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A Study of the Basic Strength Components of Asphaltic Concrete

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A STUDY OF THE BASIC STRENGTH COMPONENTS

OF ASPHALTIC CONCRETE

BY

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A STUDY OF THE BASIC STRENGTH COMPONENTS

OF ASPHALTIC CONCRETE

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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INTRODUCTION

Generally speaking, pavements may be divided into two broad classifications, i.e. rigid and flexible. The term rigid pavement is applied only to wearing surfaces constructed of portland cement concrete. The term flexible is used to denote the tendency of all layers (wearing surface, base, and subgrade) to conform to the same shape under traffic.

The basic concept in the design of flexible pavement is that a load applied to the surface is distributed over successively larger areas, as it is transmitted through each lower layer or course, until it has become so diminished in its intensity as to be less than the strength of the natural soil upon which the pavement rests.[1] This means that each succeeding course from the surface downward can be made from material of less strength than the layers immediately above. Therefore, the thickness of the flexible pavement structure is a function of the traffic loads, the load supporting characteristics of the native soil, and the structural properties of the several courses. The frequency of the load is also a factor.

It is the primary purpose of this study to evaluate with greater accuracy than has been done previously, the basic strength components of the bituminous surface course. These components make up what is known as stability which refers to the ability of the paving

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[1] Kenneth B. Woods, Highway Engineering Handbook (New York: McGraw Hill Book Company, 1960), sec. 26, p. 11.

mixture to offer resistance to deformation under sustained or repeated loads. This resistance to deformation generally manifests itself in the form of cohesion, frictional resistance, and interlocking resistance. The process of mixture design must combine these three strength components so as to obtain a maximum resistance to deformation.

DESCRIPTIONS OF TESTS USED IN THE DESIGN OF BITUMINOUS MIXTURES

The major properties to be incorporated in a bituminous paving mixture are stability, durability, flexibility, and skid resistance. The mix design methods which are presented here were established to determine which combination of asphalt and aggregate would perform the best, especially with regard to stability and durability. There are four methods of mix design used today: 1. Hubbard Field, 2. Marshall, 3. Hveem Stabilometer, and 4. Triaxial.

The criteria established for the various mix design methods are for dense-graded, hot-mix paving, except for Hveem, where it could be used for both hot-mix or mixture with liquid asphalt. The method of compactions of laboratory specimen varies from the impact compaction of Marshall specimen to the kneading compaction used in Hveem specimen. The temperature of testing the laboratory specimen varies from 140 degrees Fahrenheit for the Hveem, Marshall, and Hubbard Field specimens to 75 degrees Fahrenheit for the Smith Triaxial specimen. The rates of deformation used in testing the laboratory specimens vary from a high 2.4 inch per minute for Hubbard Field specimen to a low 0.001 inch per minute for Smith Triaxial specimen. The bulk specific gravity of the aggregate is used in Hubbard Field and Smith Triaxial methods. The apparent specific gravity of aggregate is used in the Hveem and Marshall methods.

1. Hubbard Field Mix Design Method:

This stability test was devised in the middle of the 1920's. It was one of the earliest methods for evaluating the strength properties of bituminous mixtures. It was developed by Prevost Hubbard and F. C. Field.

The two principal features of the Hubbard Field method are a density voids analysis and stability test.[2] The test consists of determining the maximum load developed as a specimen 2 inches in diameter by 1 inch high is forced through 1.75 inch standard orifice. This load is reported as the stability value.

The initial criteria developed were based on the sheet-asphalt paving mixture which was widely used at that time. It required gradation such that a minimum of 65 percent passed number 10 sieve and 100 percent passed number 4 sieve. A mixture which developed a stability of 2000 pounds or more showed no appreciable distortion under heavy traffic, but when stability values of less than 1200 pounds were obtained, pavement distortion became quite obvious.[3] Five percent air voids were found fairly impervious to air and moisture and were used as an upper limit, and two percent as a lower limit.

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[2]Martin J. Rogers and Hugh A. Wallace, Design and Construction of Asphalt Pavement (New York: McGraw Hill Book Company, 1958), p. 224.

[3]Woods, sec. 18, p. 65.

When wheel loads became heavier and traffic more intense, larger size aggregates were needed to obtain greater stability in paving mixture. Accordingly the specimens were modified to 6 inches in diameter by 3 inches high. Aggregates containing a minimum of 35 percent coarse aggregate with maximum size of 3/4 inch were used.

2. Marshall Mix Design Method:

This method was used by the United States Army Corps of Engineers during World War II. The design was conceived by Bruce Marshall of the Mississippi State Highway Department. This method is applied only to hot-mix paving mixes using penetration grade of asphalt cement and containing aggregates with maximum size of 1 inch or less. This method is used for both laboratory design and field control of asphaltic hot-mix paving. The specimens are subjected to stability and flow tests as well as density and voids analyses. The stability of the test specimen is the maximum load resistance in pounds which the standard test specimen will develop when tested. The flow value is the total movement in units of 0.001 inch occurring in the specimen between no load and maximum load during the stability test.

The Corps of Engineers was able to establish suitable criteria based upon results obtained from the Marshall test as shown in Table 1.[4]

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[4] _Ibid._, sec. 18, p. 81.

Table 1. Marshall Method Standard for Mix Design

Test Property	Type of Mix	Criteria for 100 Psi Tires
Stability	All*	Min. 500 lbs.
Unit Weight		Not Used
Flow	All*	Max. 20
Percent voids total mix	Asphaltic Concrete	3-5
	Sand Asphalt	5-7
	Binders	4-6
Percent Aggregates voids filled	Asphaltic Concrete	75-85
	Sand Asphalt	65-75
	Binders	65-75

*Asphaltic concrete, sand asphalt, and binders
United States Army Corps of Engineers Design Data

3. Hveem Stabilometer Method of Mix Design:

Developed by Francis N. Hveem of the California Division of Highways, this method is applicable to paving mixtures using both penetration and liquid grade of asphalt and aggregates up to one inch maximum size. Therefore this method can be used for both hot asphalt paving mix as well as for cold mixes prepared with liquid asphalt.

This method depends on the evaluation of surface capacity of the aggregate with respect to asphalt. This surface capacity or asphalt requirement depends upon three factors: 1. the gradation of aggregate for a given weight (small particles have a greater surface area than large ones); 2. the effect of aggregate shape and character of the surface; and 3. variation in absorption capacity of the aggregate particles.[5]

Surface area determination that included characteristics of the aggregate was devised by the California Division of Highways. Absorption capacity was determined by Centrifugal Kerosene Equivalent (CKE). This is done by immersing fine aggregate in kerosene and centrifuging it for 2 minutes at a force of 400 times gravity, or in the case of coarse aggregates using SAE number 10 oil and leaving it immersed for 5 minutes. The amount retained by the aggregate is a measure of the absorption capacity.

After preparing test specimens with the percentage of asphalt determined from the CKE test the stability is measured by the Hveem stabilometer. The stabilometer is a type of a triaxial test in which vertical loads are applied and resulting lateral pressures read at several increments of vertical load. Following this test, specimens are subjected to the cohesiometer test which measures the cohesive or tensile resistance of the compacted mix. Measurements are also made to determine resistance of the mix to the action of water or swelling.

Normally, these two tests will be run at the asphalt content indicated by the CKE test, with one specimen containing greater and another lesser amounts of asphalt in order to determine the optimum asphalt content.

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[5] *Ibid.*, sec. 18, p. 70.

A satisfactory pavement performance should have the following values:

	light traffic	all other traffic
Stabilometer value	30+	35+
Cohesiometer value	50+	50+
Swell	Less than 0.030 inch	

4. Smith, or Asphalt Institute, Triaxial Method of Mix Design:

This method was developed by Vaughn R. Smith of a California research corporation. In the triaxial test method, the stresses acting upon a specimen closely approach the system of stresses existing in a flexible pavement or pavement foundation when it is supporting a load.[6]

There are two ways of testing a specimen in a triaxial method. 1. The closed system (Smith Triaxial) encases the specimen in a rubber membrane, surrounded by a liquid for the transmission of lateral pressures developed while applying a vertical load to the specimen. Vertical loads are applied incrementally, and the developed lateral pressure is measured as soon as the rate of deformation is less than 0.001 inch per minute. The vertical load is recorded at the same time. This test is made at room temperature. 2. The open system consists

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[6] V. R. Smith, Application of Triaxial Test to Bituminous Mixture, A Paper Presented at the First National Meeting on Bituminous Paving Mixtures, San Francisco, October 10-14, 1949, Prepared by the American Society for Testing Materials (Philadelphia: American Society for Testing Materials, 1951), p. 55.

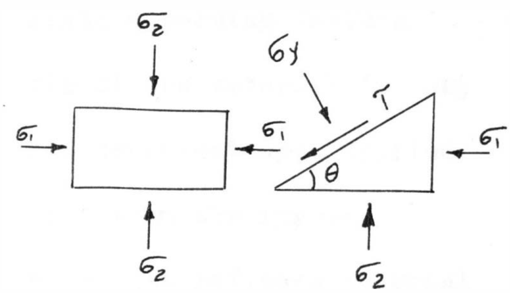
of a test whereby a prescribed lateral pressure is maintained through the liquid surrounding the specimen during the application of the vertical load required to fail the specimen.

Otto Mohr represented the mathematical relationship of the cohesion and internal friction during the nineteenth century. Mohr's interpretation is as follows:

τ = Shear

σ_1 = Axial applied stress

σ_2 = Lateral support



$$\tau = (\sigma_1 - \sigma_2) \sin\theta \cos\theta$$

$$= 1/2\ (\sigma_1 - \sigma_2) \sin 2\theta \quad - - - (1)$$[7]

$$\sigma_y = \sigma_1 \cos^2\theta + \sigma_2 \sin^2\theta$$

$$= \sigma_1 \left(\frac{1 + \cos 2\theta}{2}\right) + \sigma_2 \left(\frac{1 - \cos 2\theta}{2}\right)$$

$$= \frac{\sigma_1 + \sigma_2}{2} + \frac{\sigma_1 - \sigma_2}{2} \cos 2\theta \quad - - - (2)$$[8]

Figure I. Mohr Interpretation

Values of equations (1) and (2) are shown in Figure II.

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[7]Fred B. Seely and James O. Smith, Advanced Mechanics of Materials, (New York: John Wiley & Sons, 1959), pp. 48-49.

[8]Ibid.

Figure III represents the Mohr diagram where the magnitude of the compressive strength is laid off on the horizontal axis. The confining pressure is also plotted on the horizontal axis. The diameter is the difference between the compressive strength and lateral support. A stable, or non-failure, condition of loading is represented by any Mohr circle that lies within the Mohr envelope, and any Mohr circle touching the envelope represents a pending failure condition.[9] Mohr envelope is a characteristic of the material for any one temperature and rate of loading and is not dependent upon applied stresses. However, the Mohr circle is prepared from the imposed stresses which in turn give the diagram a shape that reflects material properties.

The major contribution of the Smith Triaxial Method to the bituminous mixture design comes from devising an evaluation chart that relates values of cohesion and angle of internal friction. The other phase of the development was that of testing numerous bituminous paving mixtures whose performance in the field were known. It was noted that satisfactory performance under heavy traffic fell near or above the 100 pounds per square inch supporting power curve.

Further studies indicated that mixtures that had enough supporting power at the beginning, but with an angle of internal friction of 20 degrees or less, shifted to the unsatisfactory region under the

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[9] Woods, sec. 18, p. 85.

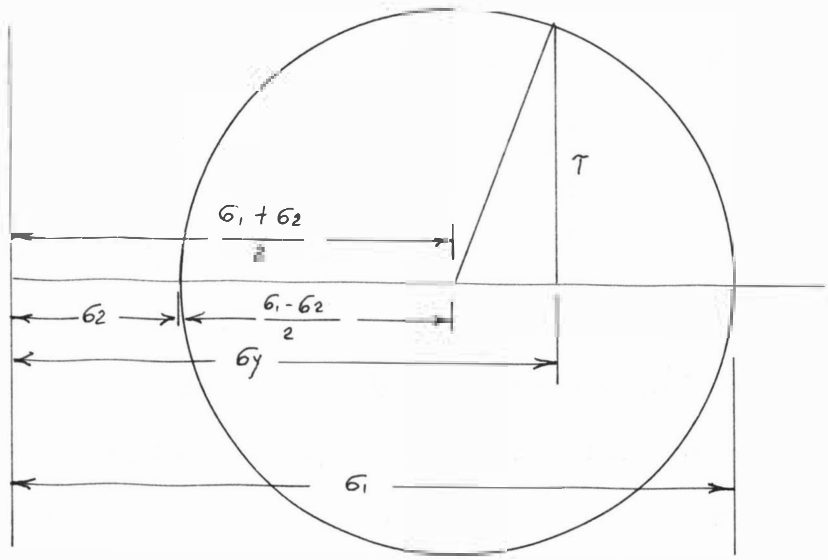

Figure II. Mohr circle for obtaining stresses on any plane in terms of principal stresses

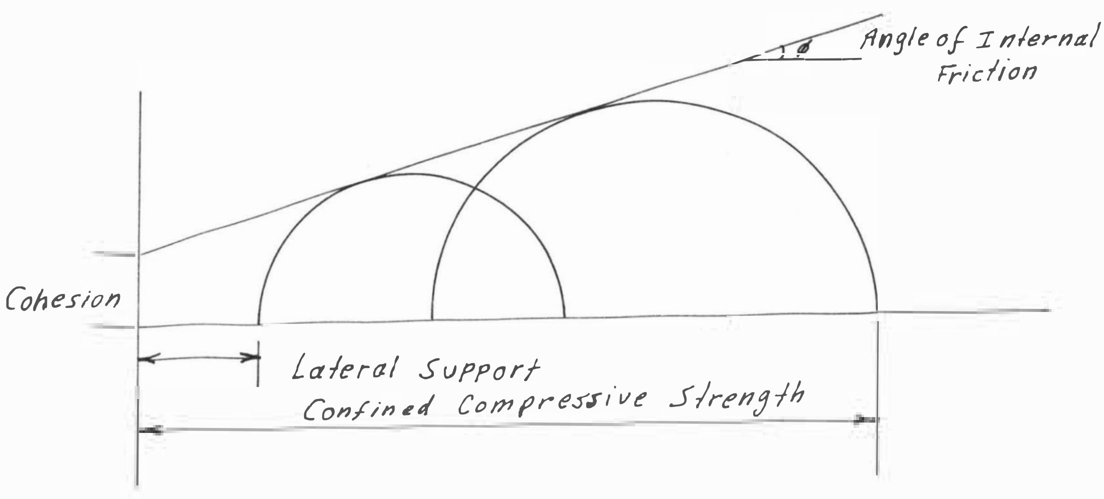

Figure III. Mohr diagram for triaxial test action of traffic. Therefore a minimum 25-degree angle of internal friction was set as shown by Figure IV. Specimens were found more stable with voids over 4 percent up to 10 percent.

Pavements that are not subjected to heavy and frequent wheel load could be judged on values less than 100 pounds per square inch as a contact pressure applied to the pavement surface.

The evaluation chart for asphaltic concrete must be limited to dense-graded paving mixture using penetration grade asphalt and containing aggregate up to one inch in diameter for maximum size.

5. Modified Triaxial Method:

This method of testing bituminous mixture is closely related to the Smith Triaxial Method of testing, which is more suitable for research work than the other three methods previously described. This method was chosen for use in the present research and is described in detail in the following section.

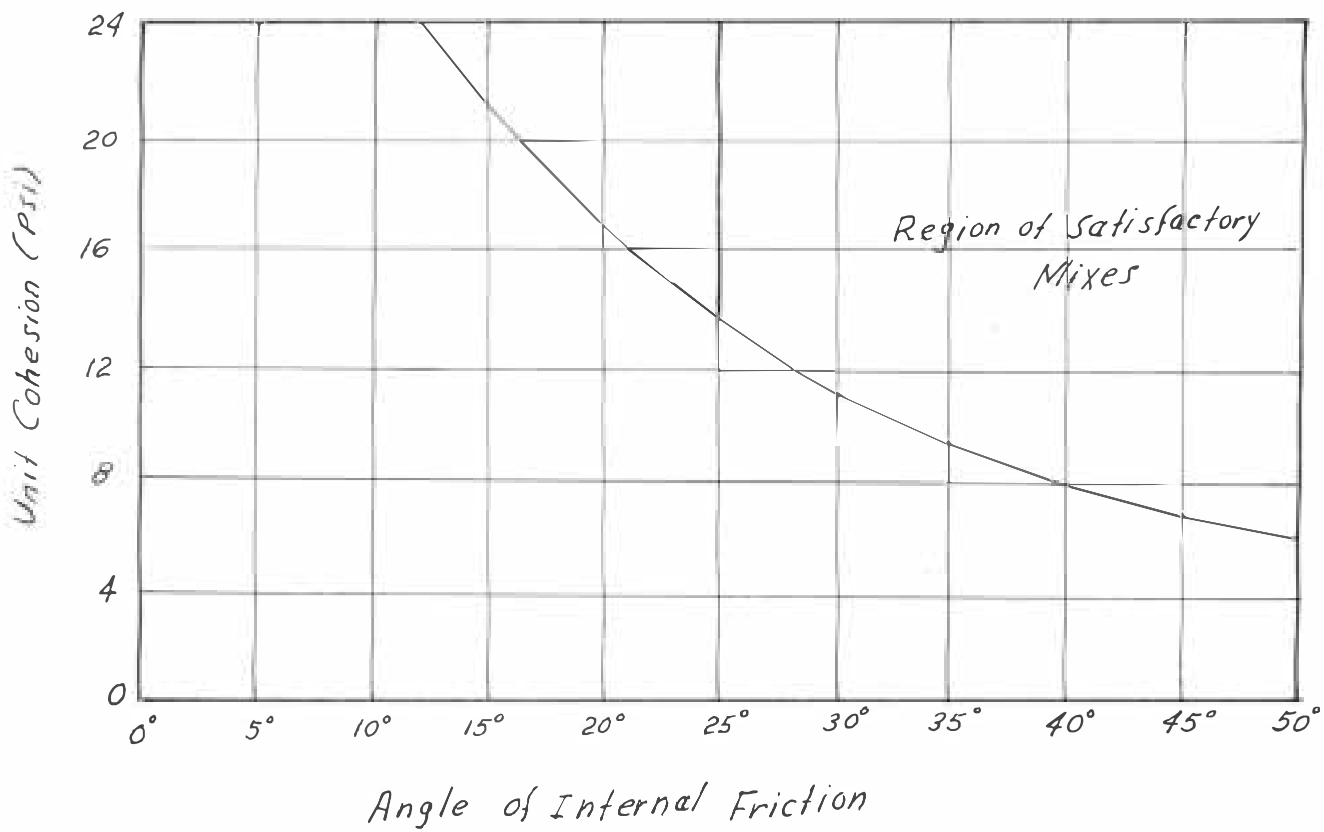

Figure IV. Evaluation chart of asphaltic concrete

TEST PROCEDURE

Associate Professor Emil R. Hargett of South Dakota State College designed the testing apparatus (Figure V) which was manufactured in the College Engineering Shop. This method is intended for the testing of hot-mix asphalt paving mixture using dense-graded aggregates with maximum size of one-half inch. Penetration grades of asphalt are used as a binder for this type of mixture. The rate of deformation of the test specimen is 0.12 inch per minute. Dimensions of the test specimen are 4 inches in diameter and 4½ inches in height. The two types of aggregate used are crushed and rounded. A fixed lateral pressure is used during the testing of each specimen to failure.

This method differs from the Smith Triaxial in the way the lateral pressure is developed, in the dimensions of the test specimen, in the rate of deformation, and in the type and maximum size of aggregates used. The two methods are similar in the following aspects: controlled lateral pressure, the type of mixture and asphalt, and the fact that both tests are conducted at room temperature.

Preparation of the Specimen: The materials used in preparing the specimen are crushed aggregate, uncrushed aggregate, and asphalt. The crushed aggregate consists of crushed quartzite produced at Dell Rapids, South Dakota. The uncrushed aggregate consists of a mixture of coarse and fine aggregate from a local concrete batching plant. Figures VI and VII show graded batches of crushed and uncrushed

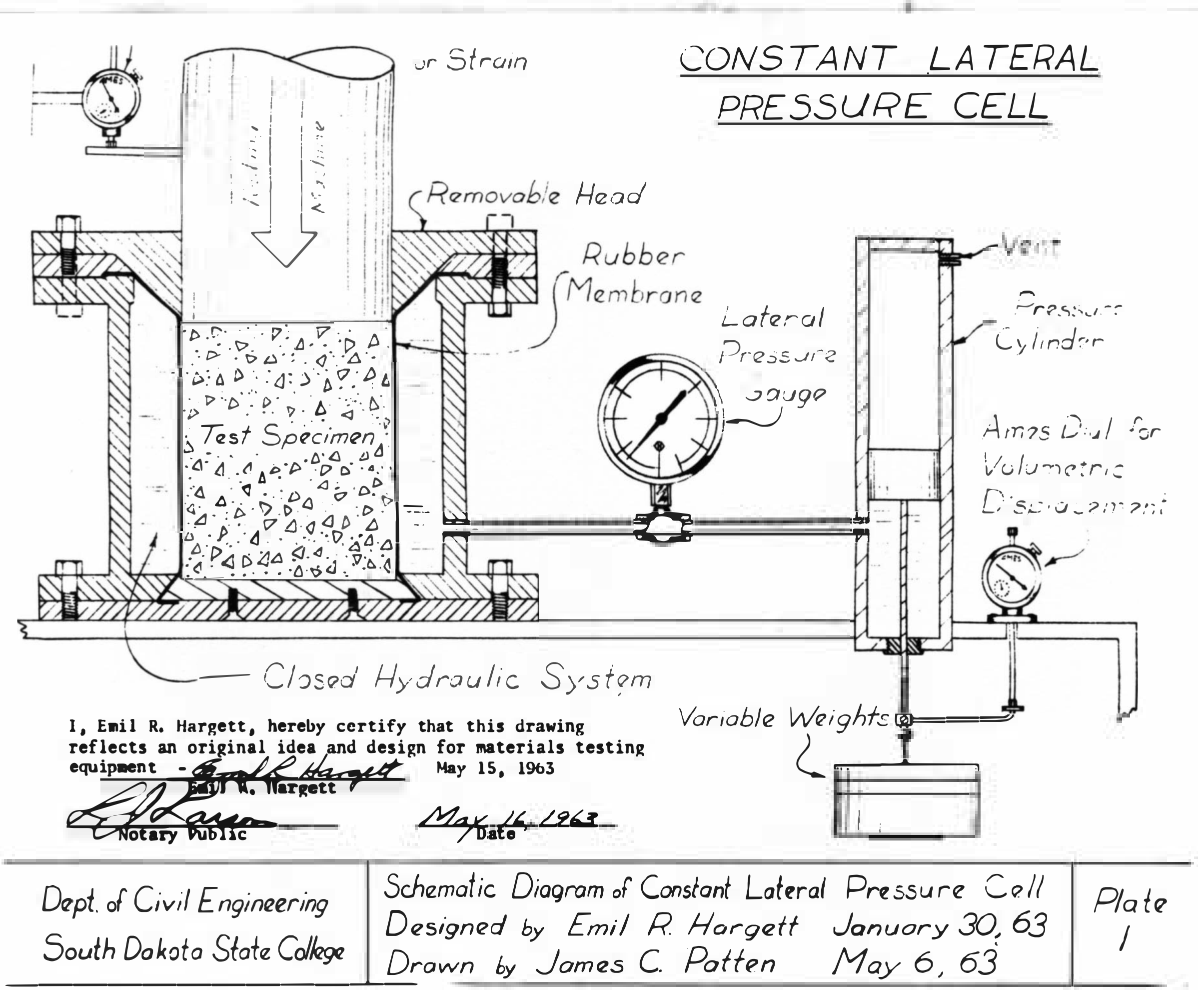

Figure V. Modified triaxial machine

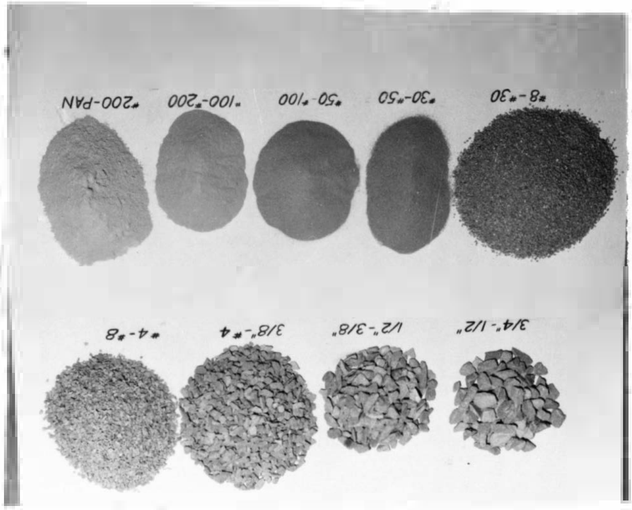

Figure VI. Crushed aggregate

Figure VII. Uncrushed aggregate

aggregate respectively. For the preparation of test batches, 2100 grams of crushed aggregate were used, and in the case of rounded aggregate 2300 grams were used as shown in Table 2.

Table 2. Aggregate Gradation Used in Preparing Test Specimens

Sieve Size Square Opening	Percent Passing	Average	Percent of Each Retained	Crushed (Grams)	Rounded (Grams)
1/2"	100	0			
3/8"	80-100	90	10.0	210	230
# 4	55-75	65	25.0	525	575
# 8	35-50	42.5	22.5	473	517
# 30	18-29	23.5	19.0	399	437
# 50	13-23	18	5.5	116	126
#100	8-16	12	6.0	126	138
#200	4-10	7	5.0	105	115
Powder				146	162

The Mobil Oil Company furnished the asphalt cement (AC 85-100) for this study. This material was shipped from the refinery at Augusta, Kansas.

All sized fractions of aggregates were placed in a pan and heated in the oven to a temperature of 320 degrees Fahrenheit. The asphalt cement required for every mix was poured into a beaker and put into an electric oven that maintained a temperature of 280 degrees

Fahrenheit. The aggregate and asphalt were poured into a preheated mixing bowl of a mechanical mixer and mixed for a period of 60-90 seconds. The molds were heated to a temperature of 350 degrees Fahrenheit.

A mechanical compactor (Model CN - 24) was used to compact the specimens. This compactor (Figure VIII) was purchased from Soiltest for the preparation of test specimens with uniform compaction and density. A modified compacting foot which has a shape of half a circle was used. The total weight of the hammer used is 5.85 pounds. The hammer was set for a stroke of 12 inches. The compacting foot was heated by a hot plate before the compaction was started.

The heated mold assembly was placed as shown in Figure VIII, and a paper towel was inserted into the bottom of the mold. The inside surface of the mold was lubricated slightly to prevent bonding.

The mixing bowl and contents were placed on a hot plate beside the compaction machine in order to maintain the temperature of the mixture above 250 degrees Fahrenheit throughout the compaction operation.

The bituminous mixture was "spooned" into the mold in four layers. Each layer received 25 blows. During compaction the mold turned 90 degrees around its vertical axis after each blow. After the fourth layer was compacted, the collar of the mold was removed, and the top surface of the specimen was smoothed with a heated trowel. The mold containing the specimen was left to cool to room temperature,

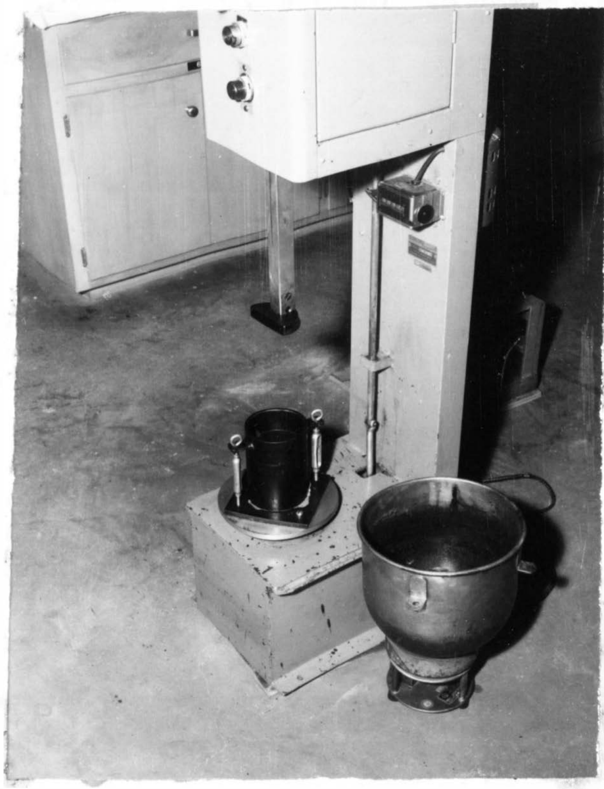

Figure VIII. Mechanical compactor

after which the specimen was removed from the mold by means of a regular compacting hammer. The specimen was weighed in air first; then in water in order to determine its density.

Test Procedure: The test specimens were wrapped in paper towels to simplify the problem of inserting and removing the test specimens from the testing machine. The paper also minimized the amount of cleaning of the rubber membrane prior to and following each test. The specimen was put in the modified triaxial apparatus and was seated firmly. The modified triaxial apparatus was positioned in a Tinius Olsen compression testing machine. Weights were added to the cable attached to the pressure cylinder in order to create the required lateral pressure in the system. (See Figure IX.) The weight combinations of 20, 25, and 37.5 pounds created 10.0, 20.0 and 30.0 psi of lateral pressure respectively. An Ames Dial for deformation was attached to the moving cylinder of the compression testing machine. The test load was applied with the compression testing machine using a head speed of 0.12 inch per minute. Loading was read from the compression machine and recorded at intervals of 0.02 inch of deformation, as was indicated by an Ames Dial that read to an accuracy of 0.001 inch deformation. Loading was recorded to about 0.1 inch of deformation beyond the failure of the test specimen.

After the necessary displacement was recorded, the test load was removed, and then the lateral pressure was reduced to zero by removal of the weights. The testing program consisted of a total of 32

Figure IX. Modified triaxial apparatus
in testing position

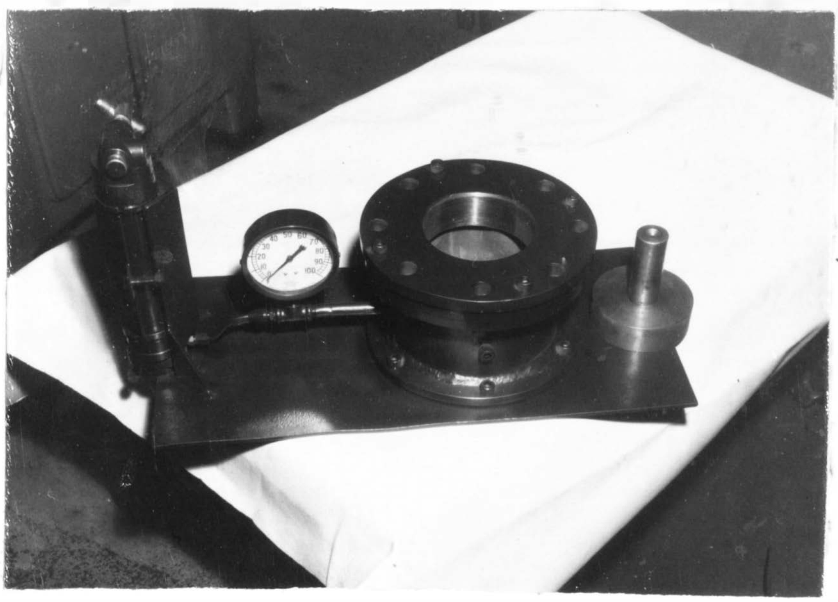

Figure X. Modified triaxial apparatus

specimens described as follows:

1. Four test specimens containing crushed aggregate and percents asphalt of 4.0, 4.5, 5.0, and 5.5 were tested at a confining pressure of 0 psi.

2. Four test specimens containing crushed aggregate and percents asphalt of 4.0, 4.5, 5.0, and 5.5 were tested at a confining pressure of 10 psi.

3. Four test specimens containing crushed aggregate and percents asphalt of 4.0, 4.5, 5.0, and 5.5 were tested at a confining pressure of 20 psi.

4. Four test specimens containing crushed aggregate and percents asphalt of 4.0, 4.5, 5.0, and 5.5 were tested at a confining pressure of 30 psi.

5. Another 16 specimens were tested using rounded aggregate with percentages of asphalt and confining pressures as indicated in numbers 1 through 4 above.

DISCUSSION OF RESULTS

Density: As can be seen from Tables 3 and 4, the average density of the crushed aggregate is (2.36 x 62.4) pounds per cubic foot, while the rounded aggregate has an average density of (2.42 x 62.4) pounds per cubic foot. It is not common to have a rounded aggregate specimen with a density value higher than a crushed aggregate specimen, provided both have been compacted with comparable compaction effort. But in using a mechanical compactor, the rounded aggregates are oriented easier to develop a higher density, since they do not have the tendency to interlock or develop an arch that prevents the lower layers from being well compacted.

Deformation: Tables 5 and 6 show the average deformation of the specimens at the time of failure. The data show that the specimen withstood greater deformation prior to failure when the lateral pressure was increased as seen in Figure XI. Figure XII shows that specimens which contained larger percentage of asphalt accommodated the larger deformation prior to failure. Accordingly, the lowest deformation (0.06 inch) occurred when the specimen was unconfined and had 4% asphalt, while the highest (0.36 inch) happened at 30 psi lateral pressure and the specimen contained 5.49% asphalt as shown in Table 8 in the appendix.

Tables 5 and 6 reveal that the average deformations for the rounded aggregate specimens are higher than those for the crushed

Table 3. Average Values of Density and Strength With Respect to Percent Asphalt

Type of Aggregate	Percent Asphalt	Average Density lbs./cu.ft.	Average Strength at Failure (psi)
Crushed	4.0	2.34 x 62.4	327
Crushed	4.5	2.36 x "	346
Crushed	5.0	2.38 x "	360
Crushed	5.5	2.37 x "	360

Table 4. Average Values of Density and Strength With Respect to Percent Asphalt

Type of Aggregate	Percent Asphalt	Average Density lbs./cu.ft.	Average Strength at Failure (psi)
Rounded	4.0	2.40 x 62.4	326
Rounded	4.5	2.41 x "	323
Rounded	5.0	2.43 x "	325
Rounded	5.5	2.44 x "	316

Table 5. Average Values of Strength and Deformation With Respect to Lateral Pressure

Type of Aggregate	Lateral Pressure (psi)	Average Strength at Failure (psi)	Ave. Deformation at Failure (in.)
Crushed	0	---	.08
Crushed	10	294	.20
Crushed	20	353	.25
Crushed	30	399	.29

Table 6. Average Values of Strength and Deformation With Respect to Lateral Pressure

Type of Aggregate	Lateral Pressure (psi)	Average Strength at Failure (psi)	Ave. Deformation at Failure (in.)
Rounded	0	---	.08
Rounded	10	279	.22
Rounded	20	332	.26
Rounded	30	384	.31

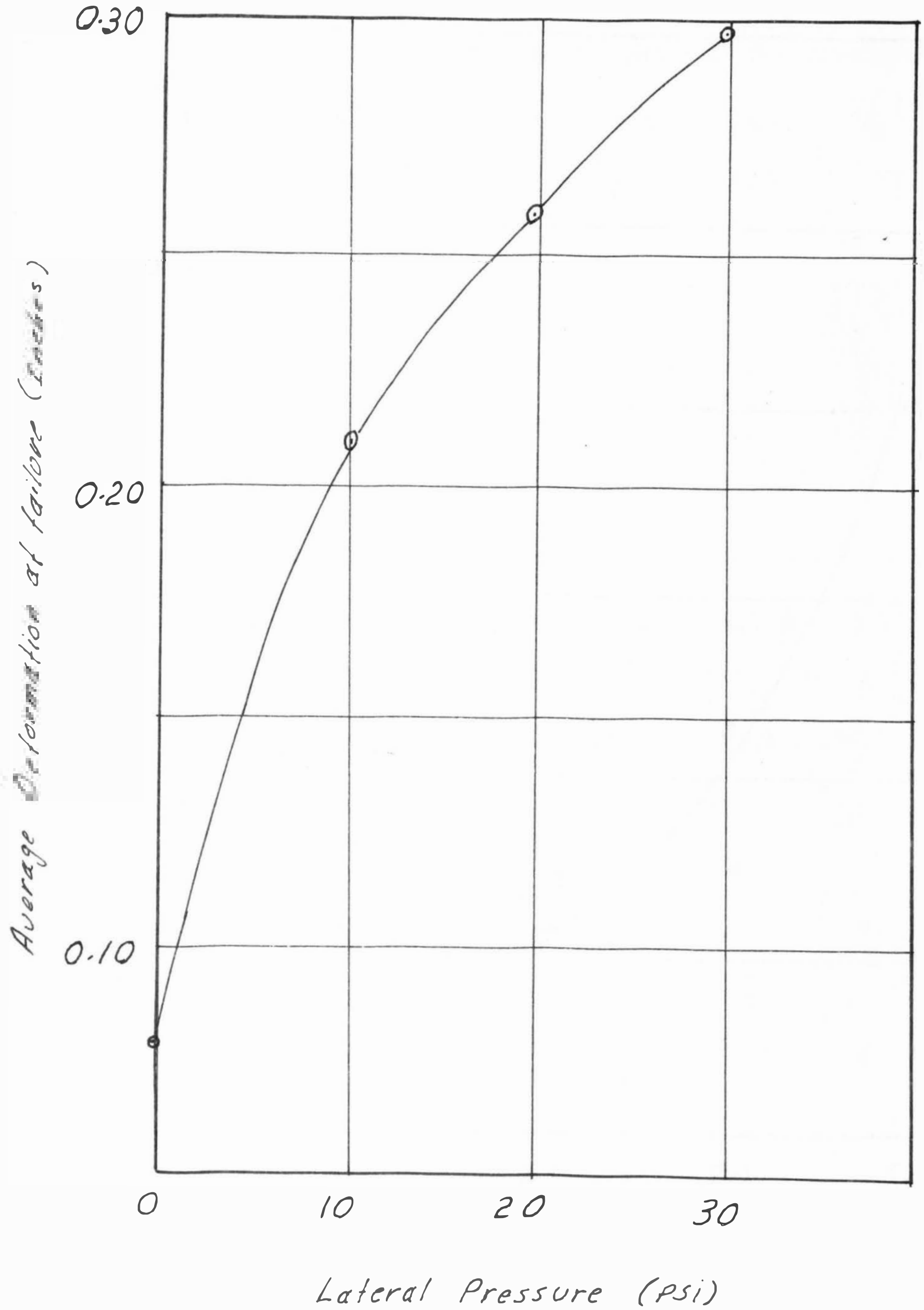

Figure XI. Effect of lateral pressure on deformation

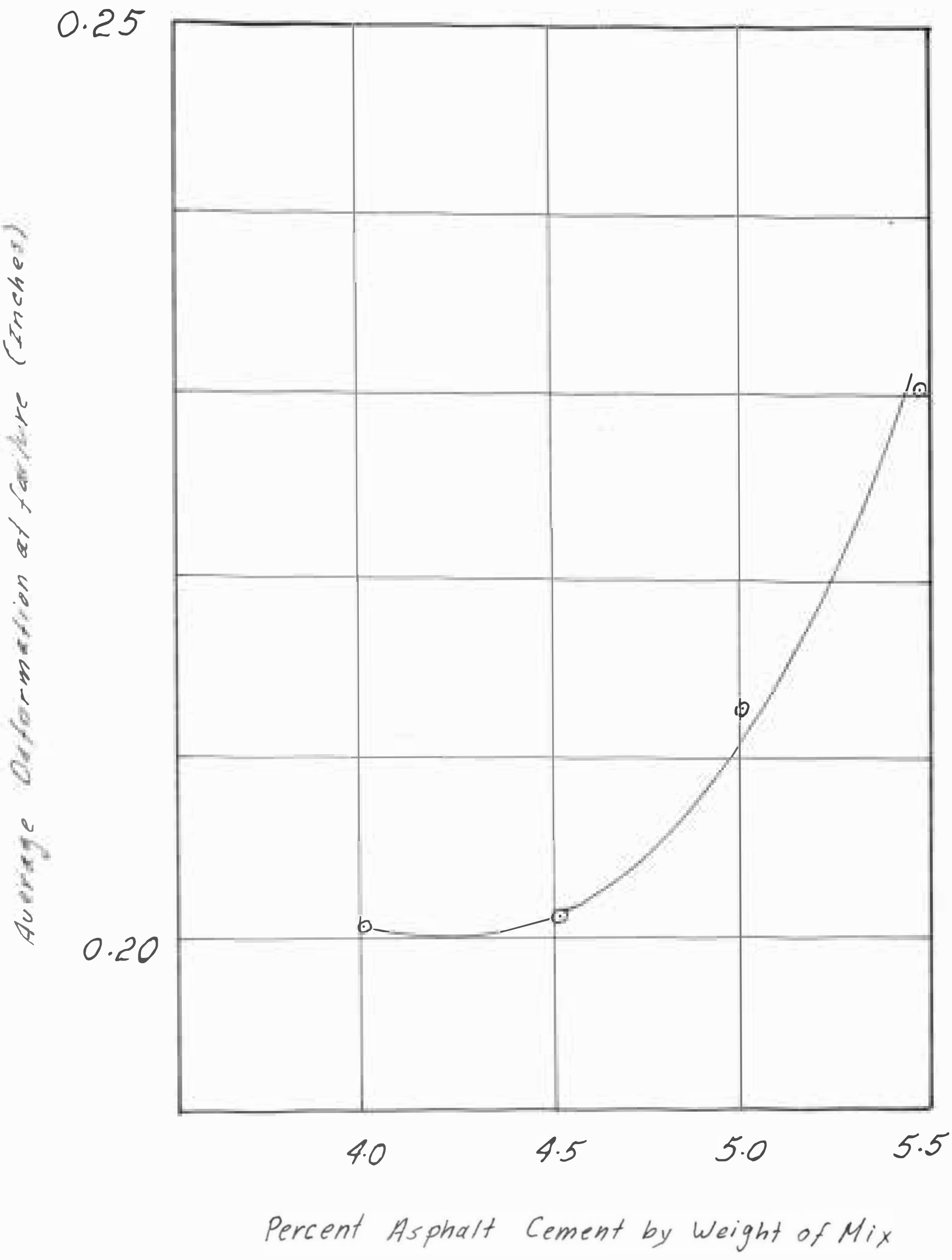

Figure XII. Effect of percent asphalt on deformation aggregate specimens. The reason for this is that the rounded aggregate do not have the absorption characteristics of the crushed aggregate; therefore, rounded aggregate specimens seem to be richer in asphalt even though they contain the same percentage as did the crushed aggregate.

Stability: The crushed aggregate specimens have higher stability values than the rounded aggregate specimens. Also the average strength value is higher as a result of increasing the lateral support as shown in Tables 5 and 6 and also in Figure XIII. Figure XIV shows the average strength at failure in pounds per square inches with respect to percent asphalt for both the crushed and rounded aggregate specimens. The figure indicates that the strength of the specimen increased with increasing percent asphalt up to a point between 5% and 5.5%. For percentages of asphalt above 5.5% there was a decrease in the strength of the mixture.

The angle of internal friction, shear and cohesion are evaluated from Mohr Diagrams (Figures XV, XVI) that were plotted from the average compressive strength and their respective lateral pressures. The results obtained are as follows:

	Crushed	Rounded
τ	= 118 psi	115 psi
ϕ	= 45°	41°
C	= 51 psi	56 psi

The above results are normal, but the difference would have been larger if the specimens had not been confined.

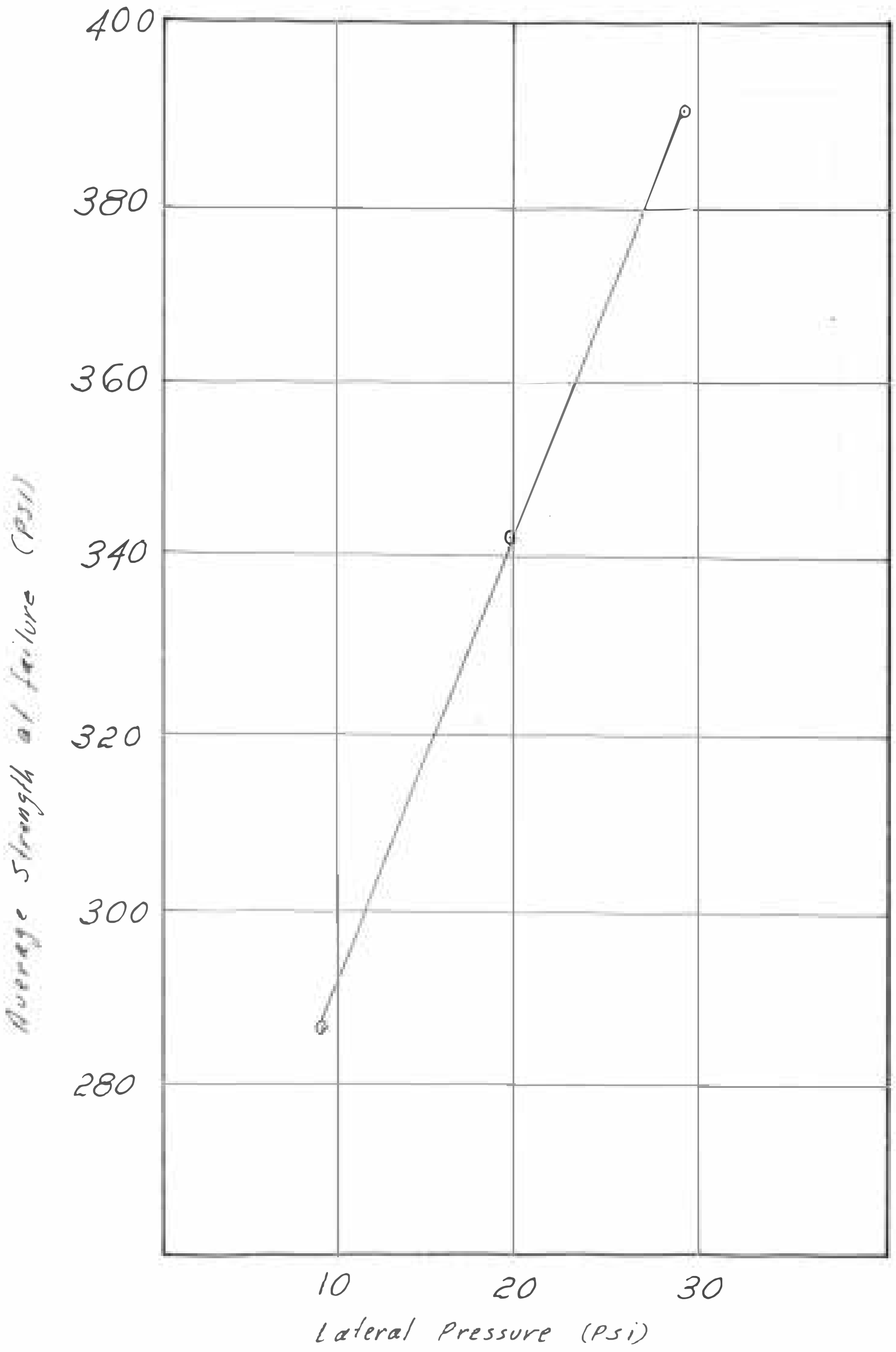

Figure XIII. Effect of lateral pressure on the strength of specimen

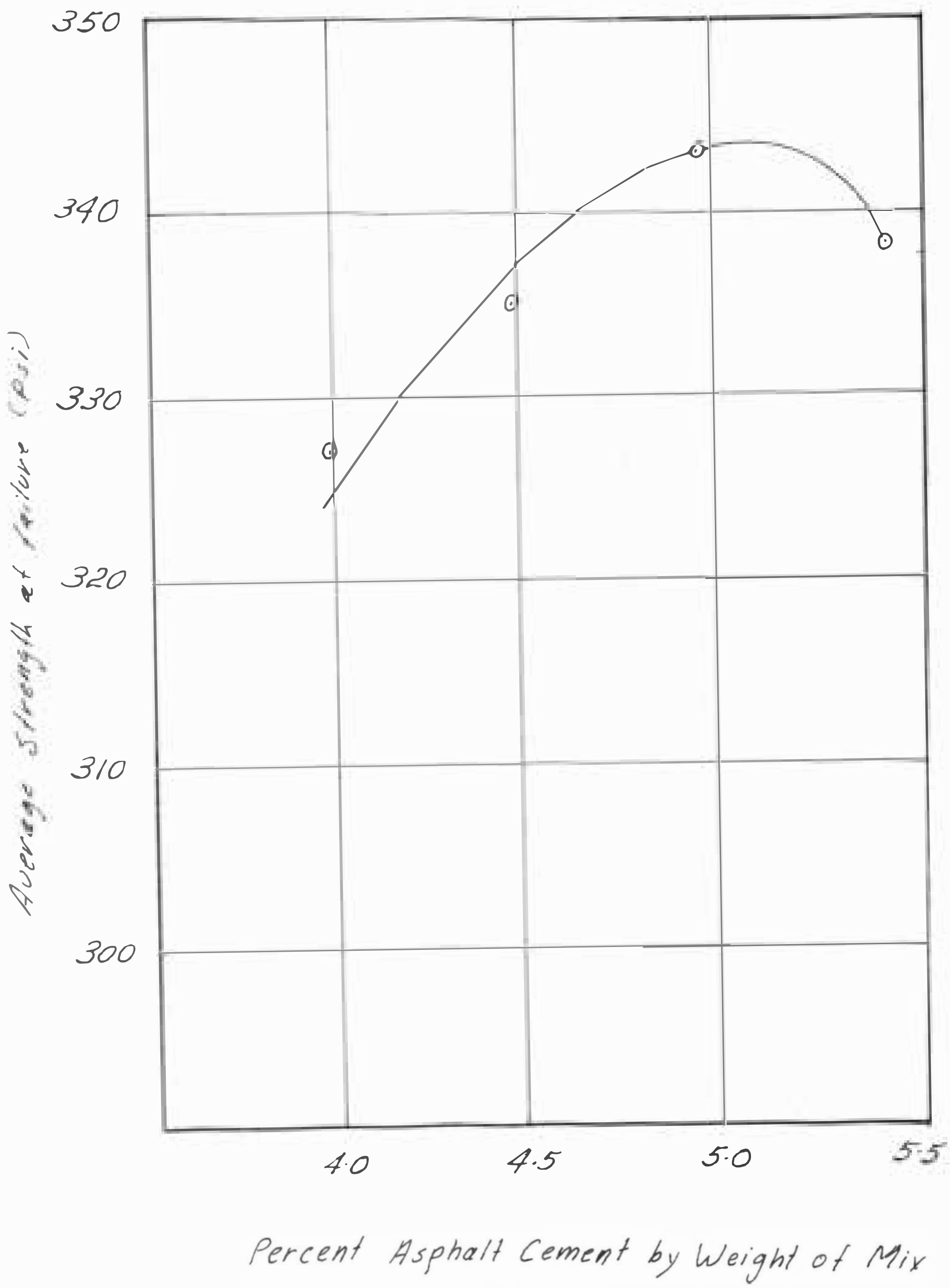

Figure XIV. Effect of percent asphalt on the strength of specimen

Comp. Strength psi	Lat. Pressure psi	Normal Pr. psi	Shear Stress psi
$\sigma_1' = 294$	$\sigma_2' = 10$	$N' = 49$	$\tau' = 101$
$\sigma_1'' = 353$	$\sigma_2'' = 20$	$N'' = 69$	$\tau'' = 118$
$\sigma_1''' = 399$	$\sigma_2''' = 30$	$N''' = 84$	$\tau''' = 136$

$C = 51$ psi $\phi = 45^\circ$ Av. $N = 67$ psi Av. $\tau = 118$ psi

Scale 1" = 100

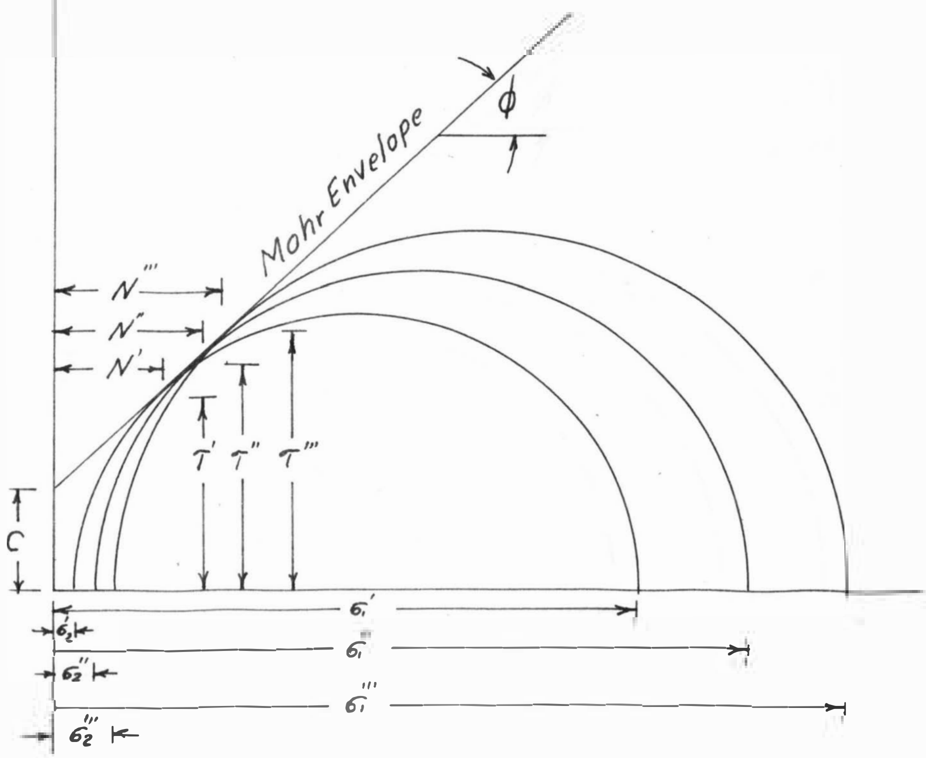

Figure XV. Mohr diagram for crushed aggregate

Comp. Strength psi	Lateral Pr. psi	Normal Pr. psi	Shear Stress psi
$\sigma_1' = 279$	$\sigma_2' = 10$	$N' = 51$	$\tau' = 100$
$\sigma_1'' = 332$	$\sigma_2'' = 20$	$N'' = 69$	$\tau'' = 115$
$\sigma_1''' = 284$	$\sigma_2''' = 30$	$N''' = 89$	$\tau''' = 131$

$C = 56$ psi $\phi = 41°$ Av. $N = 70$ psi Av. $\tau = 115$ psi

Scale: 1" = 100

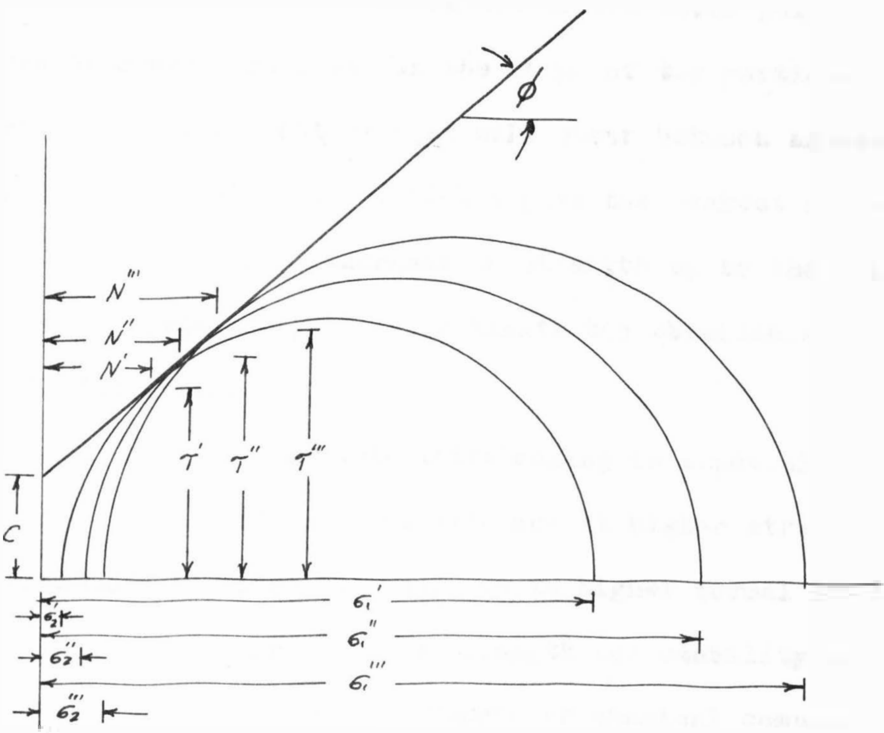

Figure XVI. Mohr diagram for rounded aggregate

In testing unconfined specimens, the rate of loading was not as carefully controlled as in the other cases, but the specimens did serve their purpose, which was to show the effect of particle interlock. This difference amounted to about 10 to 15 psi or about 5 percent of the average strength of the specimen. This interlock could be approximated from the curve of stress versus deformation by drawing a smooth curve and measuring the difference between the two curves as shown in Figure XVII.

The curve of stress versus deformation of a rounded aggregate specimen showed no distinct particle interlock as shown in Figure XX. The small amount of interlock is due to the fewer points of contact between adjacent particles, as the shape of the particles governs the number of points of contact that will occur between adjacent particles. Thus, perfectly spherical particles give the weakest aggregate, whereas chunky aggregates offer increase in strength up to the point where additional irregularity of shape limits the obtainable density and the strength falls off.

The effect of particle interlocking is especially significant at low stress, but of less significance at higher stress because of the pronounced increase in shear due to higher normal stress.

It would appear that the strength and stability do not depend ordinarily upon the internal strength or chemical composition of the material itself, but rather upon the shape and surface texture, as a failure in a solid material occurs when applied load sets up internal shear stress beyond the shear strength.

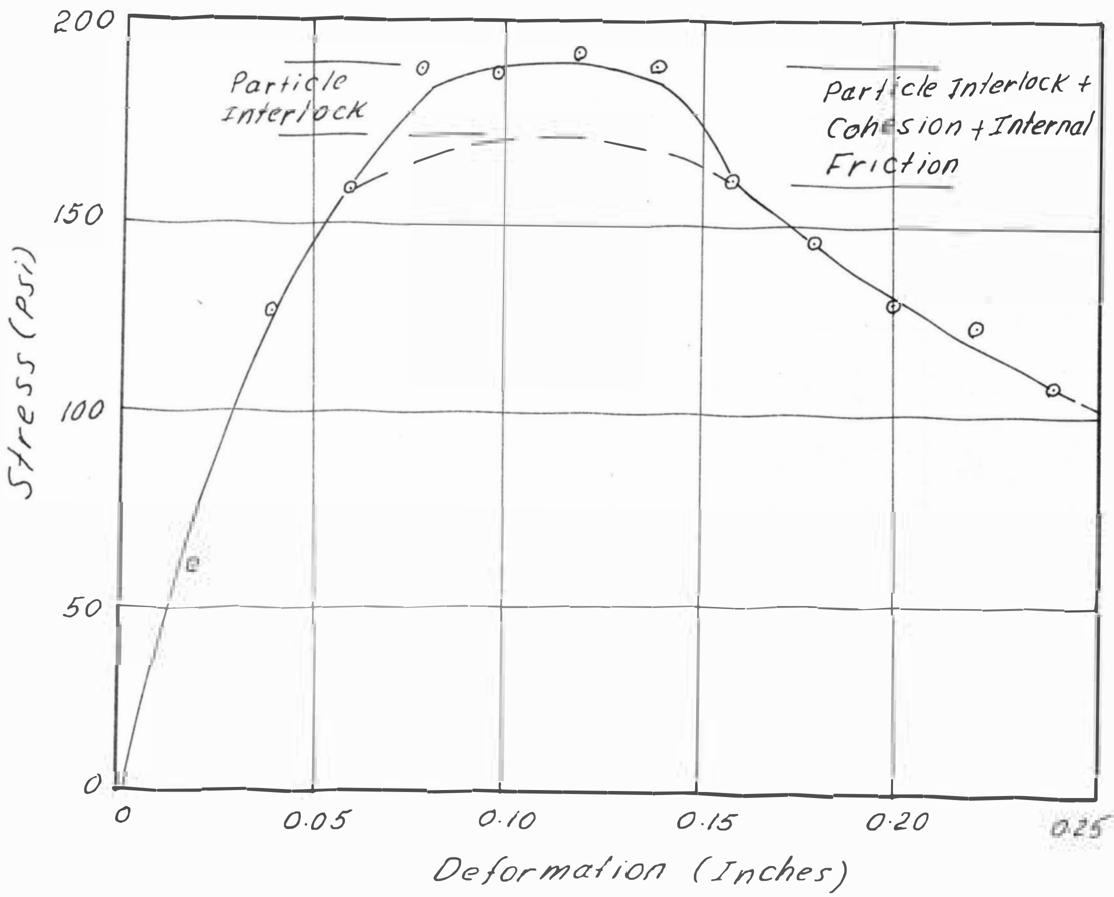

Figure XVII. Typical stress-deformation curve of unconfined crushed aggregate specimen

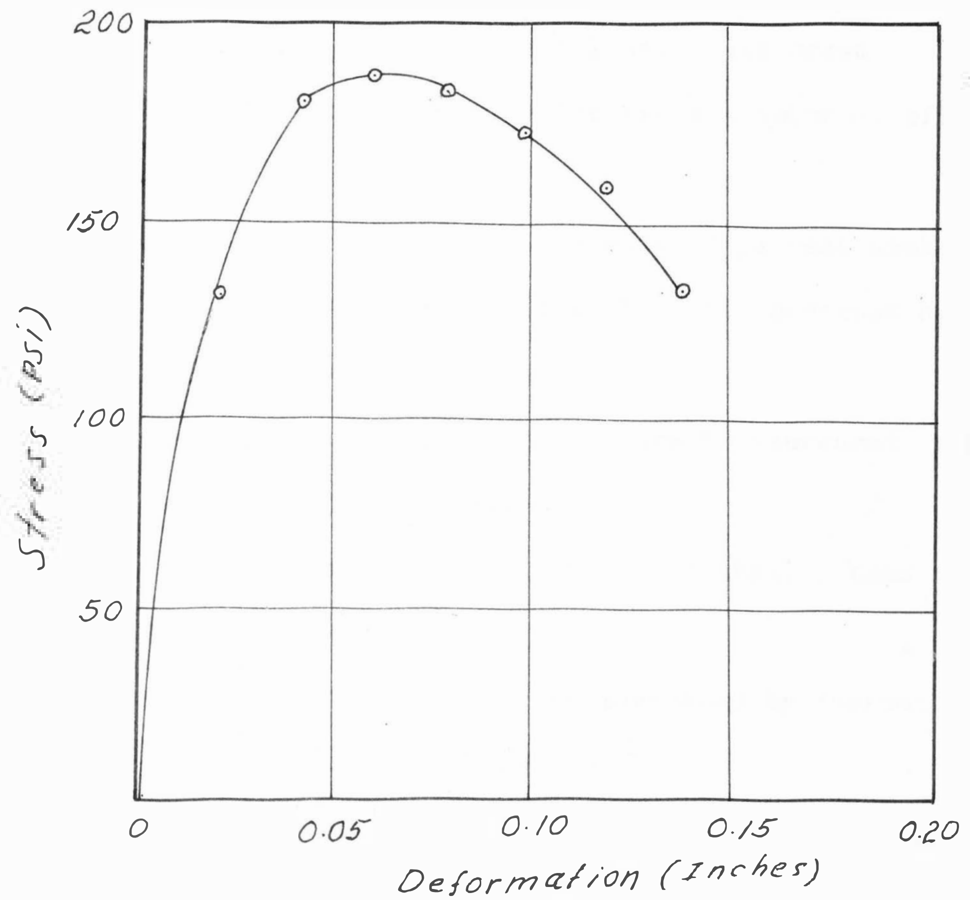

Figure XVIII. Typical stress-deformation curve of unconfined rounded aggregate specimen

CONCLUSIONS

From the test data obtained through testing the specimens in the modified triaxial apparatus and with the range of percent asphalt used (4.0% - 5.5%), the following conclusions are drawn:

1. The method and effort in compaction has a pronounced effect upon the density.
2. The density increases with the increase of percent asphalt.
3. The maximum deformation prior to failure is increased by increasing the lateral pressure.
4. The maximum deformation prior to failure is increased by increasing the percent of asphalt cement.
5. Crushed aggregate specimens show higher stability than rounded aggregate specimens.
6. Peak strength of every specimen is increased by increasing lateral pressure.
7. Maximum stability occurs in using 5% asphalt in the case of rounded aggregate specimen, while both 5% and 5.5% show high stability in the crushed aggregate specimens.
8. Crushed aggregate specimens have a larger angle of internal friction and higher shear value, while rounded aggregate specimens have more cohesive strength.
9. About 5% of the strength of the crushed aggregate specimens is due to the effect of particle interlock. Rounded aggregate specimen show no distinct effect of particle interlock.

10. The strength and stability of aggregates do not depend upon the crushing strength of the constituent particles but upon the shape and surface texture of the individual particle.

SUMMARY

This paper presents the results of testing bituminous specimens by a modified triaxial apparatus. The test specimens were prepared from a typical dense graded mixture where crushed and uncrushed aggregates were used. The method involved the use of mechanical compaction equipment and a modified triaxial testing procedure. A comparison between this method of preparing and testing specimens and other existing methods is outlined in this paper. Test results were analyzed to show the effect of percent asphalt, shape, and texture of aggregate on the basic strength components of bituminous concrete. A technique whereby the Mohr rupture envelope can be used in evaluating shear, cohesion, and internal friction is explained. Also a typical curve of stress versus deformation of unconfined specimens is presented to show the effect of particle interlocking on maximum strength.

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APPENDIX A

Adhesion: It is the inclination toward unity with other materials at a common surface. It is important to develop permanent and adequate adhesion between the asphalt and aggregate so as to utilize fully the cohesive strength of asphalt.[10]

Adhesiveness of asphalt and aggregate is difficult to evaluate because of the numerous factors involved. The nature and history of stone, the chemical properties and consistency of the asphalt all influence the bond between the solid and the binder. Stone-asphalt bond is affected by the temperature of the stone and asphalt at the time of mixing, the presence of moisture in the aggregate, and the presence of dust on the surface of the aggregate particles. Asphalt spreads easily over most dry solid surfaces, but the adhesion to a water-wet surface is very poor. Also, when water enters a stone-asphalt interface the bond is decreased and may be totally destroyed.[11] Figure I shows the loss of stability of a mixture because of entrance of water into the stone-asphalt interface. It shows the percent by weight of asphalt in a mixture plotted against compressive strength of a compacted mixture after immersion in water at 60° centigrade (140° Fahrenheit) for 24 hours.

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[10] Emil R. Hargett, Basic Material Properties for the Design of Bituminous Concrete Surface, A Report to the International Conference on Structural Design of Asphalt Pavements, Ann Arbor, August 20-24, 1962 (Ann Arbor: University of Michigan, 1962), p. 5.

[11] Ralph N. Traxler, Asphalt (New York: Reinold Publishing Corporation, 1961), pp. 215-216.

Aggregates: Aggregates are classified according to size as follows: coarse aggregates are those particles retained on number 8 sieve (0.0937 inch opening); fine aggregates are all the particles passing number 8 sieve; mineral fillers are particles passing number 200 sieve (0.0029 inch opening). The suitability of aggregates for use in asphalt pavements is determined by gradation, resistance to abrasion, soundness, cleanliness and purity, internal friction, and surface properties.

There are many combinations of aggregates and binders that will make good pavements, even under restrictive local conditions.[12] If good service is to be received from bituminous pavement, it must retain the following qualities: freedom from cracking or raveling; resistance to weather, including the effect of surface water, heat, cold, and oxidation; resistance to internal moisture, particularly to water vapor; impermeable surface; smooth riding; and nonskid surface.

Bituminous Binder: This term is used to denote substances in which bitumen is present or from which it can be derived. Bitumen is hydrocarbon material of either natural or pyrogenous origin, gaseous, liquid, semi-solid, or solid, which is completely soluble in carbon disulfide. With respect to highway construction, the term bituminous material is used to include both natural and manufactured materials

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[12]J. Rogers Martin and Hugh A. Wallace, Design and Construction of Asphalt Pavement (New York: McGraw Hill Book Company, 1958), p. 36.

regardless of origin, but is restricted to hydrocarbon materials which are cementitious in character or from which a residue of this character will develop.[13] The principal bituminous materials used in road construction classified as to type and origin are asphalt cement, cutback asphalt, slow-curing or road oils, asphalt emulsion, and road tars.

Bituminous binder must be in liquid form when combined with aggregates, regardless of the type of pavement in which the binder is to be used.[14] This fluid state may be achieved by the addition of heat, a solvent or thinner, or an emulsifying agent and water.

Cohesion: In general, cohesion is defined as the force by which molecules of the same substance are held together and resist being pulled apart.[15] The cohesion of a liquid at a given temperature is equal to twice the surface tension. This is true because when a molecule is in the body of a liquid, it will be surrounded by the attraction force from its neighbors in all directions, whereas at the boundary the attraction will be lateral from molecule to molecule. The cohesion of asphalt is measured in kilograms required to separate two halves of a mold. It is a measure of the cementitiousness of asphalt, which is

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[13] L. J. Ritter and R. J. Paquette, Highway Engineering (New York: Ronald Press, 1951), p. 353.

[14] Hewes and Oglesby, p. 446.

[15] Herbert Abraham, Asphalt and Allied Substance (6th ed.; Princeton, New Jersey: D. Van Norstrand Company, 1962), IV, 138-139.

an important property in determining the adaptability of a bituminous substance for certain definite purposes, such as paving and waterproofing. Cohesive resistance generally develops in the bituminous binder portion of the paving mixture. Its magnitude varies directly with the rate of loading, the loaded area, and the viscosity of bitumen, and inversely with temperature.[16]

Frictional Resistance: Frictional resistance in aggregate is a property of the stones to resist movement past one another under the action of an imposed load. Research has indicated that frictional resistance provides the most important element of stability.[17] Blast furnace slag, basalt, and good limestone are examples of aggregates with high internal friction. On the other hand, smooth, rounded, uncrushed gravel has low frictional resistance and consequently low frictional value, since slipping of particles past one another takes place without developing a large frictional component.

The magnitude of frictional resistance varies directly with the area of aggregate contact and applied pressure and with surface roughness of aggregate particles.[18] Frictional resistance is not dependent upon loaded area, rate of load, or temperature.

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[16] Woods, sec. 18, pp. 55-56.

[17] Howes and Oglesby, p. 470.

[18] Woods, sec. 18, p. 55.

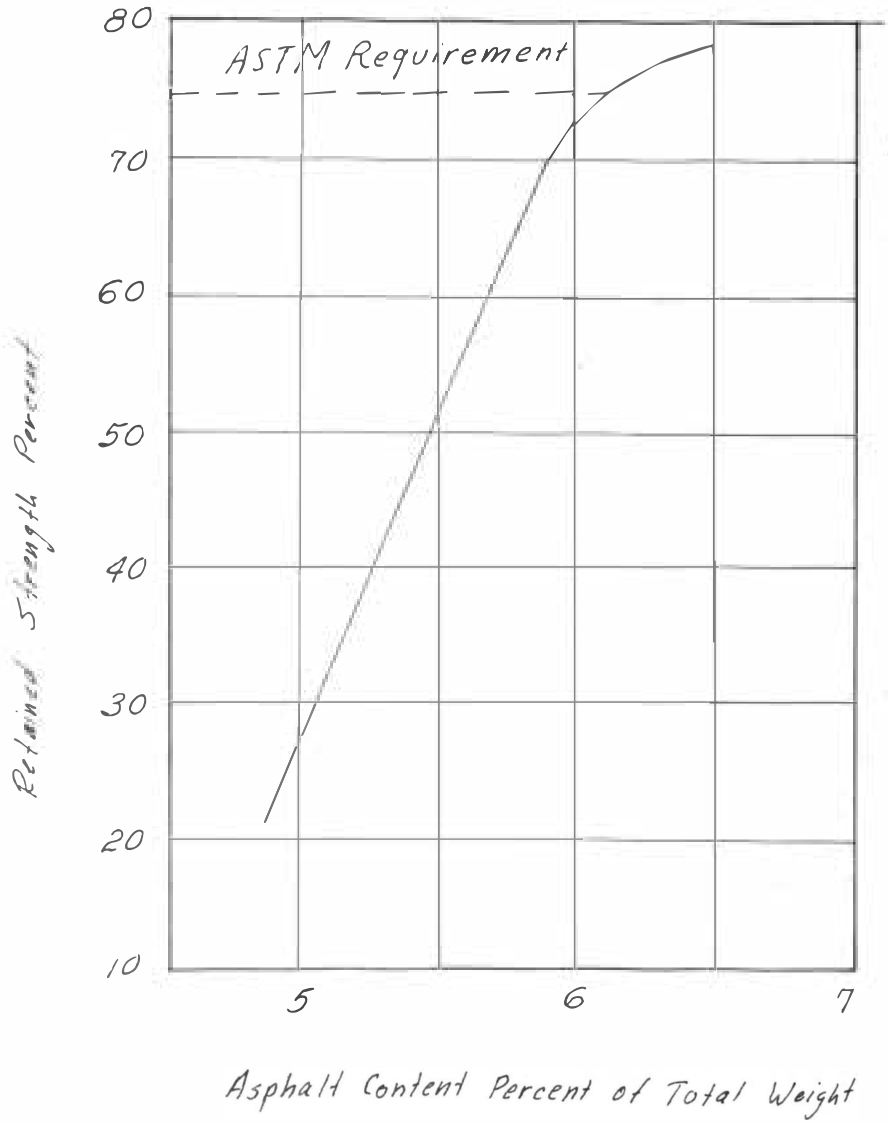

Figure XIX. Effect of amount of asphalt present on resistance of a mixture to water action

Gradation: In a bituminous mixture, the major portion of the resistance to deformation is carried by the aggregate framework. Aggregate framework has great effect on the flexibility of the bituminous mixture. A weak frame will deform easily under load, while a rigid one may result in brittleness and weakness under impact loads. The aggregate framework is a function of gradation. When particles are of uniformly decreasing size from coarse to fine and including dust, a highly stable aggregate framework may be developed because of the particle-to-particle contact in the various sizes. Curve (A) in Figure XX shows uniform gradation of aggregate. Also, with uniformly graded aggregate, the framework will form a well-packed arch that has the maximum amount of frictional resistance and interlocking of particles. In addition, a uniform gradation will furnish more surface area that has to be coated with a binder, and consequently this will increase the cohesive resistance of the mixture.

Gap or skip grading results when the coarse aggregate is present in such a quantity that the aggregate framework will have stability similar to that of coarse aggregate alone. Curve (B) in Figure XX shows such gradation. Gap grading also occurs when not enough coarse aggregate is present to form a framework, because the few coarse aggregate pieces tend to float in the bitumen and fine aggregate that surround it. The stability of this mix will have the properties of fine aggregate. Curve (C) in Figure XX shows a gradation of this type. Figure XXI illustrates the effect of well-graded aggregate.[19]

Interlocking: Interlocking resistance is dependent upon aggregate size and shape. It is the connection of the particles in such a way that the motion of any particle is constrained by the other particles. It has a profound effect on the initial resistance that a pavement can offer to shearing resistance. It is difficult to make an accurate appraisal of the magnitude of interlocking resistance offered by a mixture of bituminous concrete. However, a curve of stress vs. deformation obtained from the unconfined compressive test data is of value in making an approximate evaluation of interlocking resistance.[20] It may be assumed that the peak loop in the test data is caused by particle interlock.[21] The resistance offered by particle interlocking is not subject to any major change in temperature. The kneading action produced by wheel load repetitions during the summer months may increase the interlocking resistance by "keying" and further densifying the surface course.[22]

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[19] E. J. Yoder, Principle of Pavement Design (New York: John Wiley & Sons, 1959), p. 284.

[20] Emil R. Hargett, Strength and Performance of Bituminous Concrete, A Report to the First Paving Conference, Albuquerque, New Mexico, December 6-7, 1962, Prepared by the Civil Engineering Department of the University of New Mexico (Albuquerque: The Conference, 1962), p. 186.

[21] Ibid., p. 186.

[22] Ibid., p. 187.

Percent Bitumen: In any bituminous aggregate, the volume of bitumen is a most important factor from the standpoint of covering capacity, thickness of film, and the reduction of voids. The proper percentage of bitumen will depend on the exact grading. In general, the finer the mineral aggregate the greater will be the percentage of bitumen required to bind and waterproof it properly after compaction.[23]

There are four significantly useful properties of asphalt in a bituminous mixture.[24] 1. Asphalt is a strong cement which firmly binds the compressed paving mixture into a stable structure. 2. Asphalt is ductile; therefore it imparts resilience and controllable flexibility to the paving course, providing for the passage of wheel loads without fracture and for exposure to ranges of temperature without cracking. 3. Asphalt is a waterproof material preventing the loss of stability under adverse moisture conditions. 4. Asphalt is not affected by salt used in ice and snow removal; neither is asphalt affected by most acids.

Low asphalt content invites raveling. Too much asphalt results in an unstable pavement. Also hard asphalt will result in brittle pavement, and the same could be said about low quality asphalt.

Arbitrarily fixing the percent of asphalt by weight in a pavement mix is unsound practice. The logical practice is to maintain

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[23] E. J. Yoder, Principle of Pavement Design (New York: John Wiley & Sons, 1959), p. 284.

[24] Woods, sec. 26, pp. 10-11.

the asphalt content within whatever values will give 94 to 98 percent density in the pavement at ultimate compaction.[25]

It is desirable to provide for at least two percent air voids. However, it is hard to be that precise, and a pavement is usually designed at 96 to 97.5 percent density, which allows a margin of safety during construction and service.

The sum of the percentage of voids in the pavement plus the volume occupied by the asphalt cement, expressed as a percentage, is the Voids in the Mineral Aggregate (VMA). Poorly graded aggregates have VMA ranging up to 35% or more. Well-graded aggregates without an excess of dust, or minus 200-mesh material, will usually produce a VMA of around 15% in the compacted specimen. It is seldom desirable to reduce the VMA below 10%, for such values almost invariably have to be obtained through the use of excess mineral filler.[26]

The quantity of asphalt necessary to produce a given percentage of voids in the mix is largely a function of the surface area per unit weight of aggregate which in turn is a function of particle size. One of the formulas used to design the bitumen based on surface area is:[27]

$$P = 0.015\,a + 0.03\,b + 0.17\,c$$

where P = percentage of bitumen in the mix by weight

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[25] Martin and Wallace, p. 58.

[26] Ibid., p. 58.

[27] Woods, sec. 18, p. 57.

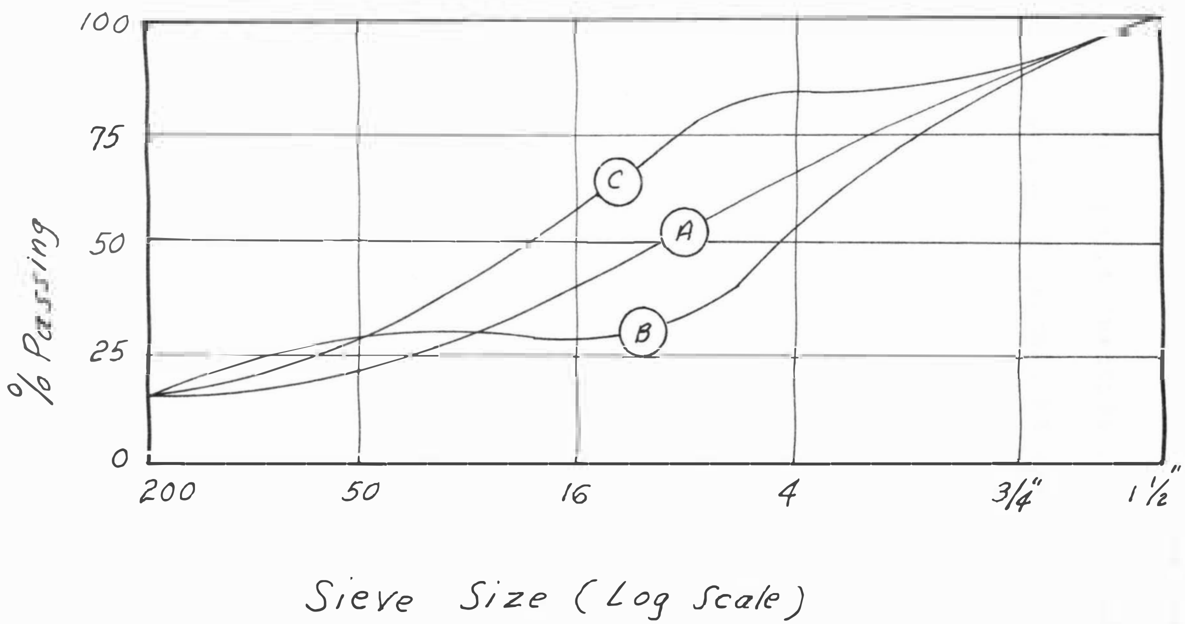


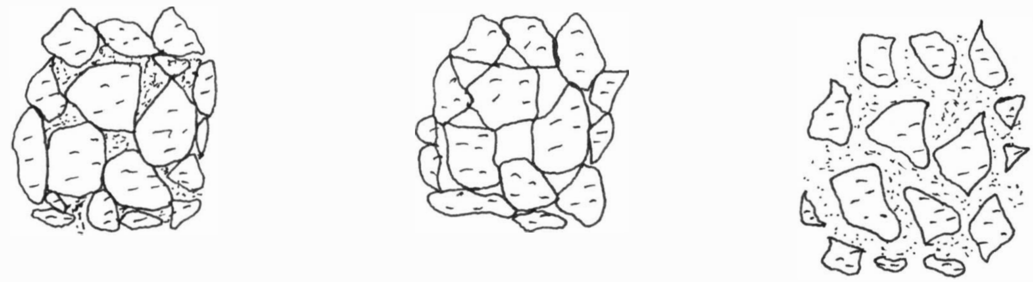
Figure XX. Uniform and gap grading

a = percentage of coarse aggregate

b = percentage of fine aggregate

c = percentage of mineral filler

This formula explains why optimum asphalt content is greater for mixes with small-top size aggregate than it is for large aggregates. Modifying factors for asphalt quantity are roughness of the aggregate surface and the amount of asphalt it will absorb.



Aggregates with sufficient fines	Aggregates with no fines	Aggregates with greater amount of fines
Grain-to-grain contact with increased resistance against deformation	Grain-to-grain contact	Grain-to-grain contact destroyed; aggregate floating in soil
Relatively high stability in confined and unconfined conditions	High stability if confined; low if unconfined	Low stability
Increased density	Variable density	Decreased density
Low permeability	Pervious	
	Difficult to compact	

Figure XXI. Gradation of aggregate

APPENDIX B

Table 7. Test Values for Crushed Aggregate Specimens

Number of Specimen	Percent Asphalt	Density Pounds/ cu. ft.	Lateral Pressure (psi)	Strength at failure (lbs.)	Strength at failure (psi)	Deformation at failure (in.)
C13	4.09	2.33	0	1830	146	.08
C 2	4.56	2.36	0	2200	175	.08
C15	5.05	2.38	0	2380	190	.06
C 8	5.7	2.36	0	2400	191	.12
C 6	4.15	2.35	10	3560	284	.22
C 3	4.58	2.35	10	3560	284	.22
C 7	5.03	2.39	10	3980	317	.20
C20	5.50	2.37	10	3620	288	.18
C 9	4.0	2.33	20	4310	343	.26
C18	4.52	2.38	20	4420	352	.22
C11	5.0	2.38	20	4440	353	.28
C12	5.59	2.36	20	4560	363	.22
C17	4.06	2.36	30	4460	356	.26
C14	4.65	2.37	30	5020	400	.32
C19	5.02	2.38	30	5160	411	.30
C16	5.83	2.35	30	5400	430	.28

Table 8. Test Values for Rounded Aggregate Specimens

Number of Specimen	Percent Asphalt	Density Pounds/ cu. ft.	Lateral Pressure (psi)	Strength at failure (lbs.)	(psi)	Deformation at failure (in.)
R 7	4.0	2.40	0	2350	187	.06
R 6	4.56	2.42	0	2860	228	.08
R10	5.0	2.44	0	2500	199	.08
R 9	5.55	2.44	0	2520	200	.10
R12	4.0	2.42	10	3500	278	.20
R 8	4.56	2.42	10	3700	295	.18
R15	5.05	2.44	10	3300	263	.20
R11	5.49	2.45	10	3520	280	.30
R19	4.09	2.38	20	3950	314	.28
R13	4.47	2.41	20	3700	295	.24
R 4	5.06	2.41	20	4020	320	.26
R16	5.49	2.42	20	4040	321	.28
R 5	4.05	2.42	30	4840	385	.28
R18	4.43	2.40	30	4780	380	.28
R 3	5.18	2.43	30	4950	394	.32
R20	5.49	2.45	30	4750	378	.36