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THE EFFECT OF THE STATIC COMPACTION ON THE MECHANICAL AND PHYSICAL PROPERTIES OF ASPHALT CONCRETE HOT-MIXES

BY

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A

THESIS

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ABSTRACT

The objective of this investigation was to study the effect of the static compaction effort upon the physical and mechanical properties of asphalt concrete hot mixes. To study the effect of the static compaction upon the physical properties of the asphalt mixes, six mixes were prepared using hard, well graded crushed limestone as an aggregate, blended with an 85-100 penetration grade asphalt cement. The control mix was prepared and tested in accordance with the Marshall method for mix design. The other five mixes were prepared and tested using the same procedures of Marshall except for compaction, where five different static pressures were applied. The effect of the static compaction upon the mechanical properties of the mixes was also studied. Test specimens 2.1 inches in diameter and 4.00 inches in height were compacted using different static compaction efforts. These specimens were tested in unconfined compression. Both of these studies indicated that a relationship exists between the static compaction effort and the physical and mechanical properties of the asphalt concrete mixes.

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I. INTRODUCTION

The importance of a good road system on the economic development of a country is generally recognized and the last century has shown a tremendous activity in the field of road building.

The great development of the petroleum industry through the last fifty years, and the production of bitumen during the distillation process at a fairly low price and with properties which could be standardized within a narrow limit, thus giving a guarantee of uniform quality, has created a big boom in bituminous pavement construction (1).

Although the use of bituminous materials for road construction has shown great increase during the recent years, natural asphalt has been in use for a long time. The earliest recorded use of asphalt was by the pre-Babylonian inhabitants of the Euphrates Valley in Southeastern Mesopatamia about 3800 B.C. (2). In Ancient Egypt natural asphalt was used as adhesive, as paints, and as water proofing mastics (2).

The first application of bitumen-bound material for pavement purposes in modern times was the laying of sidewalks in Paris in 1835, for which rock asphalt from Val de Travers in Switzerland was used. Other well-known places where rock asphalt is found are Seyssel (France), Vorwoklen (Germany), and Rogusa (Italy) (1).

The first asphalt roadway pavement in the United States apparently was a short experimental section composed of rock asphalt placed in Newark, N.J. in 1870. In 1871, pavements were constructed in Washington, D. C., which were composed of crushed rock, sand, coal-tar pitch, and creosite oil. Also, in 1871, 1872, and 1873, Val de Travers rock-asphalt pavements were laid in New York City. Congress passed an act in 1876 authorizing the paving of Pennsylvania Avenue in Washington, D. C. Part was paved with Val de Travers rock asphalt and the remainder with sheet asphalt made with Trinidad asphalt. Bermude asphalt (Venezuela) was first used extensively for paving in Detroit, Michigan, in 1892 and the following year in Washington, D. C. (2)

In all methods of mix-design for asphalt concrete, laboratory test specimens are prepared, and their physical properties are determined under conditions which can be correlated to actual pavement conditions.

In compacting laboratory test specimens of the proposed mix for the test purposes, it is desirable to have the density of these specimens closely approximate the density developed in the actual pavement. Much effort has been directed toward the formation of realistic test specimens in the laboratory that represent the structure of the paving mixture when placed in the field. Some of the major methods that are used to form laboratory specimens are the impact method, the double plunger static-compression method, the kneading-compactor method, and the gyratory molding method.

The method of compaction has a very marked effect upon mixture properties. It has been recognized that the density and stability obtained on laboratory specimens compacted by these different methods are higher than the density and stability of actual pavement cores of equivalent gradation and bitumen content, which indicates a difference in the structure of the aggregate particle arrangement and distribution. This discrepancy justifies a need for an improved or modified laboratory compaction procedure (3).

All specifications for asphalt pavement require the minimum density for cores taken at specified distances along and across the actual pavement to be 95 percent of the designed density obtained by accepted laboratory methods for mix design.

To achieve the required density in the field, equipment consists of steel wheel and pneumatic-tire rollers, or combinations of both. The number of coverages and the weight of rollers used affect the density achieved.

According to Gartner, Cobb, and Lindley, the density of the mix used in an actual pavement increases with the increase of the compaction effort to a maximum, after which the density will decrease with the increase of the compaction effort (4).

A great deal of research has been done concerning the study of the load-deformation characteristics of the bituminous concrete mixes under different conditions of temperature and rate of loading, using static and repeated loads. No work has been done to study the effect of laboratory compaction effort on the load deformation characteristics of compacted test specimens.

This paper describes laboratory tests using a single plunger hydraulic compression machine for compacting hot mix asphaltic concrete composed of dense graded limestone and an asphalt cement of (85-100) penetration. The effect of the static compaction effort on the density, stability, flow, and voids of this mix is also included. A Laboratory Study of the compaction effort upon the load-deformation characteristics of the mix is presented.

II. REVIEW OF LITERATURE

The major properties to be incorporated in a bituminous paving mixture are stability, durability, flexibility, and skid resistance. In all mix designs, the design criteria in each case was established by a correlation of results obtained from laboratory specimens with the performance of mixtures placed in actual service under traffic. The criteria in general have been set up for dense-graded, hot mix paving mixtures. The method of compaction of laboratory specimens varies from the impact compaction of the Marshall specimen to the kneading compaction used on Hveem specimen.

The Hubbard-Field stability test, which evolved in the middle 1920's, is one of the earliest methods for evaluating the mechanical properties of bituminous mixture. The test as applied to sheet-asphalt paving mixtures consists of determining the maximum load developed on a specimen two inches in diameter and one inch high as it is forced through a 1.75 inch standard orifice. The test specimen is compacted by both impact and static compaction efforts. The temperature at which the stability value of compacted samples is determined is 140^{o}F. This temperature is assumed to be the most severe temperature to which a paving mixture normally would be subjected in the field. The initial criteria developed by Hubbard and Field were for mixtures that used penetration grades of asphalt cement and aggregates having a gradation such that a minimum of 65 percent passes the No. 10 sieve and 100 percent passes the No. 4 sieve. In this method a stability of 2,000 pounds or more is required for a heavy traffic pavement. Also an upper limit of air voids of 5 percent and a lower limit of 2 percent are recommended (5).

The Hveem method of mix design has been used primarily for dense graded paving mixtures. The method depends upon the evaluation of the surface capacity of aggregates with respect to bituminous materials, which was initially reported by Stanton and Hveem in 1932. The designed asphalt content was determined from surface area formulas, based upon the asphalt demand as determined by the surface area of aggregates. A limited number of sieves was used to express the surface area of aggregates and the aggregate shape was not taken into consideration.

The California Division of Highways devised a method that included a surface deformation based upon a sieve analysis and took into account the effect of surface characteristics of aggregate. The calculation of the surface area is based upon the use of constants that represent the equivalent area in square feet per pound of material of each size. The principal features of the Hveem method of mix design are the Centrifuge Kerosene Equivalent (C.K.E.) of the aggregates to estimate the asphalt requirements of the mix, a stabilometer test, a cohesiometer test, a swell test, and a density-voids analysis. Test specimens 2-1/2 inch in height and 4 inches in diameter are compacted by means of a mechanical compactor which imparts a kneading action type consolidation by means of a series of individual impressions made with a ram having a face shaped as a sector of a 4 inch diameter circle. At each application of the ram a pressure of 500 psi is applied, subjecting the specimen to a kneading action without impact over an area of approximately 3.1 square inches. Each pressure application is maintained for approximately 2/5 of a second (6).

The concepts of the Marshall Method for designing paving mixtures were formulated by Bruce Marshall, formerly Bituminous Engineer with the Mississippi State Highway Department. The U.S. Corps of Engineers, as a result of extensive research and correlation studies, improved and added certain features to Marshall's test procedure, and ultimately developed the mix design criteria. The Marshall test procedure has been standardized by the American Society of Testing Materials listed as ASTM Designations D 1559. The specimens are compacted inside a standard mold 2-1/2 inches in height and 4 inches in diameter using an impact load provided by a standard hammer. The stability and flow, which are respectively the load necessary in pounds and the deformation in 1/100 of an inch to cause failure of a compacted specimen at a temperature of 140°F using a standard machine known as the Marshall Stability Machine, are measured. The unit weight and voids analysis of the compacted specimens, along with minimum values of stability, flow, and air voids, are incorporated into the mix design criteria (2).

It is known that the area of flexible pavement under a wheel load tends to be confined by the frictional forces of the load and by support from the surrounding material. Therefore a much higher bearing capacity of the mixture results than if the mixture were in the unconfined state. The effect of this lateral support obtained in the field is duplicated in a triaxial test developed by V. R. Smith and is known as the Triaxial Method of Mix Design. The main concept of this method is the resistance to displacement due to load developed in paving mixtures. This resistance is due to the interlocking or friction of the aggregates which is known as the internal friction, and the shearing resistance of the bituminous binder, usually referred to as cohesion. The triaxial test affords a means of evaluating these two properties. Smith's major contribution to the area of bituminous mix design is the derivation of an evaluation chart that related values of cohesion and angle of internal friction to bituminous mixtures that proved stable when placed in the field. In this method, a set of specimens 4 inches in diameter and 8 inches high, compacted by a double plunger compression procedure at varying asphalt contents, are tested. The optimum value is established as that asphalt content that best fits the design criteria. The lateral transmitted pressure and the vertical applied load are found by testing the specimens in the triaxial machine and the values of cohesion and angle of internal friction are calculated and plotted on the evaluation chart. The values of cohesion and angle of internal friction should fall in the satisfactory area, and the air voids in the total mix should be acceptable, otherwise the asphalt content or aggregate gradation, or both, should be changed (8).

In all of the methods discussed above, the compaction effort has a major effect upon the properties of the mix. The main purpose of any mix design is to obtain an asphalt concrete with properties which give the best service under the actual conditions in the field. The need for more realistic laboratory test specimens has become evident during the last few years, and a great amount of research has been conducted in an attempt to prepare test specimens which are representative of the finished pavement.

The investigation conducted by the Texas Highway Department in 1939 to develop a molding machine and method which would produce satisfactory test specimens of bituminous concrete paving mixtures, is one of the important investigations done in this area. Nine molding machines, including the Laboratory Asphalt Press at a pressure of 3125 psi, the Southwork-Emery 200,000 lb. Hydraulic Compression Machine at a pressure between 2,000 psi and 3,200 psi, the Proctor Soil Compaction Machine with three layers of 400 blows per layer compaction effort, the P.R.A. Vibratory Machine with 4,300 rpm for periods between 15 to 30 minutes, the Pneumatic Roller, Conical Roller, Horizontal Shear in a cylinder, Horizontal Shear in rectangular Mold, and Gyratory Shear Machine were used in this investigation for preparing laboratory test specimens. The factors of comparison between all these methods were the compaction factor and the degradation factor, which were defined respectively as the actual specific gravity of the specimen divided by the average specific gravity of the constituents and the percentage increase of the surface area of coarse aggregates (1/2 to 10 M) as calculated on the basis of the coarse aggregates after gradation. The specimens used in all the tests were 4 inches in diameter and 2 inches high except for the Horizontal Shear test, in which rectangular beam specimens of 2 x 2 x 8 inches were tested. While the specimens compressed by the laboratory asphalt press machine showed a reasonable degradation factor at a relatively high density, specimens compressed by the hydraulic compression machine indicated specimens with higher gradation factors at less densities. The specimens compacted by the Proctor machine were demarked, giving an indication of inefficient cohesion between layers and therefore, two planes of weakness. The density of specimens compacted by the P.R.A. Vibratory machine was low and no significant increase in density was achieved by the increase of vibration time to more than fifteen minutes. The Pneumatic Roller machine produced specimens with segregation both of coarse aggregates at the top and fine aggregates at the bottom; therefore the machine was eliminated. The Conical Roller gave specimens with very low densities. Reasonable densities with negligible degradation were obtained from the specimens compacted by the Horizontal Shear machines, however, the specimens were irregularly compacted. The Gyratory Shear machine was selected as the one offering the most promise for testing under various conditions (9).

According to Nevitt in his study of compaction techniques, it was found that the Marshall compaction hammer produces internal changes in the specimen, presumably degradation due to impact. These changes affect the density and stability values as well as increase the variation from specimen to specimen (10).

The studies conducted by McRae showed that the gyratory kneading compactor produces specimens that more closely simulate stability values of actual pavement cores than do specimens compacted by impact (3).

The results obtained by Waller on specimens compacted by the double plunger method at increasing pressure using 500 psi load increments, with maximum pressure of 3000 psi, indicated an increase of unit weight and stability of the asphalt concrete mixes as the static compaction effort was increased (11).

Hubbard and Field recognized 25 years ago the importance of deflection on the performance of asphalt concrete. It was shown by laboratory tests that pavement failures often may be caused by excessive deflection of the surface rather than by inadequate shearing resistance of the subgrade soil. A great deal of research has been conducted to study the deformation properties of asphalt concrete. The deflection of an asphalt pavement depends on several factors including the rate of loading, the magnitude and the number of repetitions of load, the temperature of pavement, and properties of the asphalt concrete mix (1).

The laboratory study conducted by Goetz, McLaughlin and Wood at Purdue University to determine the strength properties of asphalt concrete under repeated loading is a great contribution in this area. The paper presents the results of a series of laboratory tests designed to provide information on the load-deformation characteristics of bituminous mixtures under various conditions of loading. The effects of variation in temperature and strength of cylindrical specimens of sheet asphalt and asphalt concrete were presented, and the plastic deformation of the mix subjected to slow cycle and rapid cycle repeated load test both in the confined and unconfined states was discussed. From the results of these tests the authors concluded that the compressive strength of bituminous mixtures varied logarithmically with the rate of deformation and the log of the temperature. An important contribution of these last mentioned studies at Purdue University was the development of a general equation which relates the compressive strength obtained to the various temperatures and rates of loading. The equation is as follows:

$$X_o = A^{BX_1^{(CX_2 + D)}}$$

where:

X_o = maximum compressive stress in psi

X_1 = rate of deformation in inches per minute

X_2 = temperature in ^oF

A,B,C,D = constants of proportionability.

While the asphalt viscosity as a substitute for the temperature variable is considered as an interesting alternative, the equation has important implications. It suggests a means whereby the strength properties of an asphalt concrete can be predicted over a wide range of load and temperature conditions with a minimum number of tests (12).

Further study of the load-deformation characteristics of asphalt concrete mixes was conducted by Papzian and Baker at Ohio State University. The objective of this research was to study the behavior of asphalt concrete under static loading conditions. Cylindrical specimens 1.9 inches in diameter and 3 inches in height of a bituminous concrete mix were tested in unconfined compression using three rates of loading at three different temperatures. The general equation relating the compressive strength of asphalt concrete to the temperature and the rate of strain was found to hold for the given mix. Also, it was found that within limits, asphalt concrete displays elastic behavior in that an approximate proportionality exists between unit stress and unit strain in unconfined compression, and the modulus of elasticity for a given asphalt concrete is variable, dependent upon the rate of loading and temperature. However, at high rates of loading the functionality tends to cease and the modulus becomes a function of temperature only. Another very interesting conclusion resulting from this study was that a failure of the asphalt concrete pavement must develop before shear failures of the subgrade can occur. This is due to the confining nature of the pavement (13).

III. PROCEDURES AND RESULTS

A. COMPACTION STUDY

1. General.

To study the effect of increasing the static compaction effort on the unit weight, stability, flow, voids percent in mineral aggregate, and voids percent in the total mix, five different static compaction efforts were used in preparing five asphalt concrete mixes. One other mix was designed in accordance with the Marshall method using impact compaction. This mix was used as a basis of comparison with the other five mixes. The materials used, the procedures followed, and the results obtained are presented in this section.

2. Materials.

The aggregate used in this study was a hard, pure, well-graded crushed limestone, with a gradation selected to be within the Asphalt Institute recommended limits for dense-graded asphalt concrete mixes. The maximum particle size was 3/4 of an inch as shown in Figure 1 and Table I. The aggregate particles had an angular shape, and relatively rough surface texture, with a bulk specific gravity of 2.65 as determined in accordance with ASTM Method C127.

The bituminous binder used was an (85-100) grade asphalt cement. The average penetration as determined according to ASTM D5, AASHO T49 standard penetration test for asphalt cement was 89, and its specific gravity was 1.02.

The results of the Rice Method (6) for determination of the asphalt percent absorbed by aggregate showed an average value of 0.15 percent by total weight of the mix. It was therefore decided to neglect adsorption and all mixes were analyzed using the bulk specific gravity of specimen for voids analysis.

TABLE I

GRADATION OF AGGREGATE USED - PERCENT PASSING BY WEIGHT

Sieve Passing	3/4	1/2	4	10	40	80	200
Percent by Weight	100	90	60	40	20	15	7

3. Equipment.

Standard Marshall equipment was used preparing and testing the asphalt concrete test specimens. This equipment is described in detail in ASTM Method D1559.

A 350,000 lb. capacity Forney Hydraulic-Compression machine was used to provide different static compaction efforts using a top plunger having the same diameter as the Marshall hammer.

4. Compaction Effort.

An impact of 50 blows was applied on each face of the specimens using the Marshall hammer to compact specimens prepared by the Marshall procedure.

A static pressure increased in increments of 1000 psi to a maximum value of 5000 psi, was applied to mold specimens for the compaction study.

5. Size and Shape of Specimens.

As mentioned before, to facilitate comparison, the specimens were molded with the same dimensions as the Marshall specimens (2 - 1/2 inches high and 4 inches in diameter).

6. General Procedures.

Two methods for preparing test specimens were used in this study. Six asphalt concrete hot mixtures were tested. One of them was designed in accordance with the Marshall method, and the other five were prepared

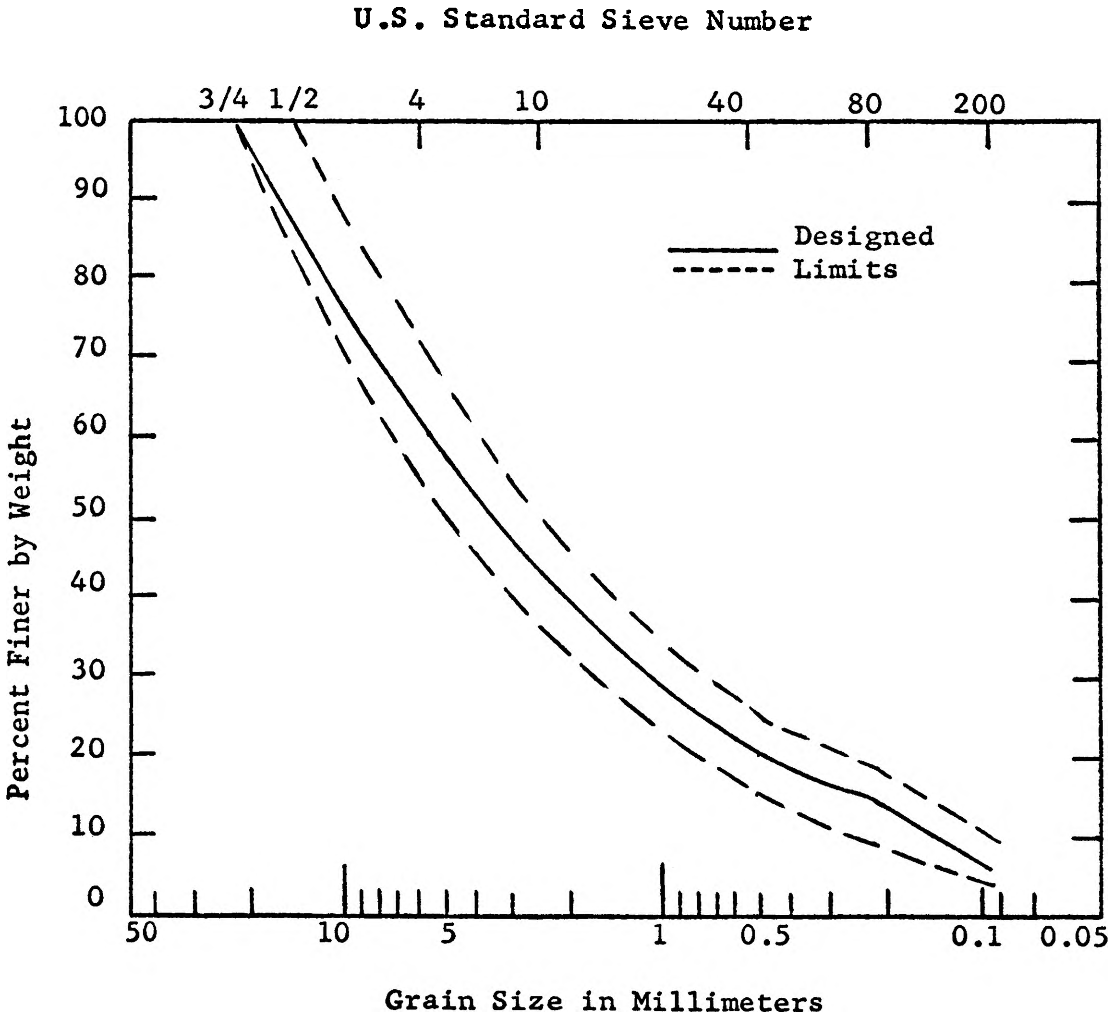

Figure 1 - Aggregate Gradation Curve

using the same procedures of Marshall except for compaction. Five different static pressures of 1000 psi, 2000 psi, 3000 psi, 4000 psi and 5000 psi were applied for 2 minutes to compact mixes A, B, C, D, and E respectively.

The main features of the Marshall method for designing hot asphalt concrete mixes, designated by ASTM test method D1559, are outlined in the following paragraph.

A sample of aggregate having the gradation previously described and a weight of 3600 grams, was heated in an electric oven to a temperature of about 325°F. The asphalt cement was heated on a hot plate to a temperature of 300°F, and then added to the aggregate. The constituents were mixed for a period of two minutes on a hot plate and then placed in an electric oven at a temperature of about 220°F. Three specimens per batch, weighing 1200 grams each, were molded in a pre-heated mold which was 2.5 inches high and 4 inches in diameter. After placing the mixture into the mold, the loose material was rodded, and then compacted by 50 blows on each face with the pre-heated Marshall hammer. The specimens were then cooled in water, extracted from the mold and cured in air for 24 hours. Several batches having different asphalt contents were prepared for each mix. The average weight and volume of the specimens at each asphalt content were determined, and the bulk specific gravity, unit weight, percent voids of mineral aggregate, and percent air voids were calculated. The specimens were then kept in a water bath at 140°F for 30 minutes, after which their stabilities and flows were measured according to ASTM specifications using the Marshall Stability Machine.

7. Sieve Analysis of Extracted Aggregate.

After measuring the properties of the mixes, the aggregate of some specimens from mixes C, D, and E, was extracted by using carbon tetrachloride in a Rotarex extractor, dried and then sieved for 15 minutes in an automatic shaker. Grain size data for aggregate extracted from molded specimens were then prepared.

8. Effect of Static Compaction on Dry Aggregate.

To study the effect of increasing the static compaction effort on the gradation of aggregate, which is considered more critical than the degradation of aggregate coated with bitumen in the compaction process for preparing specimens, five 1200 gram samples of aggregate having the same gradation as that used in the asphalt concrete mix were heated to 325°F and compacted inside the Marshall mold, applying the same pressure and period of compaction used with Mixes A, B, C, D, and E. The aggregate was then sieved for 15 minutes in an automatic shaker. Sieve analysis data for the compacted aggregate were then prepared. A factor designated as the Degradation Factor, defined as the percent loss in coarse aggregate (coarse aggregate are those particles which are retained on the No. 10 Sieve), was calculated.

9. Results.

The value of the weight, volume, bulk specific gravity, unit weight, percent voids in mineral aggregate, percent voids in total mix, stability, and flow of specimens for different asphalt contents are shown in Table II. Figures 2 through 6 show the relationship between asphalt content expressed as a percent and the unit weight, stability, flow, voids of mineral aggregate, and air voids respectively for the six mixes.

The percentage asphalt cement which would give the most desirable properties was determined for each mix. Table III gives the values of the unit weight, stability, flow, percent voids in mineral aggregate and percent voids in total mix at the design asphalt cement content for the

TABLE II

MIX DESIGN DATA

Mix No.	Applied Pressure psi	Asphalt %	Average Weight gm.	Average Volume cc	Bulk Specific Gravity	Unit Weight pcf	V.M.A. %	Air Voids %	Stab-ility lb.	Flow
A	1000	4 1/2	1190	596	2.77	141.0	23.0	8.60	310	20
		5	1188	515	2.30	143.0	21.6	6.70	963	22
		5 1/2	1207	520	2.32	145.0	20.5	4.60	1030	24
		6	1187	504	2.36	147.0	19.8	2.45	1330	27
		6 1/2	1196	506	2.37	148.0	19.4	0.96	1290	29
		7	1198	508	2.36	147.3	20.8	0.50	1150	32
		7 1/2	1177	504	2.35	146.5	21.2	0.5	1115	33
B	2000	4 1/2	1180	504	2.34	146.0	18.8	5.45	1580	19
		5	1186	503	2.35	147.0	18.6	3.94	1630	20
		5 1/2	1196	505	2.37	148.0	18.2	2.42	1685	22
		6	1188	498	2.37	148.7	18.2	1.36	1910	24
		6 1/2	1191	506	2.35	146.5	21.8	1.20	1550	25
C	3000	4 1/2	1166	498	2.34	146.0	18.7	5.82	1770	16
		5	1158	487	2.37	148.0	17.7	3.60	2715	18
		5 1/2	1135	475	2.395	149.3	17.3	1.85	2060	21
		6	1172	491	2.38	148.5	18.6	1.75	1370	22
		6 1/2	1184	501	2.36	147.0	19.5	1.10	1215	24
D	4000	4	1174	495	2.37	148.0	16.9	5.12	2220	9
		4 1/2	1164	491	2.38	148.5	16.7	3.83	2460	11
		5	1177	490	2.40	149.7	16.2	2.39	4290	12
		5 1/2	1183	490	2.42	150.5	16.7	1.10	2590	15
		6	1173	489	2.39	149.0	18.4	1.00	1520	18

TABLE II (Continued)

Mix No.	Applied Pressure psi	Asphalt %	Average Weight gm.	Average Volume cc	Bulk Specific Gravity	Unit Weight pcf	V.M.A. %	Air Voids %	Stab-ility lb.	Flow
E	5000	3 1/2	1196	505	2.37	148.0	16.0	5.00	2480	9
		4	1139	474	2.40	149.7	14.0	3.87	3510	11
		4 1/2	1196	502	2.38	148.5	15.6	2.90	3100	14
		5	1193	501	2.37	147.7	17.8	1.70	2330	17
		5 1/2	1187	505	2.36	147.0	19.0	1.30	2030	19
		6	1206	516	2.34	146.0	21.4	1.20	1630	20
Marshall 50 blows		4 1/2	1174	495	2.37	147.5	17.1	4.30	2700	6
		5	1135	475	2.40	149.2	16.6	2.52	3050	8
		5 1/2	1183	490	2.42	150.5	16.5	1.10	3000	10
		6	1119	504	2.40	149.5	17.6	0.50	2600	14
		6 1/2	1165	491	2.38	148.5	17.9	0.25	2350	18

TABLE III

COMPACTION EFFORTS, AND THE DESIGNED A.C. CONTENT, UNIT WEIGHT, STABILITY, AIR VOIDS PERCENT, V.M.A. PERCENT, AND MAXIMUM UNIT WEIGHT AND STABILITY VALUES

No. of Mix	Compaction Effort psi	Designed Values						Max. Values	
		Asphalt %	Unit Wt. 10 pcf.	Stability lb.	Flow 10^{-2}	Air Voids %	V.M.A. %	Unit Wt. pcf.	Stability lb.
A	1000	6.1	147.0	1330	26	2.6	19.6	148.0	1400
B	2000	5.5	148.0	1640	20	2.6	19.0	148.7	1930
C	3000	5.1	148.3	2750	18	3.0	18.5	149.3	2780
D	4000	4.9	149.5	4300	16	3.0	16.0	150.5	4300
E	5000	4.0	149.5	3500	12	4.0	14.0	149.7	3570
Marshall blows	50	5.0	149.0	3050	8	2.7	17.0	150.5	3150

TABLE IV

DEGRADATION OF MIXES C, D, E
PERCENT PASSING AGGREGATE BY WEIGHT

	Sieve Designation						
	3/4	1/2	4	10	40	80	200
Percent Passing by Weight Mix C	100	90	65	44	22	15	10
Percent Passing by Weight Mix D	100	92	70	44	23	19	12
Percent Passing by Weight Mix E	100	97	72	60	25	21	13

TABLE V

EFFECT OF STATIC PRESSURE ON DRY AGGREGATE

Static Pressure psi	1000	2000	3000	4000	5000
Degradation Factor	6.3	9.1	9.7	14.6	18.8

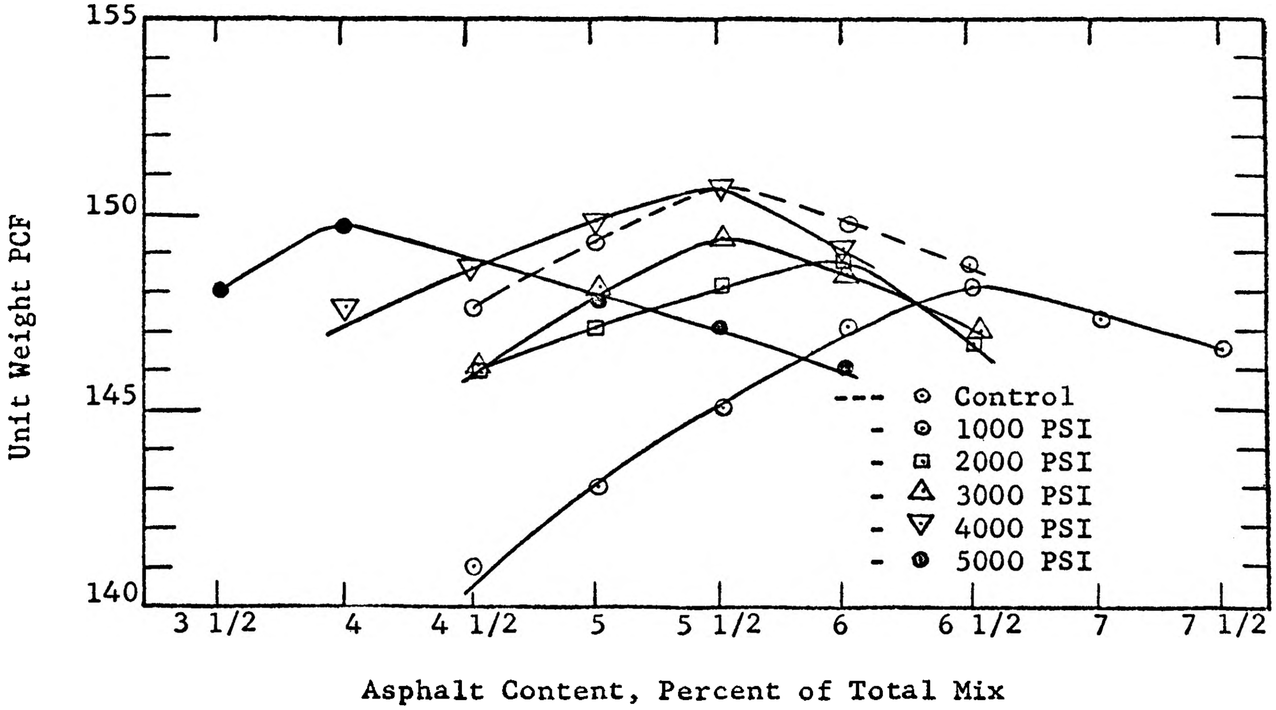

Figure 2 - Unit Weight and Asphalt Content Relationships

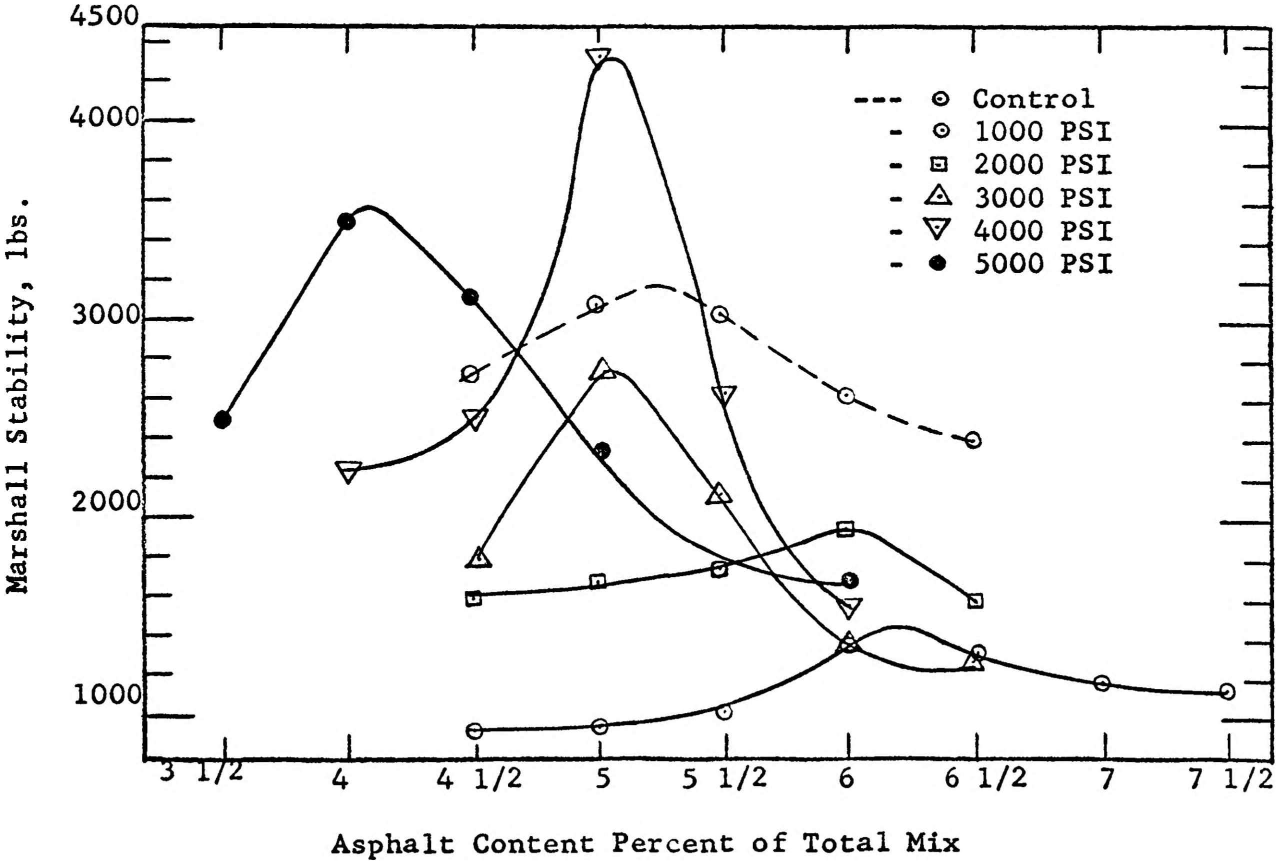

Figure 3 - Marshall Stability and Asphalt Content Relationships

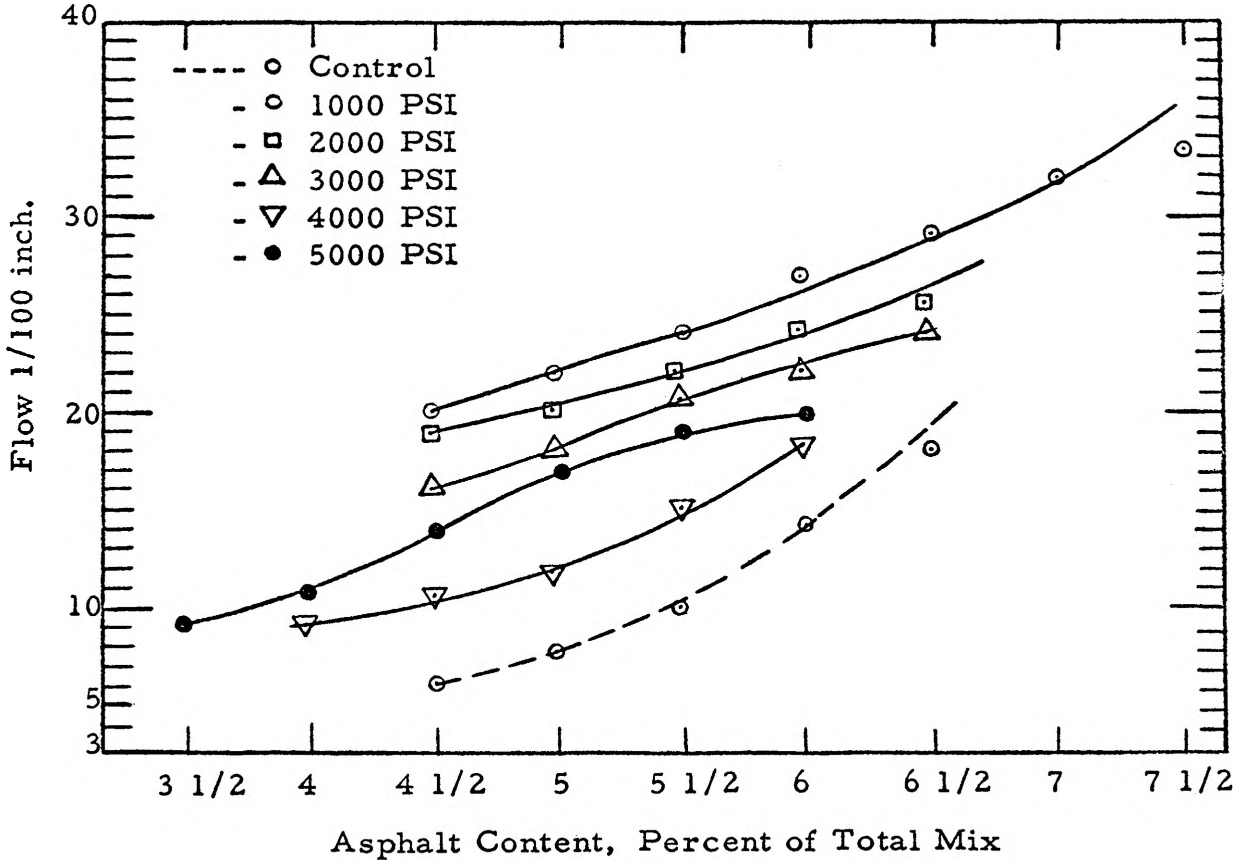

Figure 4 - Flow and Asphalt Content Relationships

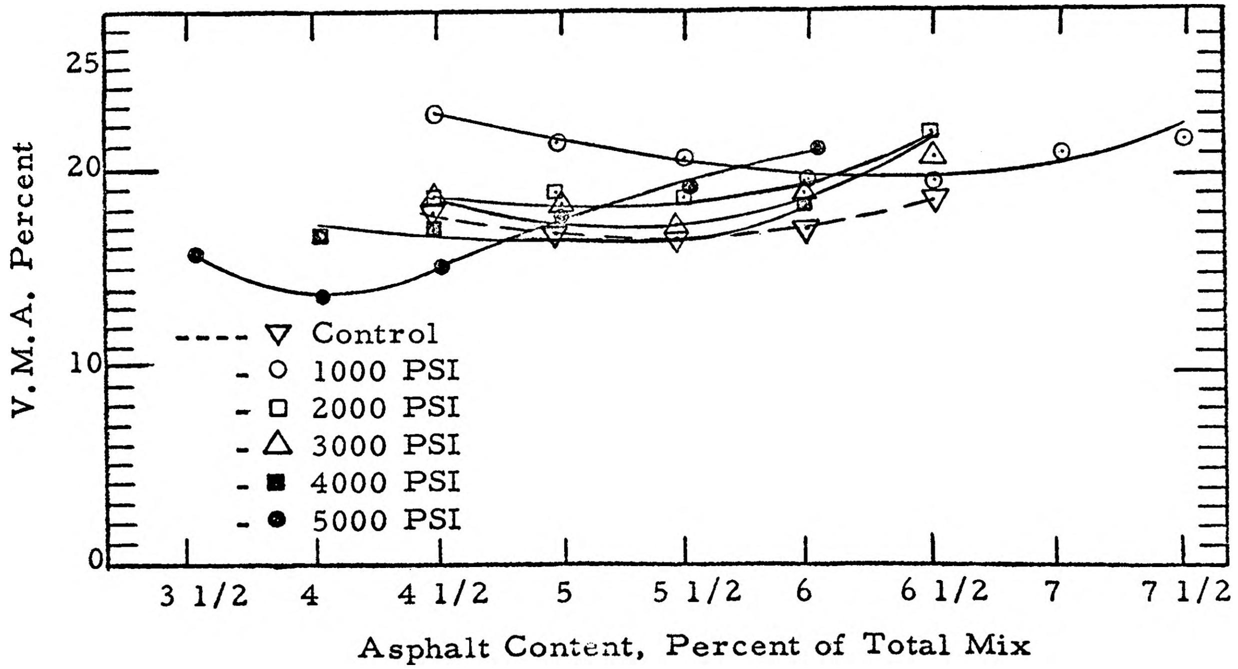

Figure 5 - V.M.A. Percent and Asphalt Content Relationships

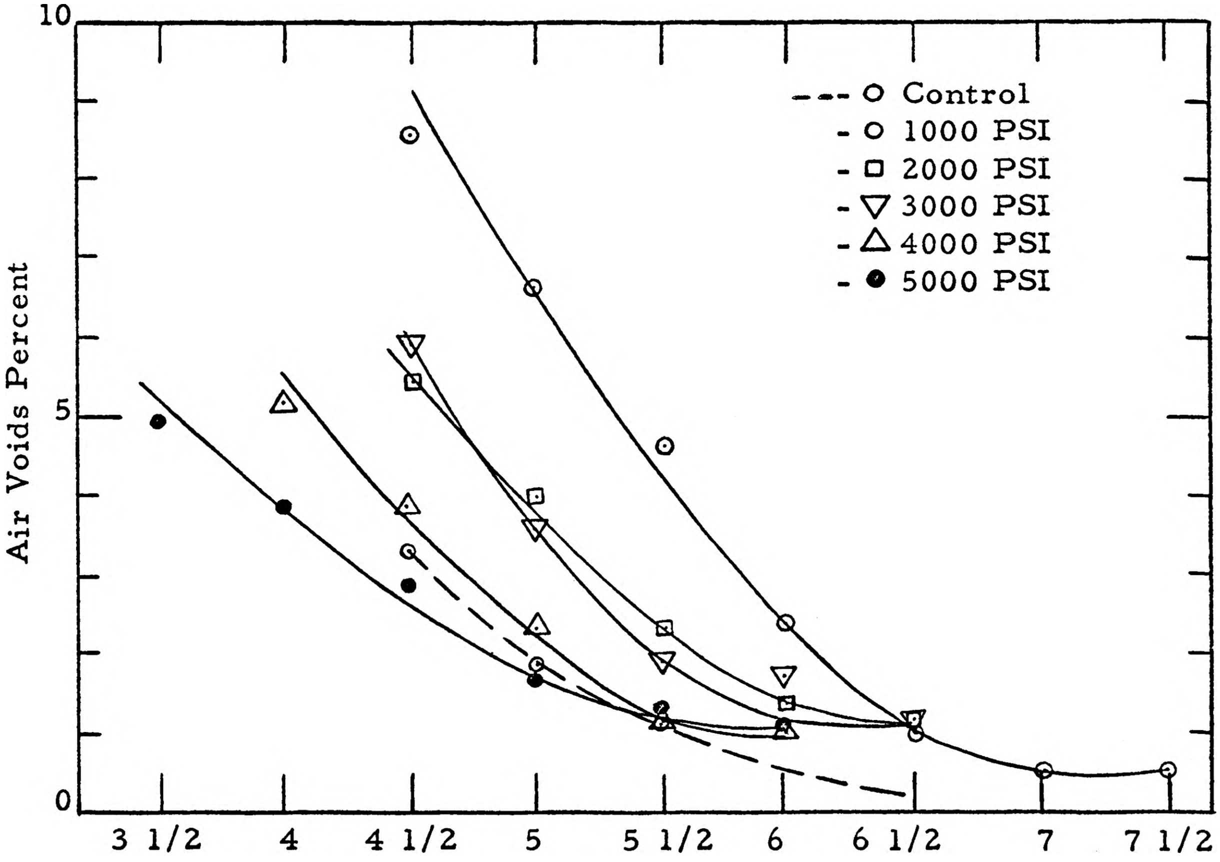

Figure 6 - Air Voids Percent and Asphalt Content Relationships

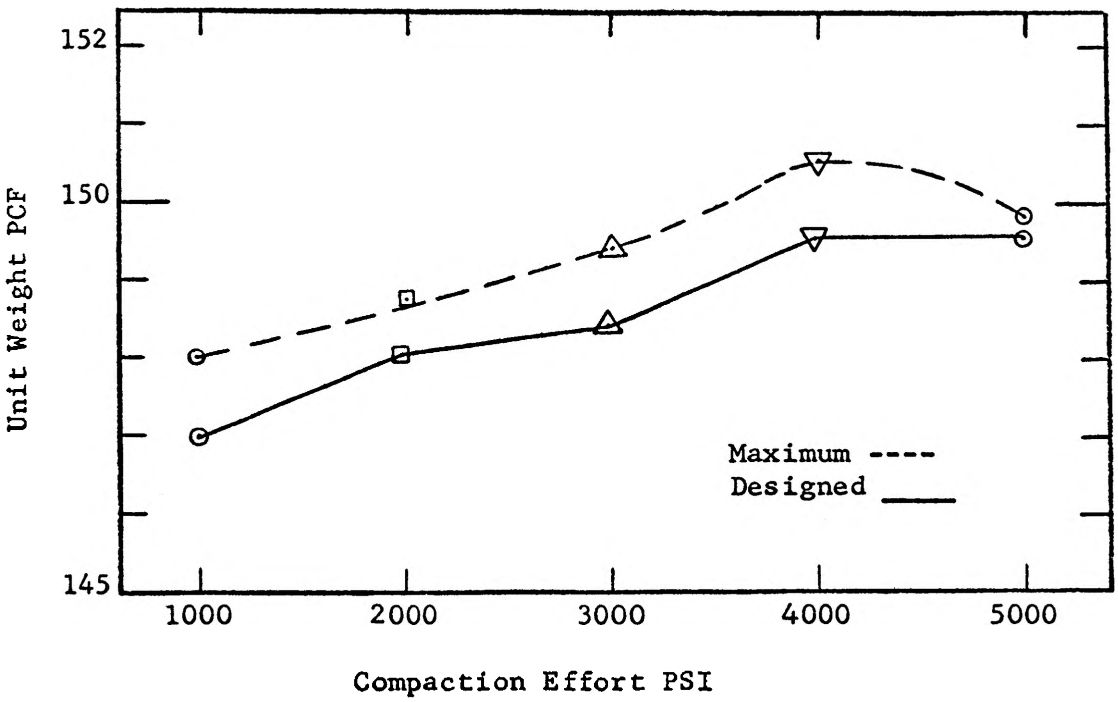

Figure 7 - Compaction Effort and Unit Weight Relationships

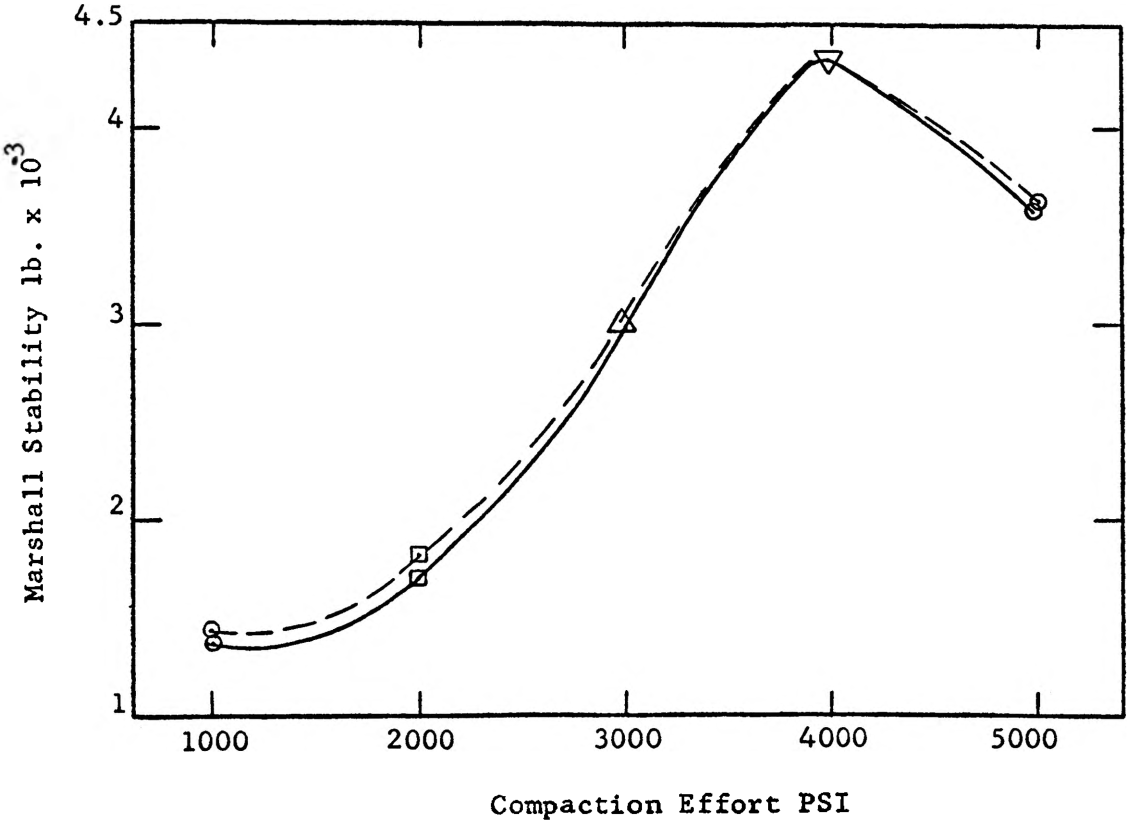

Figure 8 - Compaction Effort and Marshall Stability Relationships

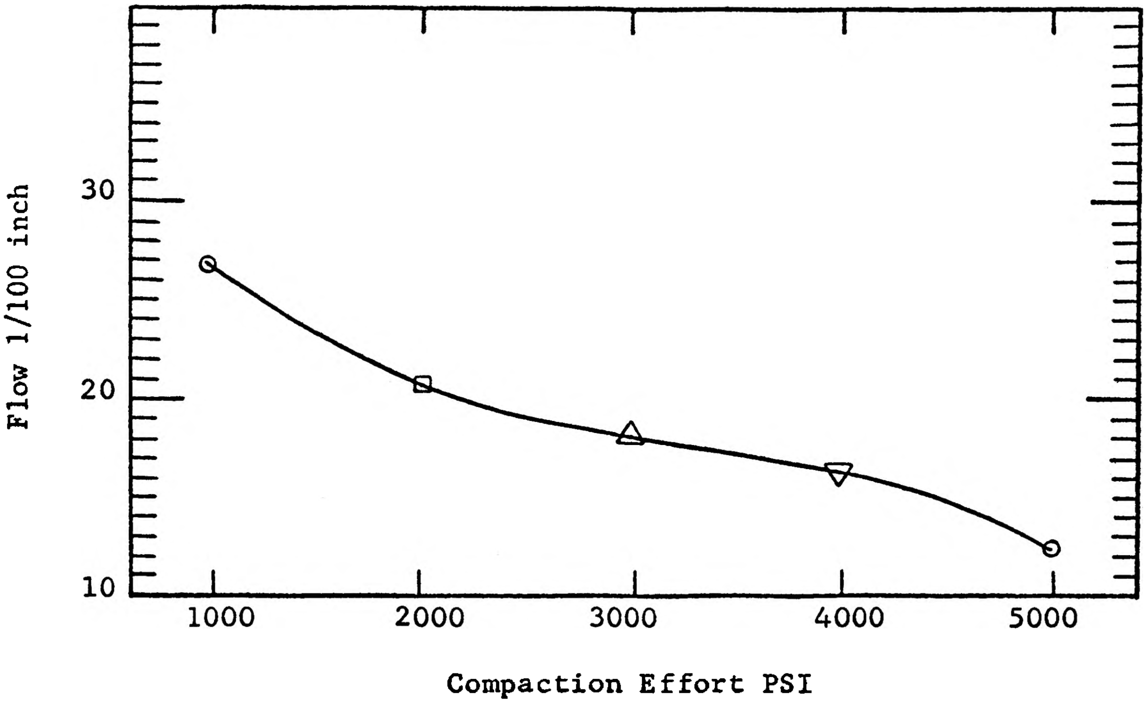

Figure 9 - Compaction Effort and Flow Relationships

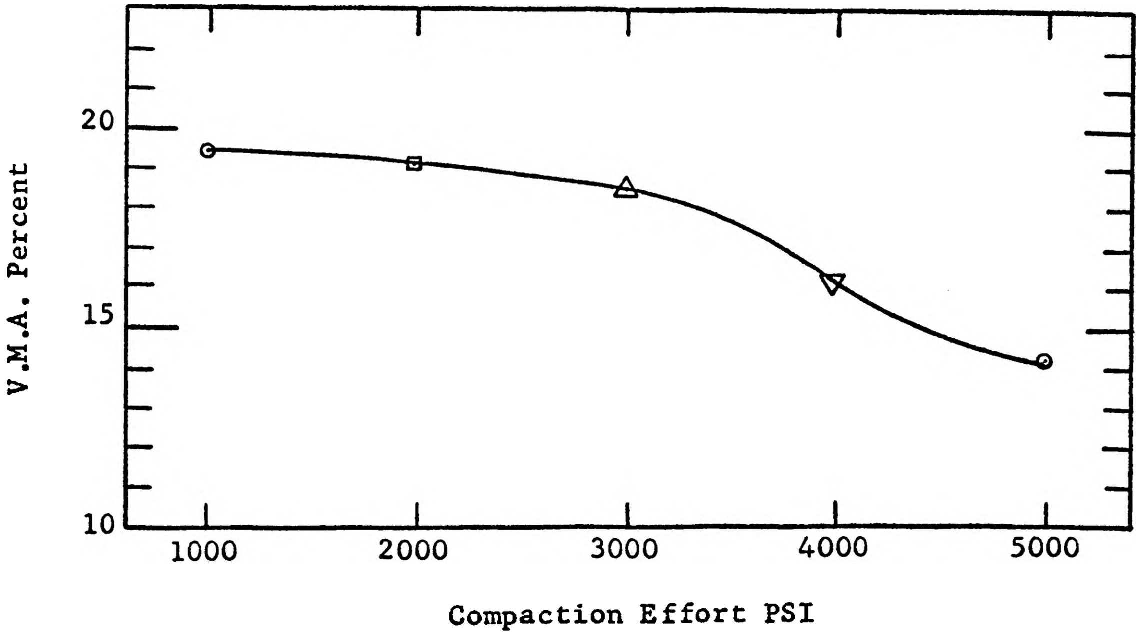

Figure 10 - Compaction Effort and V.M.A. Percent Relationships

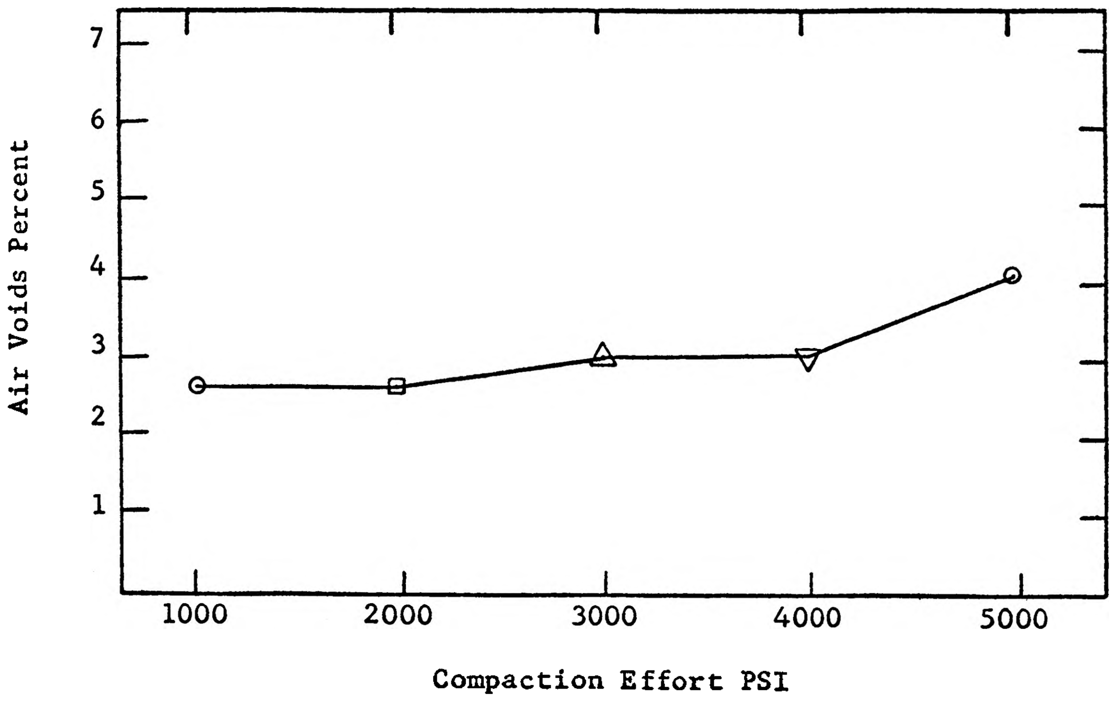

Figure 11 - Compaction Effort and Air Voids Relationships

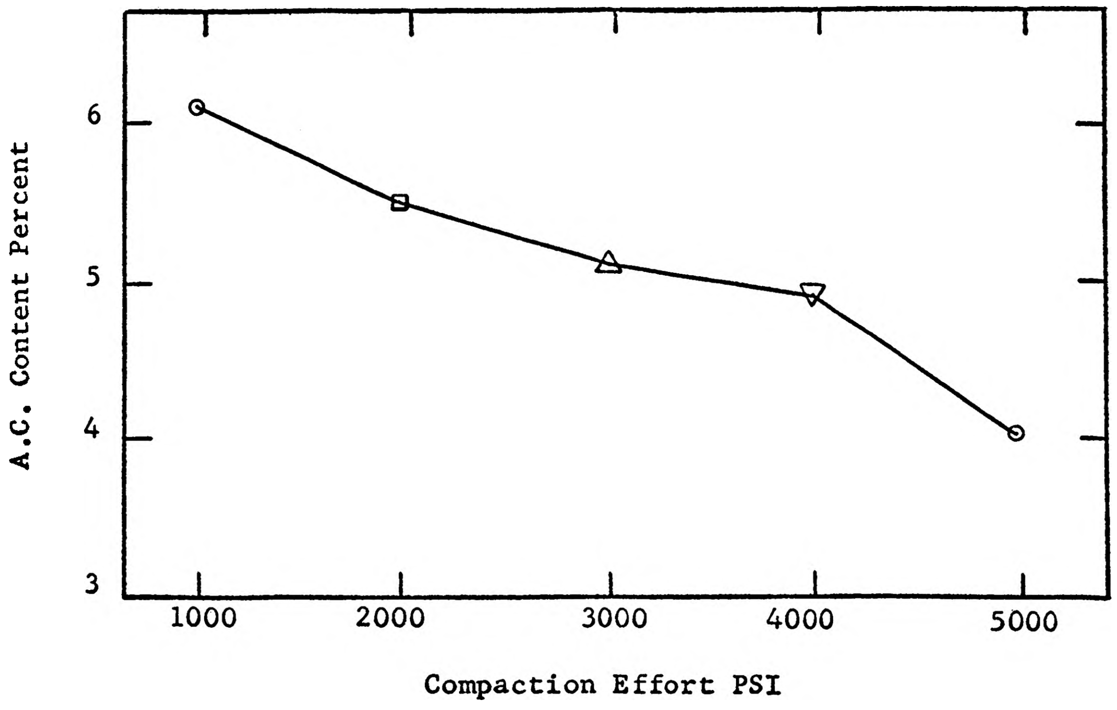

Figure 12 - Compaction Effort and Asphalt Content Relationships

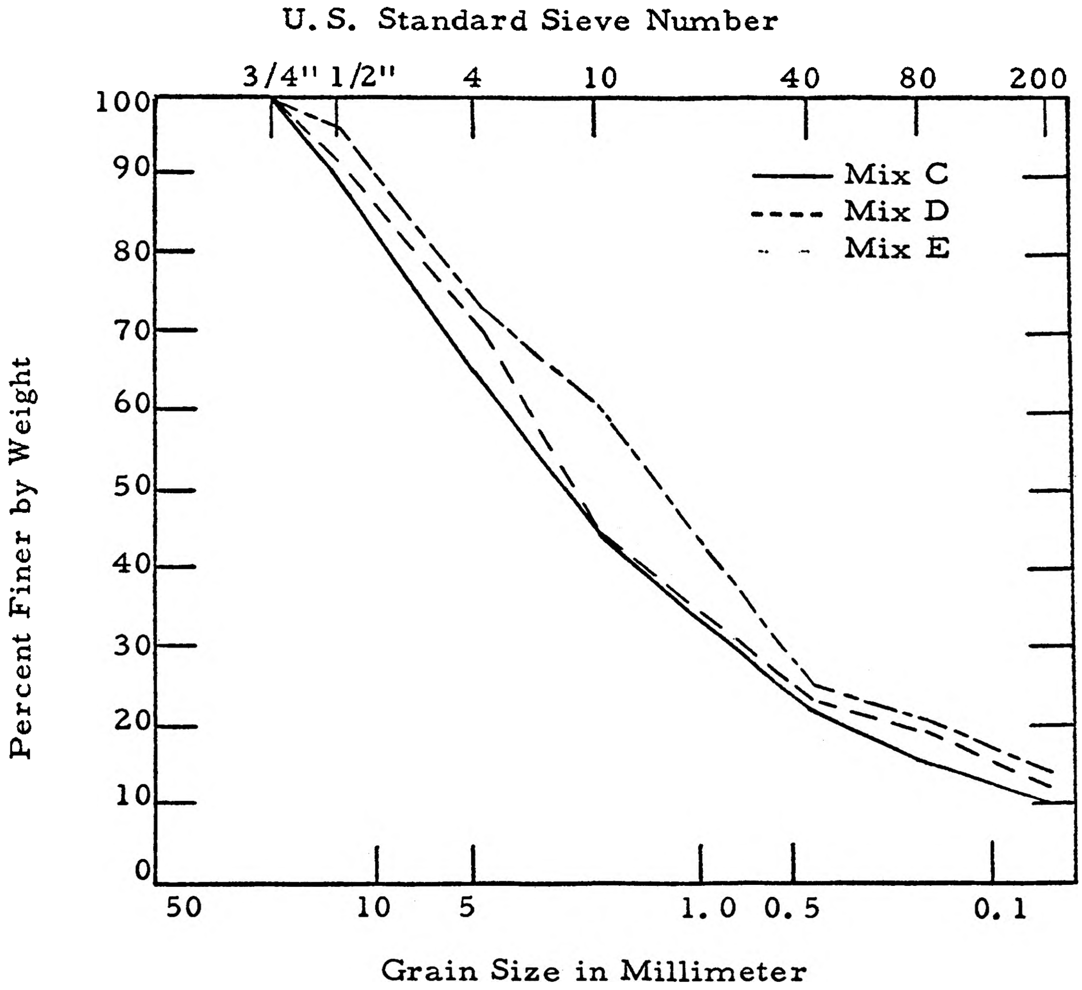

Figure 13 - Aggregate Degradation in Mixes C, D, E

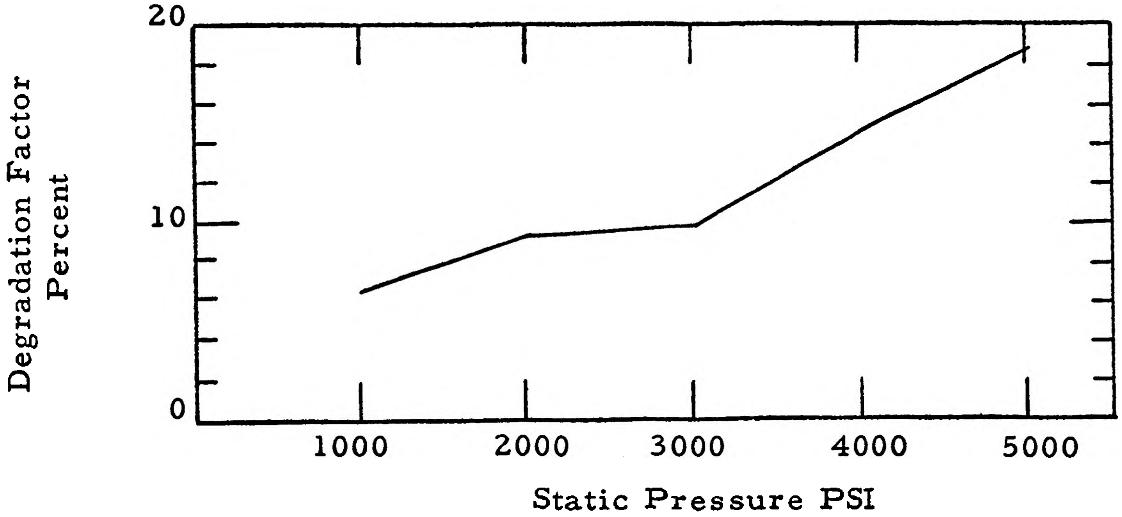

Figure 14 - Relationship between Static Pressure and Degradation Factor

different mixes. It also shows the maximum unit weight and stability for each mix. Figures 7 through 12 show the relationship between the compaction effort used for each mix and the maximum and design unit weight and stability, and the design value of flow, percent voids in mineral aggregate, percent air voids in the mix, and asphalt content. An example of the calculation procedure used is presented at the end of this chapter.

The results of the sieve analysis data for aggregate extracted from molded specimens of mixes C, D, and E are presented in Table IV and Figure 13. Also, the values of the degradation factors for the dry aggregate subjected to different compaction efforts are summarized in Table V and Figure 14.

B. STRESS-STRAIN STUDY

1. General.

In all the literature reviewed it was found that the effect of temperature and rate of loading upon the load-deformation characteristics of the asphalt concrete mixtures has been extensively studied. The equation developed at Purdue University established the relationship between temperature, rate of loading, and the ultimate compressive strength of asphalt concrete mixes (12). In this study the relationship between compactive effort, ultimate unconfined compressive strength and the properties of the stress-strain curve have been investigated.

Specimens compacted by the same static pressures used for the five mixes studied in part (A) were tested in unconfined compression under three different rates of deformation.

2. Preparation of Test Specimens.

Specimens 2.1 inches in diameter and 4 inches high were prepared using the same aggregate and bituminous binder as used in part (A). A double plunger method of static compaction was used. Five mixes using asphalt cement contents determined in accordance with the data obtained from the compaction study (Table III) were used for preparing the specimens. An effort was made to secure maximum uniformity for the specimens of each mix.

3. Unconfined Compression Tests.

The specimens of each mix were loaded to failure in a compression machine using three rates of strain, 0.16 in/min, 0.016 in/min, and 0.0016 in/min. For each rate of strain, two specimens from each mix were tested at constant load increments and the average deformation at each load was found from both results. The specimens were tested at a temperature of 90°F. This temperature is comparable to that found in the field and was the most feasible for the laboratory tests.

4. Results.

Table VI shows the results of the stress-strain test at deformation rates of 0.16 in/min, .016 in/min and .0016 in/min. Figures 16 through 19 are the stress-strain curves for each mix at the different rates of deformation. The Modulus of Elasticity which is defined as the slope of the line drawn from the origin tangent to the stress-strain curve (13) was calculated, and the ultimate compressive strength was determined for the different mixes at each rate of loading as shown in Table VII and Figure 20. Also, the ultimate compressive strengths for each mix are plotted as a function of the compaction effort in Figure 21.

TABLE VI

STRESS-STRAIN DATA FOR MIXES STUDIED AT 90°F

			Rate of Strain inch per minute					
		Unit	0.16		0.016		0.0016	
Mix No.	Asphalt %	Weight pcf	Stress psi	Strain x 10^{-4}	Stress psi	Strain x 10^{-4}	Stress psi	Strain x 10^{-4}
A	6.10	147.00	29	14	17	19	16	19
			55	26	35	35	23	26
			72	33	52	41	26	28
			100	44	61	50		
			120	49				
B	5.50	148.00	29	14	35	32	16	19
			55	19	55	41	23	28
			72	31	64	48	35	38
			100	46	76	63	47	54
			120	50	85	110	55	108
			129	55				
C	5.10	148.50	29	12	26	20	16	18
			55	20	40	28	23	28
			70	27	55	40	35	36
			100	44	46	54	47	58
			120	54	99	108	63	92
			143	61				
			152	74				
D	4.90	149.5	29	13	35	27	23	24
			55	18	58	38	52	50
			70	26	76	45	70	65
			100	33	99	53	86	94
			120	38	114	62		
			162	68	140	80		
			184	72	158	105		
			224	79				
			250	89				
E	4.00	149.5	29	10	35	25	16	15
			55	20	55	33	23	27
			70	25	85	45	35	36
			100	27	102	50	47	50
			120	37	122	55	70	72
			143	56				
			162	64				
			184	74				

TABLE VII

THE ULTIMATE COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY VALUES AT DIFFERENT RATES OF DEFORMATION FOR ALL MIXES STUDIED

Mix No.	Applies Pressure psi	Compressive Strength psi			Modulus of Elasticity psi		
		Rate of Strain in/min			Rate of Strain in/min		
		0.16	0.016	0.0016	0.16	0.016	0.0016
A	1000	120	61	26	22000	13000	9000
B	2000	129	85	55	24000	13000	9000
C	3000	152	99	63	25000	13000	9000
D	4000	250	158	85	30000	14000	9400
E	5000	184	122	70	26000	13000	9200

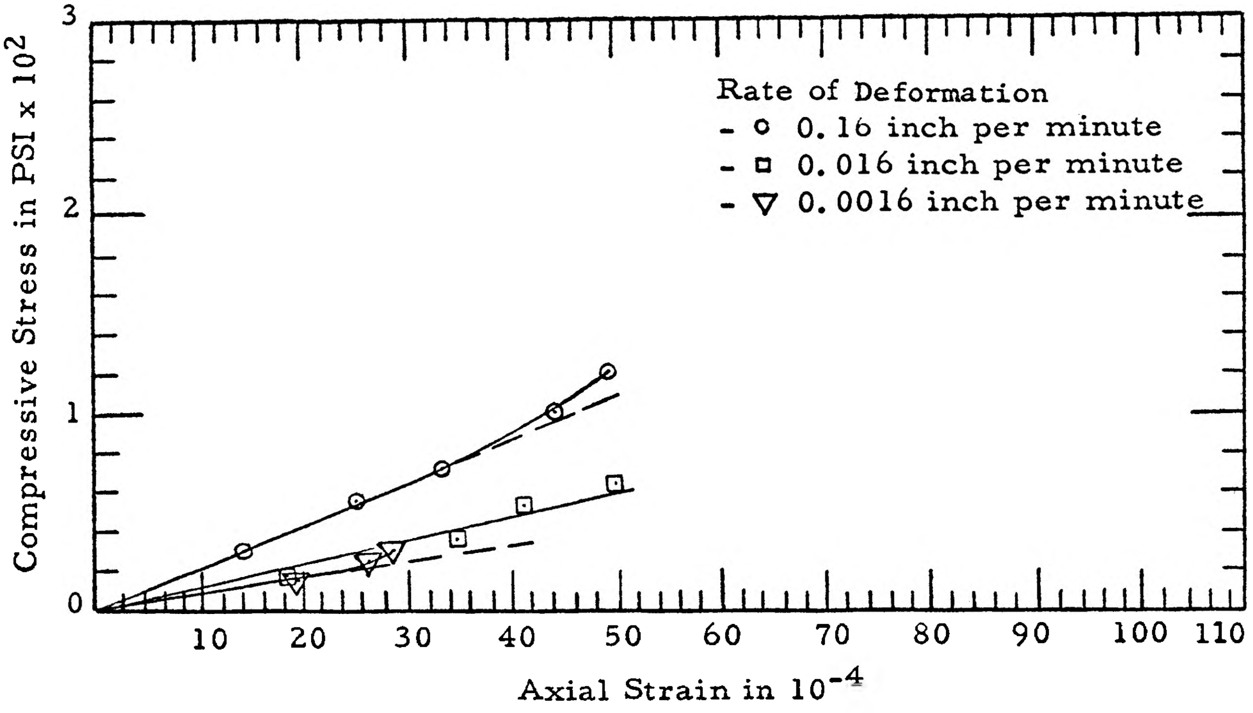

Figure 15 - Stress-Strain Relationships for Mix A

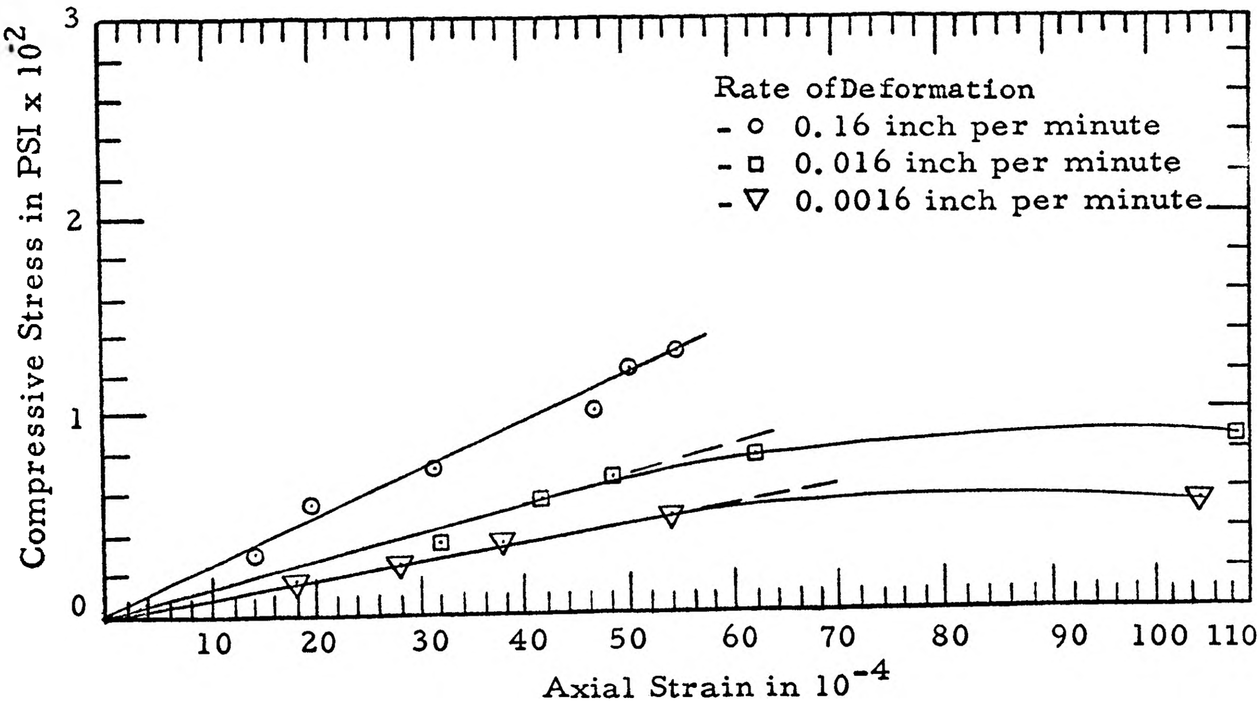

Figure 16 - Stress-Strain Relationships for Mix B

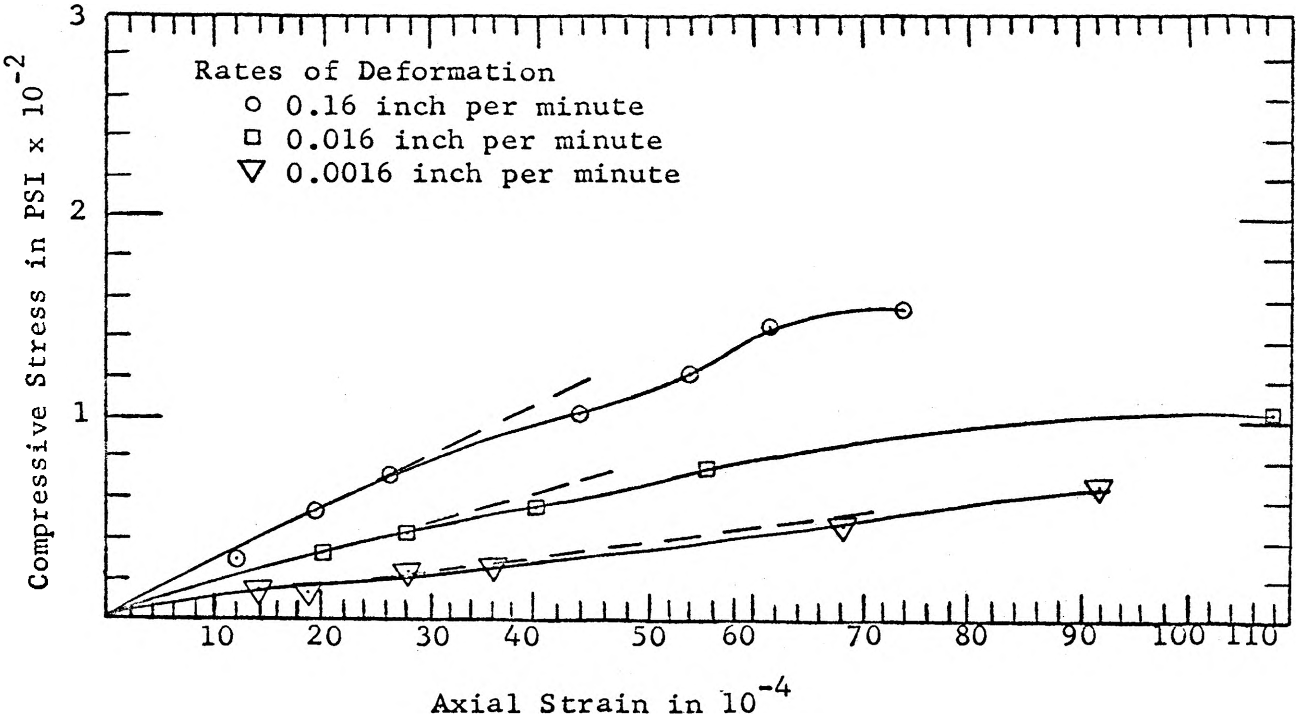

Figure 17 - Stress-Strain Relationships for Mix C

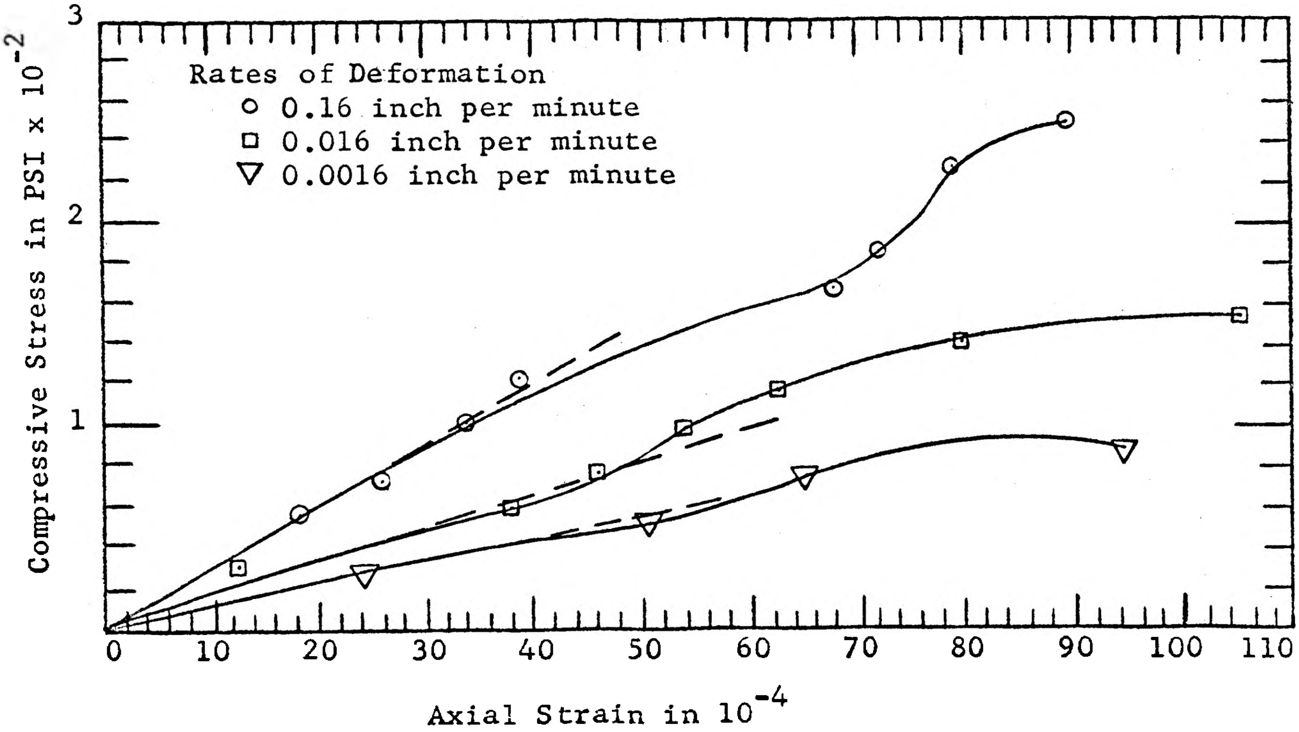

Figure 18 - Stress-Strain Relationships for Mix D

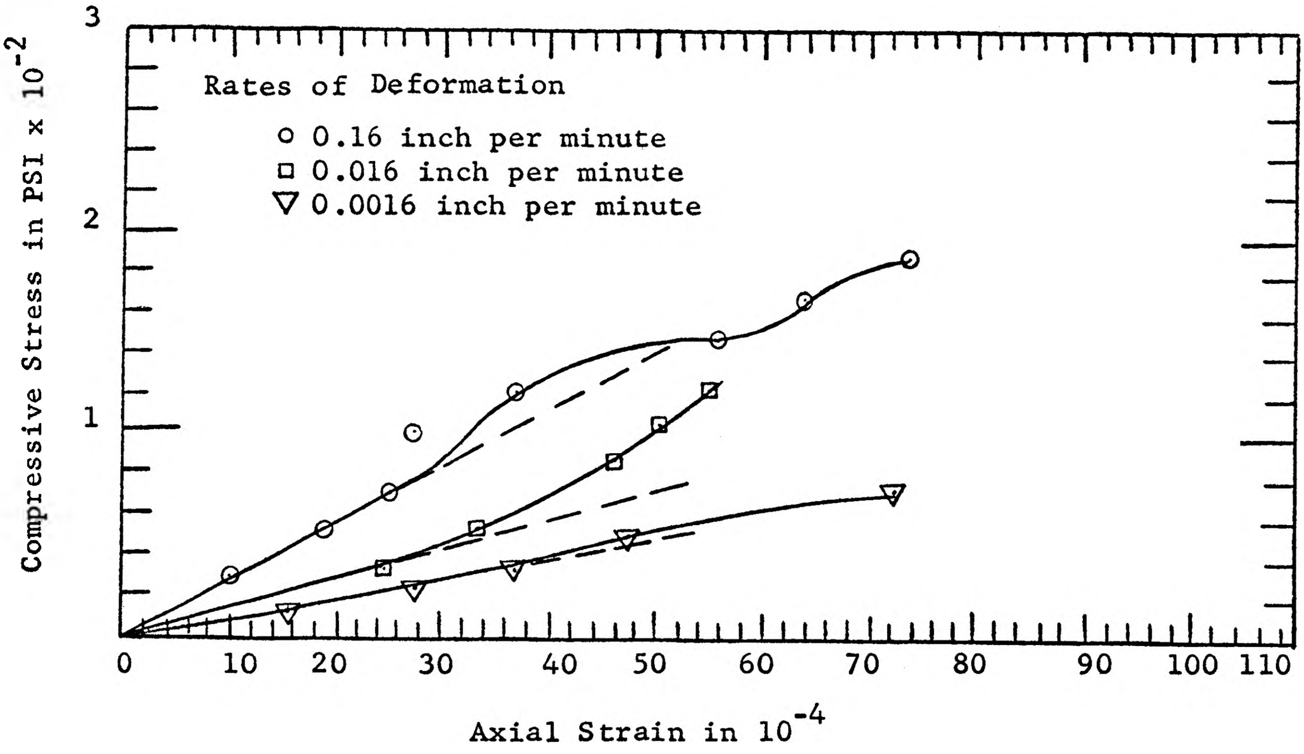

Figure 19 - Stress-Strain Relationships for Mix D

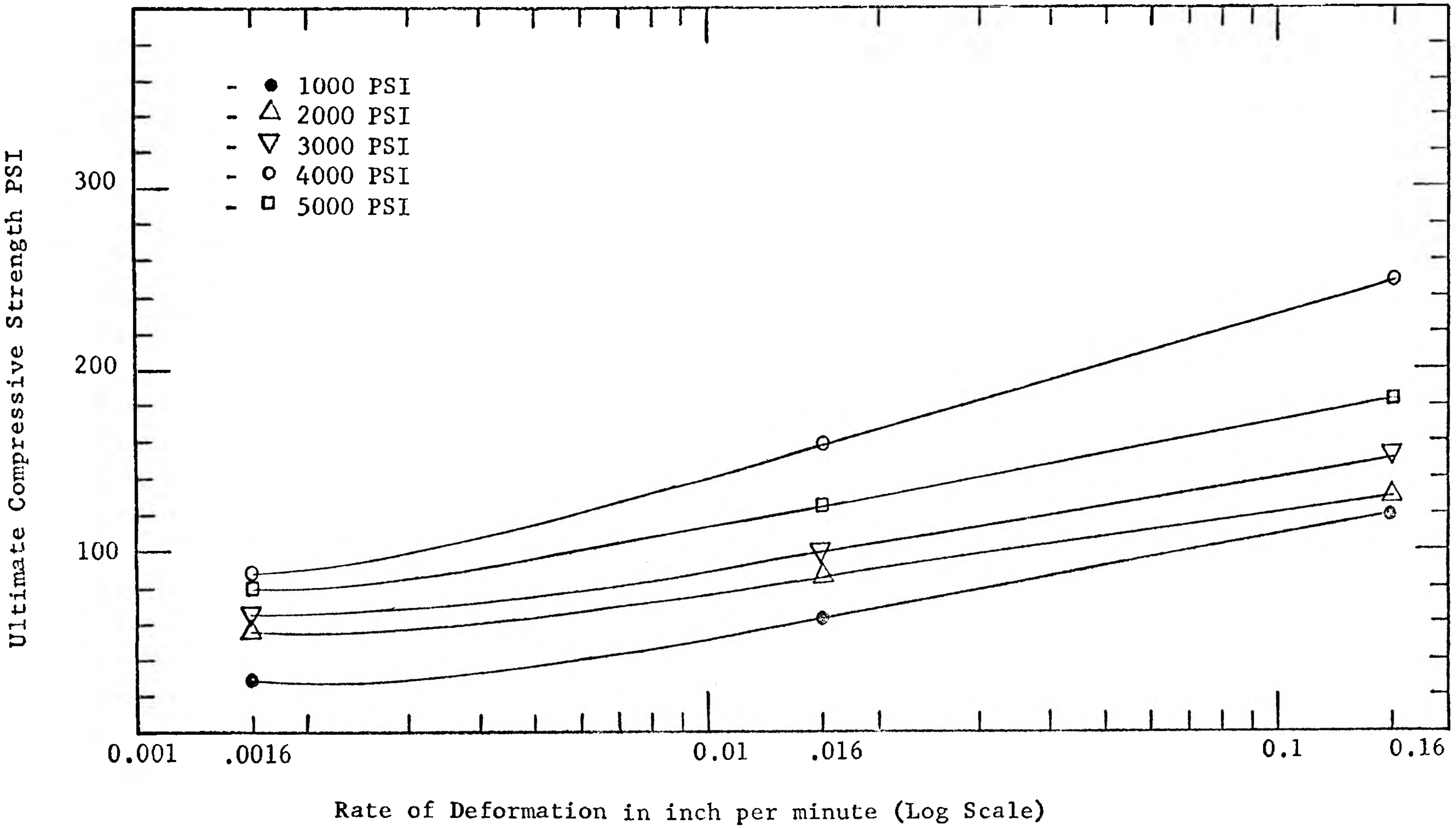

Figure 20 - Ultimate Compressive Strength and Rate of Deformation Relationships

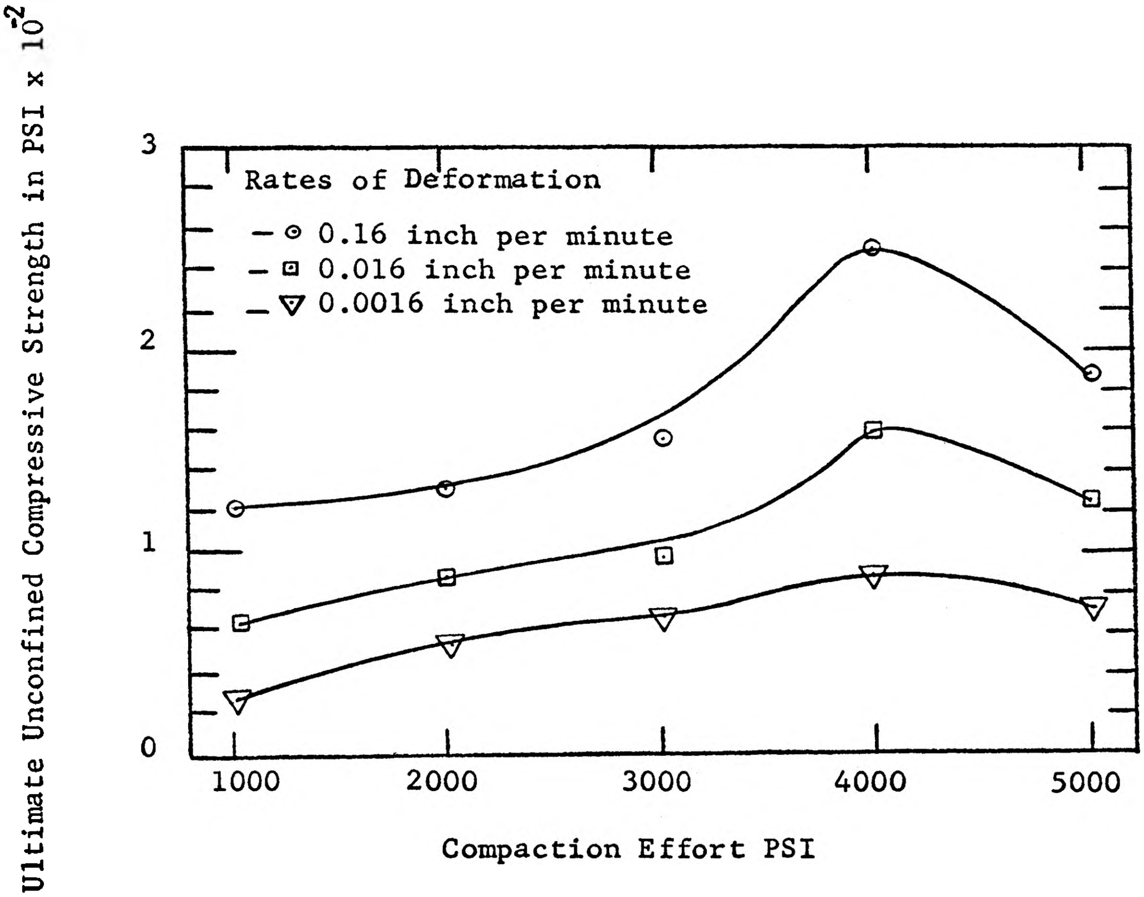

Figure 21 - Compaction Effort on Ultimate Stress Relationships

Sample of Calculations
Control Mix (Marshall)
5.00% Asphalt Content

Aggregate Bulk Specific Gravity = 2.65

Asphalt Apparent Specific Gravity = 1.02

Asphalt Content Total Weight = 5%

Average Unit Weight of the Mix = 149.2 pcf

Asphalt by weight in 1.00 cu. ft. of asphaltic mixture = 149.2 x 0.05 = 7.46 lbs.

Aggregate by weight in 1.00 cu. ft. of asphaltic mixture = 149.2 - 7.46 = 141.74 lbs.

Asphalt by volume in 1.00 cu. ft. of asphaltic mixture = 7.46/1.02 x 62.4 = 0.1177 cu. ft.

Volume of Aggregate + Asphalt = 0.1177 + 0.857 = 0.9747 cu. ft.

Air voids in 1.00 cu. ft. of asphalt mixture = 1.00 - 0.9747 = .0253 cu. ft.

Air voids Percent = .0253 x 100/1.00 = 2.52%

Voids in Mineral Aggregate = 1.00 - 0.857 - 0.143 cu. ft.

Voids in Mineral Aggregate = 0.143 x 100/0.857 = 16.6%

IV. DISCUSSION

A. COMPACTION STUDY

Compaction, as the term is applied to the field of asphalt concrete mixtures, is considered to be one of the most important stages in both mix design process and pavement construction. Proper compaction is a necessary item in building all types of satisfactory flexible pavements. The first result of any compaction application is merely to squeeze the particles together with only minor relocation of the particles relative to each other. Some procedures have the additional effect of re-adjusting the relative position of particles and changing their relative orientation as the compactive effort increases. The nature of some compaction methods does not allow this readjusting without breaking the aggregate particles and degrading them. Compaction, merely as a densification process, is a function of many factors including type, direction, and duration of forces during application. In bituminous mixes the binder has the direct effect of lubricating agency which facilitates movement of particles during the compaction process. The degree of densification of the compacted mix is dependent upon the percentage asphalt and the compaction effort. At high compaction effort the maximum change in the orientation of aggregate particles can take place at a relatively low asphalt content. A somewhat higher asphalt content is required to achieve maximum density if the compactive effort is low.

The results of this study indicate that there is a direct relation between the physical properties of a design asphalt mixture and the type and magnitude of the compaction effort used to compact the test specimens. These relationships are shown in Figures 2 through 14.

The effect of the type of compaction was clearly reflected when comparing the properties of Mix D and the control mix. While both of these mixes showed the same maximum unit weight at the same asphalt content the maximum stability of Mix D was relatively higher than that of the control mix. The reason for this higher stability is the fact that impact compaction causes a relative relocation of aggregate particles without breaking them, whereas the high static pressure applied in Mix D used to achieve the same degree of densification crushed some of the aggregate particles, which increased the surface area, and consequently, the internal friction between the aggregate particles. The lower flow value of the control mix also reflected the degradation in Mix D. The coated aggregate surface in the control mix, which failed at a lower load in the Marshall Machine, prevented an excessive deformation at failure due to the existence of cohesion between the particles. The higher flow values of Mix D were due to the lack of cohesion between the broken aggregate surfaces once the high internal friction was overcome.

The effect of the magnitude of static pressure can easily be explained when comparing properties of Mixes A, B, C, D, and E all at the same time. The relatively lower unit weight, stability, and higher flow values of Mixes A and B at much higher asphalt contents was due to the application of insufficient compaction effort. The effect of the compaction effort used with these two mixes was squeezing the aggregate particles together without reasonable interlocking between the particles. The higher values of both air voids and voids in mineral aggregate were further indications of improper particle orientation.

Both the extraction test of Mix C, and the compaction of dry aggregate with 3000 psi static pressure indicated negligible degradation of this mix during compaction. The reasonable values of unit weight, stability and flow at lower asphalt contents than Mixes A and B were the results of a sufficient compaction effort, allowing both squeezing and minor relocation of aggregate particles caused by a rotational motion of particles to reach the best orientation without noticeable aggregate degradation.

Reaching the best possible particle orientation with the application of 3000 psi static pressure, the increase in compaction effort of Mix D, without any possible particle relocation, caused breaking of some aggregate particles and resulted in the highest possible densification at the same asphalt content as Mix C.

In Mix E the small drop in maximum unit weight value at much lower asphalt content was due to more degradation, making it easier for the particles to have better orientation but with more voids than in Mix D. The stability of this mix showed higher values than those of Mixes A, B, C, and the control mix. The reason for this was the increase of the aggregate particle surface area. This stability value, however, was less than that of Mix D because of the lack of cohesion at this very low asphalt content.

B. STRESS-STRAIN STUDY

The objective of this portion of the investigation was to determine the effect of the static compaction efforts on the mechanical properties of the asphalt concrete mixtures. The mechanical properties under consideration included the ultimate unconfined compressive strength and the modulus of elasticity for the asphalt concrete specimens.

A direct relation between the ultimate unconfined compressive strength of the asphalt mixtures and the static pressure applied for their compaction was indicated. At all rates of strain applied an increase in the ultimate stresses was noted with the increase of compaction efforts up to a static pressure of 4000 psi. For specimens compacted at 5000 psi, however, a drop in the ultimate stress was indicated (Figure 21). This was due to the improvement in orientation of the particles in the mixes with the increase of the applied compaction pressure up to 3000 psi. The highest ultimate stresses obtained by specimens compacted at 4000 psi static pressure were, as mentioned before, the result of an increase in the internal friction between the aggregate particles. As in the case of the compaction study, this was also due to the increase of aggregate surface area caused by the breaking of some aggregate particles while compacting at such a high pressure. The drop in the ultimate stress of specimens compacted at 5000 psi was due to the lack of cohesion between the broken uncoated particles and the low asphalt content.

The behavior of the asphalt in the asphalt concrete mixtures provides an explanation for the change of the stress-strain characteristics of the mixes tested at various rates of strain (Figures 16 through 19). Asphalt is a rheological material whose stress-strain characteristics are time dependent and it induces the same properties into the asphalt concrete mixtures.

Both the ultimate compressive stress and modulus of elasticity values for all samples tested were affected by changes in the rate of strain. The ultimate strength of all samples tested increased as the applied rate of strain was increased. The relative increase in ultimate stresses associated with increased rates of strain was much greater in mixes having high asphalt contents than those with lower asphalt contents (Figure 20).

All mixes tested, regardless of the static pressure applied in compacting their specimens, verified the relation developed at Purdue University which relates the ultimate unconfined compressive strength to the rate of strain (12). The ultimate compressive strength for all mixes is a logarithmic function of the rate of strain (Figure 20). However, it may be seen from this figure that at very low rates of deformation, and for each compactive effort, the value of the ultimate stress deviates from this relation and tends to reach a horizontal asymptote and to become a function of the compaction effort alone.

The effect of the different compactive efforts applied to the test specimens on the values of their modulus of elasticity was negligible. This was due to the fact that the same asphalt cement grade and the same type of aggregate were used with all mixes. However, rather large variations in values of this modulus were indicated by changing the rate of deformation. An increase in the modulus of elasticity values was a direct result of increasing the rate of deformation. Specimens tested at higher rates of deformation withstood higher stresses with less strain than those tested at lower rates of deformation. This again was due to the existence of asphalt in the mixes which behaves as an elastic material at high rates of loading and as a plastic material at low rates of loading.

V. CONCLUSIONS

On the basis of the data accumulated during the experiments and the analysis thereof, certain trends of the structural behavior of bituminous paving mixtures have been mentioned which, when viewed in the light of existing knowledge, lead to the following tentative conclusions:

1. Compaction has definite effects on the test properties of bituminous mixes and is dependent upon the type and magnitude of the compactive effort used.

2. Impact compaction causes a relative relocation of aggregate particles to provide a better orientation without excessive degradation of aggregate.

3. Improvements in the test properties of bituminous mixes, without noticeable degradation of aggregate, can be achieved by increasing the static compaction effort up to 3000 psi.

4. The nature of static compaction does not allow the relative relocation of aggregate particles in bituminous mixes. Extensive change in aggregate gradation occurs if static pressures above 3000 psi are applied.

5. Bituminous mixes compacted by static compaction generally have higher flow values than those compacted by impact.

6. The optimum asphalt content in a bituminous mix is a direct function of the static compaction pressure. By increasing the compaction effort, the optimum asphalt content decreases.

7. Satisfactory test specimens can be obtained by applying a static compaction effort of 3000 psi for a period of 2 minutes.

8. A very high stability value of a bituminous mix is not an indication of satisfactory performance of a pavement because it may be due in part to degradation of aggregate.

9. Similar to the findings of other investigators, it was found that the stress-strain characteristics of asphalt concrete mixtures depend upon the rate of strain.

10. The ultimate unconfined compressive strength of a bituminous mix is a function of the designed unit weight of the mix when tested at a constant temperature and rate of deformation. Mixes with higher designed unit weight withstand higher unconfined compressive stresses.

11. At a constant temperature, the ultimate compressive strength of bituminous mixes varies logarithmically with the rate of strain regardless of the compaction pressure applied. This verifies the relation developed at Purdue University (14). However, at very low rates of strain, the ultimate stress seems to be constant and dependent upon the designed unit weight only.

12. The modulus of elasticity of bituminous mixes is a function of the rate of strain. Higher values of this modulus are expected with higher rates of deformation, provided that the temperature remains constant.

13. For the same rate of deformation and at a constant temperature, the modulus of elasticity appears to be constant, depending upon type of aggregate and bituminous binder used. It is not affected by the change in the magnitude of the static compaction effort.

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VITA

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In 1955 he enrolled in the School of Engineering of Cairo University and in 1960 he received a Bachelor of Science Degree in Civil Engineering and a minor in Transportation. From 1960 to 1963 he worked as a part time assistant instructor and as a full time instructor of Civil Engineering at Cairo University. During the same period he worked as an assistant researcher at the HYDRAULIC RESEARCH CENTER in Cairo, and also held the same position at the RESEARCH AND PLANNING Unit of the Ministry of Public Works of Egypt. In 1962 he registered for graduate studies in Hydraulics and Irrigation Design at the Graduate School of Cairo University.

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