Bulk	Hveem			Bulk	Hveem	
Oper.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.
R. W.	1.97	2.409	44	318	1.96	2.417	39.5	377
R. W.	1.96	2.412	43	385	1.95	2.419	40	378
R. W.	1.98	2.410	43.5	405	1.95	2.408	46	369
R. W.	1.97	2.406	49.5	341	1.95	2.410	39	361
R. W.	1.95	2.416	49.5	338	1.96	2.408	37.5	400
R. W.	1.95	2.413	45	266	1.95	2.418	33	300
Average Values	1.96	2.411	46	342	1.95	2.415	39	364

mixes studied this appears valid for those mixes that might be expected to produce very fine particles during compaction. This explanation does not appear to apply for materials that granulate under stress such as sandstone. If excessive fines are produced by this granulating attrition process, the cohesiometer value may be expected to drop.

7. Where differences in operator stamina and physical strength are apparent, the THD standard molding procedure may produce specimens with the most consistent stability values. With the other variations in compaction energy used in this study the operator of least strength and stamina produced test specimens of the lowest density but of the highest stability.

For the material and design used in Phase VI the operator variable affected the cohesiometer values more than did the differences in energy of compaction. Averages of cohesiometer values for different operators and energies of compaction ranged from 225 to 366. Yet the cohesiometer values peaked for each operator, but at different levels of compaction energy; and it might be further added that this peaking was also a function of operator stamina and strength.

8. Differences in test specimens created by different operators and with different amounts of compaction energy have a materially greater effect on test results than do allowed differences in the testing procedures of Texas or California.

9. Specimen density variability is reduced for a given mix design by using a compaction procedure consisting of a fixed number of gyrations and a constant foot and leveling pressure.

10. Hveem stability variations do not appear to correlate with compaction method or density for all the mixtures studied; however, for these same mixes Hveem stability can normally be expected to be within plus or minus ten percent of the mean value two out or three times.

V. A LABORATORY STUDY OF THE EFFECTS OF OVEN CURING LOOSE AND COMPACTED ASPHALTIC CONCRETE MIXTURES

Introduction

Absorption of a viscous liquid by solids such as aggregates used in asphaltic concrete is a time related process. Closely related to absorption in systems such as these is adhesion or bond. Paving grades of asphalt cement have desirable temperature susceptibility characteristics. This makes possible the establishment of an adequate bond between the asphalt and the aggregate under construction conditions.

The rate at which the bond is developed between the stone and the cement is largely affected by the viscosity of the cement at the time the bond is developing. Bond strength or tenacity at a given temperature is in turn primarily a function of the viscosity of the binder. Looking at this from another vantage point one might say that for given materials and conditions the more fluid (less viscous) asphalts would develop bonds or wet the surface in question more readily than would a more viscous cement. A highly viscous cement would, however, develop a bond more slowly for the same conditions and materials but once the bond is established it would be stronger than that involving the less viscous asphalt.

It was the purpose of this study, of which this is a summary report, to measure the effects of oven curing on loose and compacted asphalt-aggregate mixtures produced in the laboratory from dense graded aggregates and penetration grade asphalt cements.

Materials and Tests

The program of study included three distinct types of dense graded aggregates meeting the general requirements of aggregates for use in Texas Highway Department Class A Type D hot-mix asphaltic concrete. The aggregates included consisted of an all rounded silicious gravel, a crushed "quartzite" and a crushed limestone. The gradings of the three systems of aggregate were essentially identical and carefully controlled. Gradings are shown in

Table 5 and other pertinent data are listed in Table 6.

These aggregates were combined with different amounts of three different grades of asphalt cement, namely 60-70, 85-100 and 120-150 penetration materials. For each grade and amount of asphalt cement used, duplicate batches of mix were prepared in a standard manner. One batch was molded into laboratory test specimens while the companion batch was left loose. Both batches were then cured in a forced draft oven set at 140° F for selected periods of time. The time intervals used included 5, 15, 20 and 30 hours. A control batch was also prepared and processed in accordance with standard laboratory procedures of the Texas Highway Department.

The loose mixes that had been oven cured were then brought to molding temperature and laboratory test specimens were prepared in the identical manner used to prepare the companion molded samples. Both sets of specimens were then evaluated for bulk specific gravity, Hveem stability and Hveem cohesion. Sufficient loose material was available to study possible changes in the vacuum saturation specific gravity of the numerous mixes prepared.

The extractions and Abson separations were performed and the recovered asphalt cement was checked for changes in penetration and absolute viscosity. Absolute viscosities were obtained by use of the sliding plate microfilm viscometer.

A typical tabulation of a part of the data on one of the aggregates studied is shown in Table 7.

Conclusions

Based on the materials and conditions of tests encountered in this study the following conclusions appear to be warranted.

1. Oven curing of both the loose and molded asphalt-aggregate mixtures for time intervals up to 30 hours did not materially affect the Hveem stability. This held true for all three aggregates studied.

2. The Hveem cohesion values were generally increased with

TABLE 5

Grading Analyses of Aggregates Used
(Percent Retained Basis)

Sieve Size	Gravel Conc. Gravel 48% Conc. Sand 32% Queen City Sand 20%	Quartzite Quartzite 48% Coarse Screenings 16% Fine Screenings 36%	Limestone Limestone 100%	Averages
5/8-inch	0	0	0	0
1/2-inch	4.1	4.0	4.1	4.1
3/8-inch	24.9	24.0	23.3	24.1
No. 4	47.5	48.0	47.5	47.7
No. 8	54.0	52.0	53.8	53.3
No. 16	58.7	57.3	59.0	58.3
No. 30	64.4	64.0	64.9	64.4
No. 50	76.6	75.5	79.1	77.1
No. 100	89.5	90.4	90.4	90.1
No. 200	98.3	97.3	96.7	97.4
Passing No. 200	1.7	2.7	3.3	2.6

TABLE 6

Physical Properties of Aggregates and Asphalt Demand

Physical Property		Rounded Gravel	Crushed Quartzite	Crushed Limestone
Surface Area, sq. ft./lb.		29	31	29
Sand Equivalent		72	50	45
Apparent Sp. Gr.		2.65	2.80	2.71
Asphalt Content, %				
by CKE	60 - 70	4.5	5.3	7.4
	85 - 100	4.1	5.0	7.3
	120 - 150	3.9	4.8	7.2

TABLE 7

Effects of Curing on Bulk Specific Gravity, Stability and Cohesion of Mixture with Crushed Quartzite Aggregate

Asphalt Grade	Curing Time-Condition	Asphalt Content, % 3.80 Bulk Sp.Gr.	Hveem Stab.	Hveem Coh.	4.30 Bulk Sp.Gr.	Hveem Stab.	Hveem Coh.	4.80 Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.	5.30 Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.
	Standard	2.41	56	261	2.46	61	294	2.45	56	284	2.46	56	334
	5 hr. Molded	2.45	64	424	2.47	61	454	2.50	55	536	2.49	45	329
	Loose	2.43	60	383	2.44	61	446	2.48	52	473	2.48	39	389
	15 hr. Molded	2.41	57	268	2.44	57	335	2.48	59	439	2.48	51	486
60-70	Loose	2.43	59	351	2.48	60	508	2.48	62	422	2.49	43	385
	20 hr. Molded	2.43	60	399	2.43	62	490	2.48	58	547	2.48	44	479
	Loose	2.45	59	240	2.45	61	410	2.47	58	315	2.48	32	260
	30 hr. Molded	2.42	62	250	2.45	65	293	2.48	57	384	2.48	27	329
	Loose	2.43	59	229	2.44	67	210	2.48	54	339	2.48	30	291
		4.00			4.50			5.00			5.50		
	Standard	2.44	56	179	2.44	62	184	2.47	60	281	2.47	49	227
	5 hr. Molded	2.44	58	222	2.47	57	329	2.48	41	326	2.49	22	288
	Loose	2.43	51	170	2.44	58	189	2.47	58	339	2.48	16	261
	15 hr. Molded	2.46	57	205	2.48	56	256	2.48	59	223	2.49	32	184
85-100	Loose	2.45	60	225	2.45	59	251	2.44	59	225	2.47	37	237
	20 hr. Molded	2.42	58	198	2.44	57	226	2.47	52	316	2.49	26	263
	Loose	2.44	56	202	2.46	52	144	2.47	50	245	2.47	14	239
	30 hr. Molded	2.45	57	201	2.48	60	301	2.49	44	295	2.49	10	271
	Loose	2.44	61	255	2.46	60	256	2.49	53	302	2.48	15	224
		3.75			4.25			4.75			5.25		
	Standard	2.45	62	154	2.44	60	136	2.48	56	241	2.46	51	216
	5 hr. Molded	2.46	54	161	2.47	55	175	2.48	49	214	2.49	49	201
	Loose	2.45	55	133	2.46	56	162	2.47	53	157	2.49	42	209
	15 hr. Molded	2.44	55	120	2.45	55	113	2.48	52	259	2.49	53	283
120-150	Loose	2.43	56	99	2.45	60	102	2.49	52	236	2.49	42	262
	20 hr. Molded	2.43	58	134	2.47	61	177	2.47	59	191	2.50	40	256
	Loose	2.44	57	122	2.47	56	153	2.48	59	145	2.49	24	220
	30 hr. Molded	2.45	58	143	2.45	54	159	2.47	55	125	2.49	40	203
	Loose	2.44	57	152	2.47	54	150	2.47	56	112	2.48	44	219

increasing curing time for mixes made with the rounded gravel and the two harder asphalt cements. For the crushed limestone the cohesiometer value appeared to peak at about 15 hours of curing and this peaking was not relegated to state of compaction, that is, it did not appear to matter whether the mix was loose or molded during exposure. The quartzite blends presented no definite patterns in cohesiometer values. As expected, cohesiometer values decreased in all mixes with decreasing viscosity of asphalt cement.

3. Oven curing of the loose mixtures for periods of time up to 30 hours did not appear to affect densification effected during molding of the test specimens.

4. Vacuum saturation specific gravities of the loose mixes were essentially unaffected by oven curing of the loose mixes for periods of time varying from 5 to 30 hours.

5. Data on the standard penetration and absolute viscosity of the asphalt cement recovered from the various mixes revealed an expected general increase in viscosity with exposure to heat and a somewhat greater increase in viscosity with exposure to heat and air, if it is assumed that the loose mix was more exposed to air than the molded specimen duplicating the loose sample. In certain instances measured viscosities of cement recovered from mixtures cured in the loose state were lower than that for the molded specimen. Such differences may be attributed to differences in test procedure train.

VI. LABORATORY AND ROAD TESTS ON HOT-MIX ASPHALTIC CONCRETE

A study was made of materials, tests, and evaluation of asphaltic concrete in Texas. The materials used in 12 asphaltic concrete pavements were evaluated by different test procedures for possible correlation with service performance.

Testing and Evaluation of Materials

From each of the construction areas, samples were taken of (1) aggregates from the hot and cold bins, (2) asphalt from the storage tank, and (3) asphaltic mixture from the paving machine. The asphalts were tested for absolute viscosity values and also exposed to different aging atmospheres to determine the degree of hardening resulting from such exposures. Viscosity and aging data of the asphalts tested are presented in Table 8. It can be seen from this table that exposure to light caused the least hardening and that the atmosphere of heat and air was the most severe. A typical rheological diagram is shown in Figure 19.

A typical summary sheet on the evaluation of aggregates and mixtures is shown in Table 9. The study on gradation of aggregates showed that a fairly unique gradation was obtained from use of the State's specification. Figure 20 shows the narrow gradation band established for Type D gradation and Figure 21 presents a graphical illustration of the gradation limits that appear to be set by specifications but in reality are not as open as that shown. Also on Figure 21 are gradation limit lines followed by TTI for Type D aggregates.

The upper portion of Table 9 shows the various gradations obtained and that these met specification requirements. The middle portion of this table shows comparative values obtained by THD and TTI for the physical characteristics of the construction mixture. From these data it can be seen that the greatest difference was obtained in the value for theoretical maximum specific gravity. The TTI value was obtained by the vacuum-saturation method for the loose asphalt-aggregate blend which accounts for absorption of asphalt by the aggregate. The lower portion shows design values obtained for mixtures made

TABLE 8

Viscosity and Aging Data

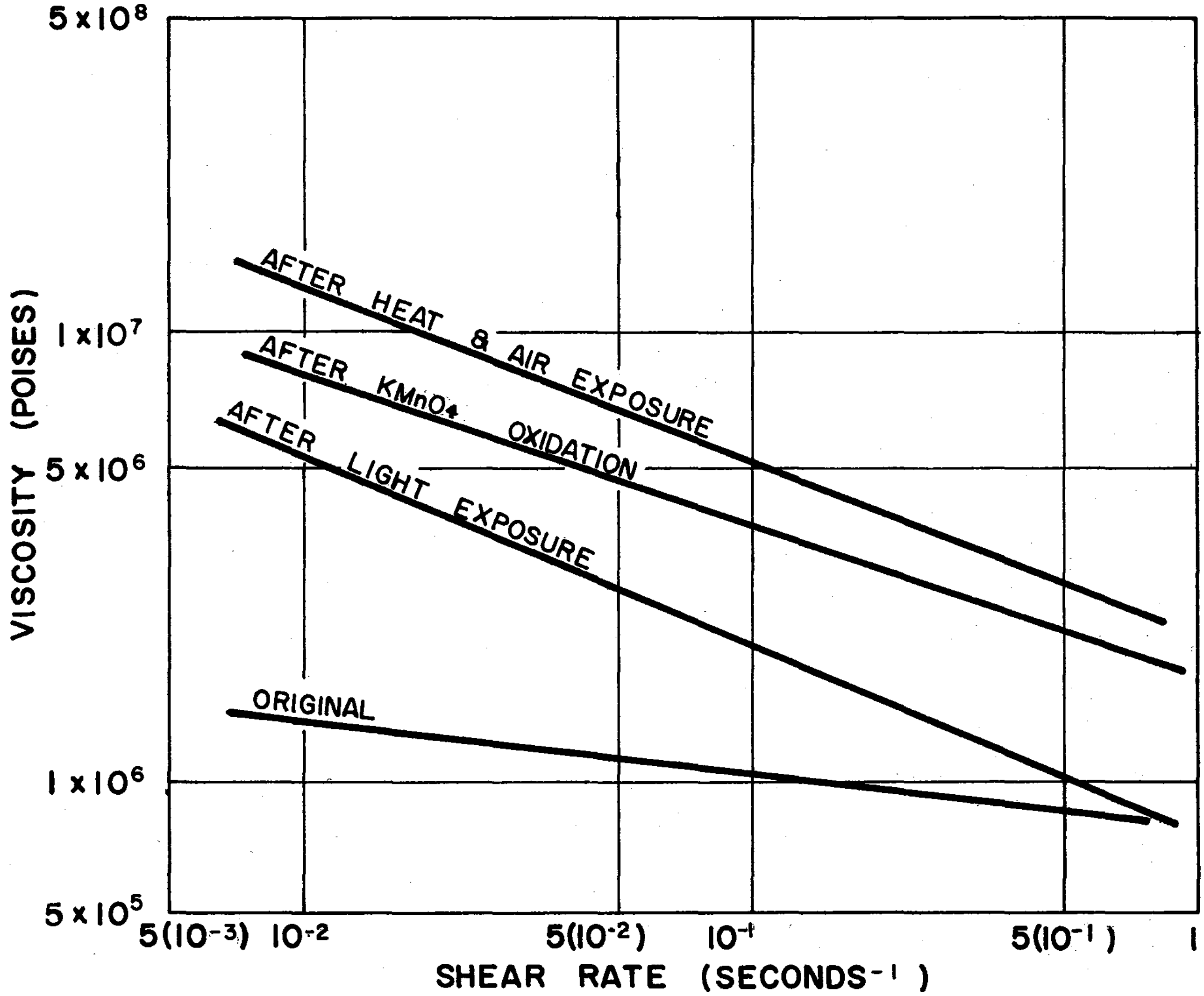
Sample	Original Viscosity Megapoise	After KM_nO_4[1] Viscosity Megapoise	After KM_nO_4[1] Oxidation Value	After Light[2] Viscosity Megapoise	After Heat[3] Viscosity Megapoise	Relative Viscosity[4]
1A	0.56	2.42	1.54	1.27	3.60	4.0
2B	1.10	4.65	1.14	2.65	6.70	3.1
3A	0.86	4.25	1.28	2.77	5.80	7.7
4C	1.19	2.55	1.15	3.00	6.00	3.5
5D	1.10	5.45	0.85	3.30	8.80	5.1
6E	0.74	2.98	1.45	2.06	3.55	---
7B	1.08	3.95	0.83	2.70	5.70	3.1
8F	1.16	5.05	1.00	2.05	6.05	---
9G	0.96	6.90	1.05	----	6.00	4.1
10H	0.88	6.45	1.26	----	4.05	5.1
11I	1.95	5.15	1.48	----	9.90	---

1. Ebberts.

2. Light (ultraviolet) 15-20 μ, 180-185°F. for 24 hrs., covered.

3. Exposed films 5 μ in thickness stored for 2 hrs. at 225°F.

4. 1962 samples direct from manufacturer exposed 2 hrs. at 225°F in 15-micron films. Data after Traxler.[14] The relative viscosity is obtained by dividing the viscosity after exposure by the viscosity of the unexposed material.



RHEOLOGICAL DIAGRAM

FIGURE 19

TABLE 9

Construction Material Evaluation

AGGREGATE

Combination	3/4"	1/2"	1/4"	#10	#40	#80	#200	Washed -#200	S.E.	Vac. Sat. Sp. Gr.
		Percent Passing Sieve								
THD Design	99	86	56	38	29	10	7			
THD Mold Spec.	100	94	77	57	50	18	4			
TTI Hot Bin	98	82	48	31	23	9	3	9.5	23	2.651
TTI Cold Bin	86	78	57	46	39	16	2	7.9	24	2.634 2.634

Construction Mixture

		Spec. Density	Theor. Sp.Gr.	Vac.Sat. Sp. Gr.	Rel. Density	Hveem Stab.	Cohesi-ometer	Asp. content	I-C %
THD Molded	THD Value	2.174	2.253		96.5	50		7.5	
	TTI Value	2.169		2.341	92.7	46	375	7.6	
TTI Molded	THD Value					43			
	TTI Value	2.182		2.341	93.2	48	390		72

TTI Laboratory Mixture

(one grade and source of asphalt)

Agg.	Asp. Content by C.K.E.	Vac. Sat. Sp. Gr.	Spec. Density	Rel. Density	Hveem Stab.	Cohesi-ometer	I-C %
Hot Bin	6.9	2.335	2.249	96.3	44	532	54
Cold Bin	7.0	2.378	2.185	92.0	48	397	37

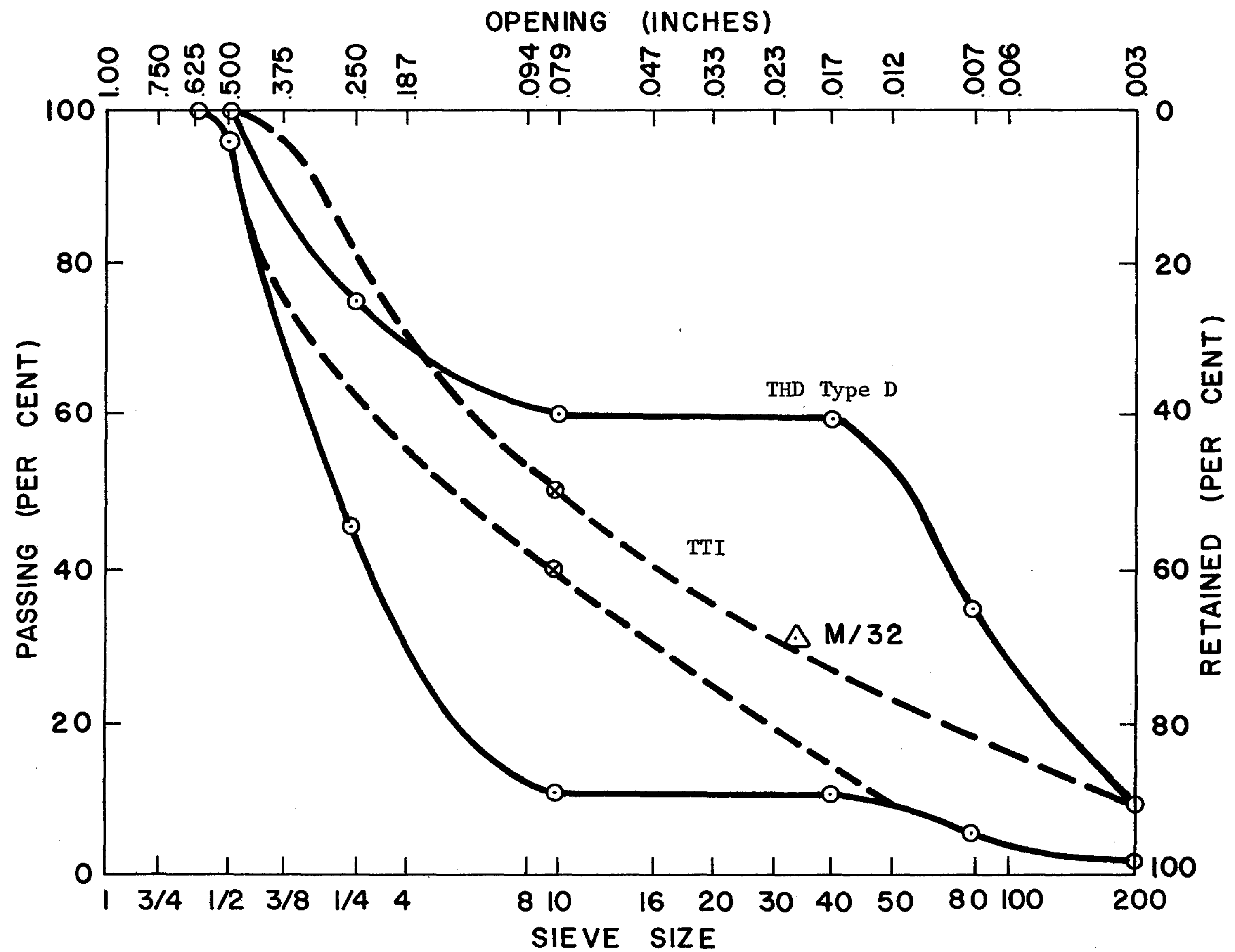


FIGURE 21 AGGREGATE GRADATION LIMITS

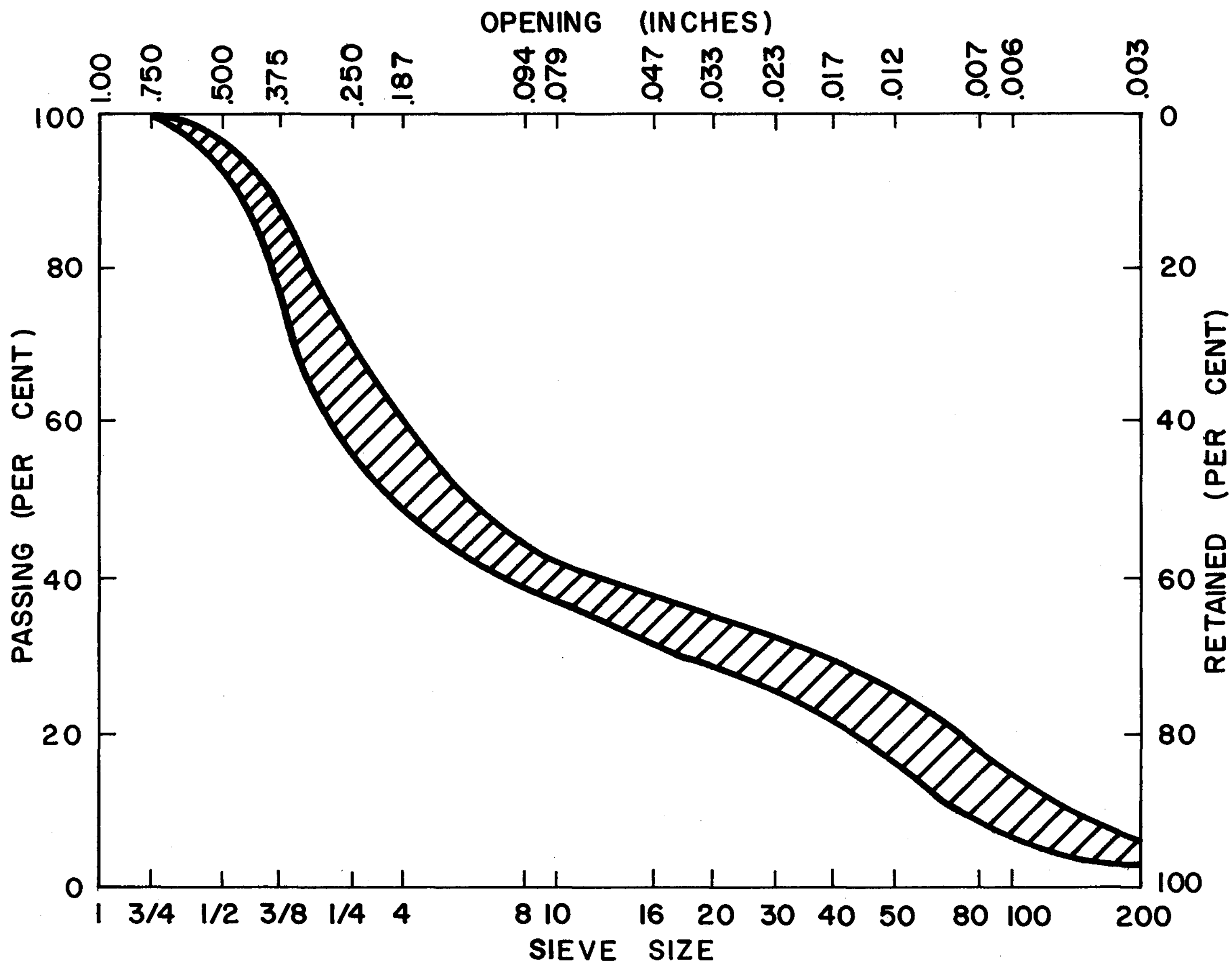


FIGURE 20 GRADATION BAND OF DIFFERENT MIXTURES

from hot and cold bin aggregates mixed with the amount of asphalt determined by the centrifuge kerosene equivalent test.

As shown in Table 9, the sand equivalent test was performed on both the hot and cold bin aggregate combinations and also that the immersion-compression test was utilized to obtain a measure of durability of these asphaltic mixtures. A comparison of the values of sand equivalent and retained strength from the immersion-compression test is shown in Table 10. These data indicate that the required minimum value of 75 percent retained strength for the I-C test will be met by the blends having a sand equivalent value above 45. It is not implied that aggregate cleanliness is the only factor influencing the I-C test value.

Evaluation data of samples taken from a test pavement are shown in Table 11 in which changes in aggregate gradations, pavement density, and asphalt consistency are listed. Studies of these data showed that pavement densities reached laboratory densities within eight months if the foundation was rigid and over this period of time if the base was flexible. Void contents decreased with pavement age and this value was smaller when based on THD theoretical than if compared with the vacuum-saturation specific gravity.

There was no trend established for degradation of aggregate as related to time. It is believed that variations within the pavements precluded establishing such a correlation. However, it was noted that the amount of the larger particle sizes was generally reduced within the early life of surfacings built with crushed limestone.

The hardening of asphalt in the pavements approached a limiting value in about two years. The viscosity obtained for an original asphalt after exposure in the laboratory to heat and air was found to be comparable to the viscosity of the asphalt in the pavement at about 5 months of service. Hardening during and very shortly after construction would normally account for most of this increase in viscosity.

Deflectometer Study

This study was initiated to compare the fatigue characteristics of laboratory prepared specimens to those of large diameter cores

TABLE 10

Comparison of Sand Equivalent Values and Immersion-Compression Results

Sample	S. E.	I-C Ret. Strength, % Laboratory Mixture	I-C Ret. Strength, % Construction Mixture
5 Cold Bin	60	92	--
5 Hot Bin	56	96	76
4 Hot Bin	55	102	88
10 Hot Bin	53	105	72
4 Cold Bin	52	92	--
1_D Hot Bin	49	75+	77
11 Cold Bin	43	93	75
12 Hot Bin	42	98	92
6 Hot Bin	42	62	96
8 Hot Bin	37	93	91
10 Cold Bin	35	54	--
3 Hot Bin	34	70	56
9 Cold Bin	32	64	--
12 Cold Bin	32	120	--
9 Hot Bin	30	33	49
2 Hot Bin	29	--	45
1_D Cold Bin	27	84	--
3 Cold Bin	26	71	--
1_C Cold Bin	24	57	--
7 Cold Bin	24	37	--
8 Cold Bin	24	95	--
1_C Hot Bin	23	74	81
7 Hot Bin	23	54	72
2 Cold Bin	21	50	--

TABLE 11

Road Specimen Evaluation

Compacted Densities

Age, mos.		Lab. Spec.	4	16	30
Density	THD	2.376			
	TTI	2.397	2.344	2.366	2.372
Voids	THD		3.5	2.6	2.3
	TTI		4.3	3.5	3.4

Vacuum-Saturation Sp. Gr. of Stored Construction Mixtures

Age, mos.	0	10	11	16	28
Sp. Gr.	2.455	2.455	2.462	2.456	2.494

Asphalt Consistencies

Age, mos.	Original	4	16	30
Content	4.8	5.7	5.6	5.1
Pen.		27.5	20.	25.
Viscosity	1.16	19.5*	25.5	25.5*
A.I.	5.21	1.33	1.20	1.13

* Film thickness greater than 10 microns

Aggregate Gradation, percent passing

Sieve	3/4"	1/2"	1/4"	#10	#40	#80	#200
THD Design	98	74	50	35	23	19	6
THD Specimen	100	74	55	42	28	21	8
Road Age, mos.							
4	100	85	65	42	27	21	8
16	100	91.1	62.7	43.6	29.9	20	3.8
30	100	83.1	59.3	42.7	28.2	21	7.9

taken from the roadway. In this comparison mixtures from eight sections in different roads were tested in the deflectometer. As in the parent study, mixtures were taken from the laydown machine and sent to the laboratory for analysis and testing. Also the road base was prepared for future sampling which involved the taking of 20-inch diameter cores.

Table 12 presents typical data obtained for comparing the fatigue characteristics of field and laboratory specimens. Unfortunately only cores of one age were taken from any test section. However, even though a limited amount of data were obtained, certain similarities were found between the laboratory and field specimens tested in the deflectometer.

As presented previously, there was not much difference in the shapes of the aggregate gradations curves obtained for the eight sections. Figure 22 shows a band depicting the limits of gradation.

Figure 23 shows data plotted for comparing the effects of strain and stress on fatigue life for both laboratory prepared and field specimens. From this figure it appears that both types of specimens show comparable responses to the deflectometer test. Differences in fatigue life between laboratory and field specimens are attributed to differences in viscosity of the asphalt in these mixtures.

Conclusions

1. The State's specifications for aggregate gradation on Types C and D generally result in yielding dense graded aggregate blends. However, it is possible to meet specification requirements with an overly gap-graded blend. It is recommended that gradation be expressed in "total percent passing."

2. The sand equivalent test is recommended for use in controlling the cleanliness of aggregates for hot-mix asphaltic concrete. A minimum sand equivalent value of 45 is suggested since the data showed that immersion-compression test requirements were met for such mixtures.

3. The centrifuge kerosene equivalent test was capable of establishing the design-amount of asphalt for the aggregates evaluated.

TABLE 12

DATA FROM DEFLECTOMETER STUDY

Sample No. 17 County Caldwell Road U.S.183 (N. of Lockhart)

MIXTURE COMPOSITION

	Aggregate Gradation Percent Passing on Sieve 3/4	1/2	1/4	#10	#40	#80	#200	Asphalt Content Percent
Lab Mold - 18" D		100	72	47	37	15	3	5.2
Field Core - 18" D		100	75	50	38	15	3	5.3

PHYSICAL PROPERTIES

	Spec. Density gm/cc	Vac.-Sat. Sp. Gr. gm/cc	Rel. Density %	Hveem Stab. %	Cohesiometer gm/w/3"H	Recovered Asphalt Pen. 77°F	Recovered Asphalt Visc., 77°F Megapoises
Lab Mold							
Standard THD-4"D	2.238			52	160		
Vib.-Knead-4"D	2.116			41	133		
Vib.-Knead-18"D	2.077					28	15.4
Field Core - Age 11 mos.							
18"D	2.162					27.5	19.3
4"D from 18"D	2.158						

DEFLECTOMETER TEST RESULTS

	Reps. To Fail $x10^{-3}$	Radial Stress, S_R psi	Radial Strain $x10^4$
Lab Mold (3 Spec.)	9.6	140	14.1
Field Core (3 Spec.)	(52) (100)	(161) (106)	(12.6) (9.7)

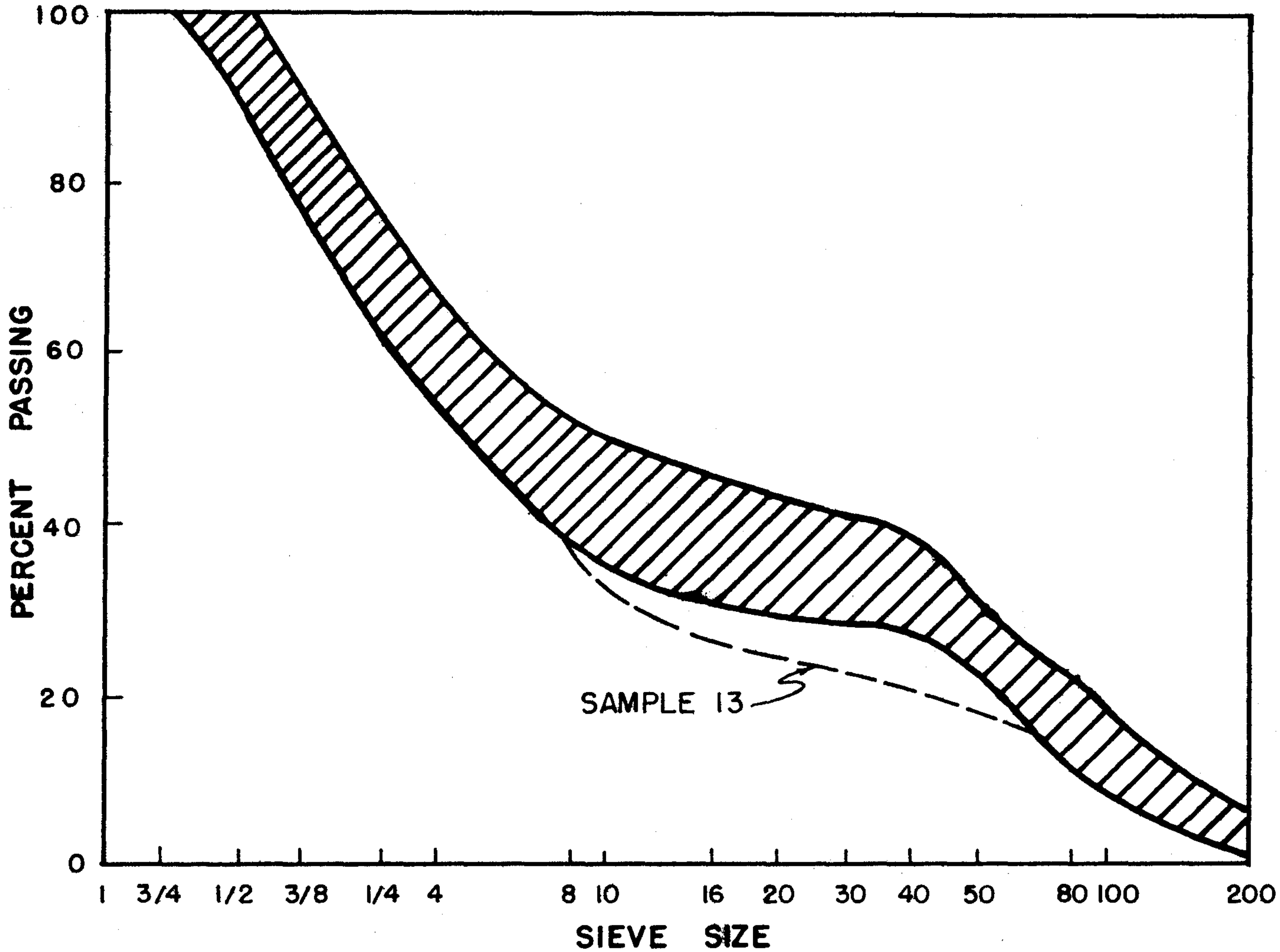


FIGURE 22 GRADATION BAND FOR ROAD SAMPLES

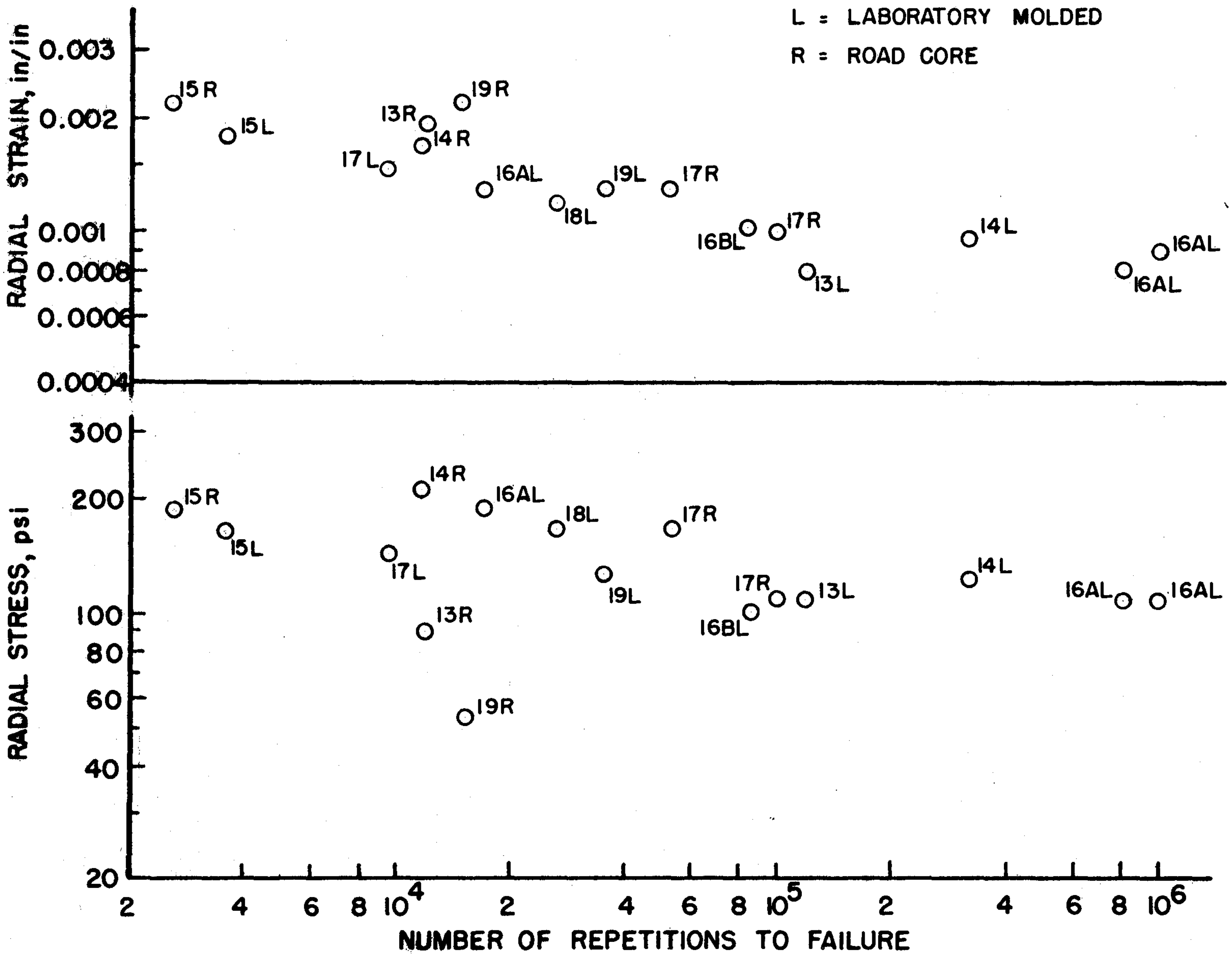


FIGURE 23 STRESS AND STRAIN VS. NUMBER OF REPETITIONS TO FAILURE

4. The vacuum-saturation specific gravity of the loose asphalt-aggregate mixture is recommended for the basis of computation for void content. The use of this specific gravity value is logical since it allows for absorption of asphalt by the aggregate and the data have shown that this value was not exceeded by pavement densities.

5. Laboratory design of asphaltic concrete should include some type of durability test. The immersion-compression test was not investigated for this purpose and at this time not enough information is available to verify the present requirement of 75 percent retained strength; however, adoption of this or a similar test is suggested.

6. Variabilities in the manufacture of and construction with asphaltic concrete precluded establishing a correlation between laboratory aging of asphalt with performance of pavements. The upper limit of asphalt hardening in a pavement was found to be reached at about 2 years of service.

7. Final voids in an asphaltic concrete mixture have a critical affect on the rate of hardening taking place in the binder. Rate of hardening of the binder is also directly related to temperature and exposure during mixing, transporting and placing of a mix. Every effort should therefore be made to minimize the mixing temperature, the mix cycle, the handling time, and the delay between the laydown operation and compaction.

8. Field density measurement should be required. It is recommended that field density should be not less than 96 percent of laboratory density based on laboratory samples made from material of the same batch on which field density checks are made. Randomized samples should be taken.

9. It is recommended that a minimum cohesiometer value of 100 be specified in the design for asphaltic concrete to be used in the higher type pavements. A maximum cohesiometer value should also be specified but as yet data are not available to be specific; however, it is the feeling that the maximum cohesiometer value should not exceed 300 to 350. An upper limit for Hveem stability should also be considered.

10. In reference to the deflectometer study, the amount of data obtained is too limited to warrant positive conclusions. However, there are indications that because of similar aggregates and gradations a unique relationship existed between applied strain and number of repetitions to result in failure.

From the deflectometer study, it is apparent that any attempt to duplicate road mixtures must be done completely in the laboratory since the reheating of actual paving mixtures in preparation for compaction hardens the asphalt to a degree not usually found in the pavement during its early life.

PUBLICATIONS

Project 2-8-57-3
Road Tests on Hot-Mix Asphaltic Concrete

1. Research Repot 3-1, "A Laboratory Study of the Operator Variable on Molding Procedure and Mix Design Variations in Hot-Mix Asphaltic Concrete" by Bob M. Gallaway and R. A. Jimenez.

2. Research Report 3-2, "A Laboratory Study of Oven Curing Loose and Compacted Asphaltic Concrete Mixtures" by R. A. Jimenez and Bob M. Gallaway.

3. Research Report 3-3, "Road and Laboratory Tests on Hot-Mix Asphaltic Concrete" by R. A. Jimenez and Bob M. Gallaway.

4. Research Report 3-4, "Abridgments of Reports Resulting from Studies on Project, 'Road Tests on Hot-Mix Asphaltic Concrete'" by R. A. Jimenez and Bob M. Gallaway.