VOID EFFECTS ON FATIGUE LIFE OF ASPHALTIC CONCRETE

by

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ABSTRACT

The data reported in this study was concerned with the analysis of void effects on fatigue life of asphaltic concrete mixtures. Air voids were varied by changing the asphalt content, density and aggregate gradation. Effects of these variables on fatigue response of coarse, medium, and fine graded mixtures were investigated. It was found that there is an interaction between asphalt content and compactive effort.

The Jimenez deflectometer was used as test apparatus. A detailed review of the literature related to fatigue testing has also been reported.

CHAPTER 1

INTRODUCTION

The rapid and continuous growth of highways along with the advent of larger wheel loads and heavier traffic has created additional and extreme demands for improved pavement systems. The provision of safe, economical, durable and smooth pavements that are capable of carrying the anticipated load is a necessity.

Damage in the flexible highway pavements has two main forms: cracking and pavement deformation, both of which are either due to load repetitions or environmental factors. Failure associated with pavement deformation is attributed to volumetric deformation and shear distortion in the pavement. Cracking due to repeated loading occurs primarily as a result of bending deflection. This type of failure is designated as fatigue failure. In recent years, considerable evidence has been accumulated that attests to the fact that flexible highway pavement surfaces can exhibit distress due to flexural fatigue as a result of repetitive applications of vehicular loads.

Flexible pavement surfaces are currently designed primarily in an effort to reduce potential distress due to instability, lack of durability, inadequate skid resistance, and expanding subgrade materials. Improved mixture and thickness design procedures must be developed if fatigue cracking is to be consistently avoided in flexible pavements. A satisfactory design from the standpoint of stability does not necessarily reduce significantly the possibility for fatigue cracking. In the past, the fatigue problem has been limited in extent because of failures to recognize the nature of and possibilities for fatigue of flexible surfaces and because traffic volumes and load magnitudes have normally been small relative to the traffic of today. Future increases in traffic volumes and weights coupled with the necessity in some cases for utilizing resilient or elastic foundations will doubtlessly focus increasing attention on the fatigue problem.

Advance stages of flexible pavement distress due to transient or repeated deflections can be recognized primarily by a pattern of "chicken net" or "alligator" cracking of the bituminous surfaces (1). This form of cracking has been attributed to fatigue failure of the pavement as a result of repeated stress over a prolonged period of time. A typical example of such a pavement failure of a Tucson street is shown in Figure 1.

Pavement distress resulting from repeated flexure (fatigue) of asphaltic concrete was recognized as early as 1948 by Hveem and Carmany (2). They recognized the

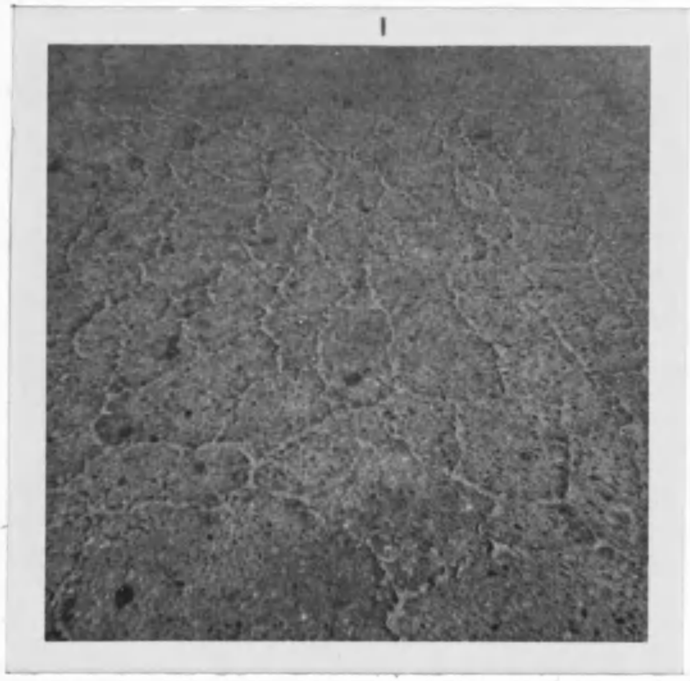


Figure 1. "Chicken Net" or "Alligator" Cracking of Asphaltic Concrete

possibility that highly resulient or elastic foundations could cause the cracking of surface courses due to excessive flexing under traffic loads and properly suggested that the type of distress so engendered was associated with fatigue effects. Such fatigue failures were thought to be related to three primary factors. The first concerns the potential deflecting effect of vehicular traffic which depends on the speed of the vehicles as well as the magnitudes and numbers of applications of the various wheel loads. The second involves the resiliency or springiness of the basement soil which is determined primarily by its degree of compaction and composition, and also its moisture content. The third was listed as the flexibility of the base and surface combination which depends chiefly on the thickness and effective stiffness of the base and surface layers.

Extensive studies of laboratory fatigue behavior of asphaltic concrete mixtures has been carried out in Europe and in the United States. These included the notable works of Nijboer and Van der Poel (3), Saal and Pell (4), and Pell (5) with his associates (6, 7). Monismith (8, 9, 10) has conducted numerous investigations from 1958 to date. Other investigators who have conducted fatigue tests on asphaltic concrete include Papazian and Baker (11), and Jimenez (12, 13, 14). A detailed review of the literature will be presented in Chapter 2.

In an attempt to examine the nature and causes of fatigue distress, it has been natural and proper to investigate the behavior of asphaltic mixtures subjected to fatigue loading in the laboratory. Numerous flexural-fatigue tests and procedures have been proposed. Hveem (1), Monismith (8, 9), and Papazian and Baker (11) have used equipment which tests beams in flexure while Jimenez (12) has used circular slab specimens supported on a hydraulic pressured rubber membrane to flex his specimens. The main disadvantage of the model using beam type specimens is that the specimens are subjected to only an uniaxial state of stress whereas an actual pavement is subjected to at least a biaxial state of stress such as that approximated by the apparatus developed by Jimenez. Hence the procedure advanced by Jimenez (12) was found to possess the most favorable model characteristics. In this study the Jimenez deflectometer will be used to evaluate the fatigue characteristics of asphaltic concrete. The detailed description of this apparatus will be presented in Chapter 5.

Fatigue has been defined as (15, p. 45):

> The process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations.

The laboratory equipment developed by the above mentioned investigators all produce repeated stresses and strains within a specimen.

The specimens are subjected to the fluctuating stresses and strains in the fatigue testing equipment by either controlled-stress or controlled-strain mode of loading. In controlled-stress or controlled-load tests the stress level or load is maintained constant throughout the fatigue life. However, the strain increases during the life of the tests. Controlled-strain or controlled-deformation tests maintain the strain level or deflection at a constant level throughout the life of the specimen. In order that the strain may remain constant, the stress must be reduced during the life of the tests. Modes of failure of the two types are different. In the case of controlled-stress a flaw will lead to stress concentration at the point of initiation, which will in turn lead to fast propagation and complete failure. In controlled-strain, cracking will result in a decrease in stress and therefore a slower rate of propagation. The deflectometer is essentially a controlled-stress type testing device.

The scope of this study is directed towards the analysis of the effect of voids on the fatigue life of asphaltic concrete. A number of mixture variables affect the fatigue behavior of asphaltic mixtures. Among these variables are:

1. Aggregate gradation
2. Asphalt content
3. Viscosity of asphalt
4. Air void content

A laboratory study was designed such that aggregate gradation, amount of asphalt, and specimen air void effects on fatigue could be evaluated.

The effect of aggregate grading was investigated by using three different aggregate gradations: a coarse, a medium and a fine. One penetration grade asphalt was used to study the effect of asphalt content. The different compactive efforts were used to obtain variable densities.

It is hoped that this study will be of some help in assessing the fatigue characteristics of asphaltic concrete.

CHAPTER 2

REVIEW OF THE LITERATURE

Work on fatigue cracking of bituminous roads has been carried out in Holland, South Africa, and Great Britain, but it has probably received more attention in the United States than anywhere else.

A review of the early efforts to consider the destructive action of repetitive vehicular loads in flexible pavement design is very well documented by Deacon (16). According to him, Bradbury considered the problem of failure by flexural fatigue in portland cement concrete pavement design. This influenced Grumm to consider the repetitive nature of traffic loading in flexible pavement design. A term "fatigue effect" was used in describing the destructive action caused by the repetitive application of heavy wheel loads; but it did not solely limit failure to fatigue effects as noted by Deacon (16, p. 6):

> It appears that his analysis of pavement distress included surface cracking due to factors other than fatigue effect such as rutting and shear deformation.

Hveem (1) was among the first highway researchers to emphasize the importance of the problem of flexural fatigue. A lead to this problem was provided by an early investigator. In 1936, Rader (17, 18) performed bending tests on asphaltic concrete beams at low temperatures. Beams 8 inches in length, 2 inches wide and 1½ inches deep were loaded at mid point by means of a lever system and then tested at a uniform rate of strain until failure occurred. He reported that: increase in modulus of elasticity is caused due to increase in density (within limits), and that high modulus of elasticity was responsible for high tensile stresses which resulted from low temperatures. Since Rader considered that cracking of asphaltic pavements results due to the shrinkage stresses developed by low temperatures, he concluded that low temperature cracking could be resisted by mixtures having low modulus of elasticity and high modulus of rupture. His findings paved the way for further research leading towards flexural fatigue of asphaltic concrete.

In 1942, Porter (19) recognized that the permissible deflection under a moving wheel load depends upon the number of load repetitions as well as on other factors. He found that flexible pavements failed under deflections as small as 0.02 inch - 0.03 inch if repeated a few million times. He wrote that (19, p. 100):

> ...failures are primarily due to progressive plastic deformation of the foundation which, with sufficient repetitions causes excessive deformation and bending of the base and pavement.

Thomas (20), in 1948, reported first repeated-loading test by testing 16 inch diameter asphaltic concrete specimens $1\frac{1}{2}$ inches thick supported on a spring base and loaded centrally over a concentric surface 4 inch in diameter. He applied 8 repetitions of load on either side of the specimens, and the strength, based on damage due to load applications, was determined. It was concluded from these tests that the stiffer mixtures were disadvantageous in spite of their greater load distribution characteristics.

It was Hveem's work (1), which sparked the considerable interest for research in asphalt mixture fatigue behavior. In an outstanding paper in 1955, Hveem (1) correlated the deflection under various axle loads with the actual performance of the pavement, and stressed the fact that cracking was the result of fatigue and hence dependent on both the magnitude and the number of repetitions of the deflection. These conclusions were based on the result of a great many measurements taken on different roads in California. A typical example of a pavement failure due to fatigue has been described in considerable detail by him. A four-lane highway pavement showed extensive cracking of the "chicken net" or "alligator" form. Cracking was first observed and became more clear in the outer lane which carried over 80 per cent of the traffic. Measurement of the pavement deflection occurring in the badly cracked and uncracked section of this lane clearly showed that cracking is associated with the section exhibiting the higher pavement deflection, which was due to loss of stiffness. It also indicated that cracking is the result of the repetition of loads. The deflection occurring in the lightly travelled passing lane is approximately equal to that of the heavily travelled one. The absence of cracking in the passing lane can only be attributed to the smaller number of load repetitions.

Much of the current concern for collecting fundamental laboratory data on the fatigue behavior of bituminous materials can probably be traced to work of Nijboer and Van der Poel (3) presented in 1953. These investigators realized at an early date that cracking of bituminous pavements in service could result from the inability of the surface material to withstand repeated flexure. They suggested that the fatigue process might be a significant cause of cracking in bituminous pavements. Thus they concluded (3, p. 197, 198):

> The authors now put forward the hypothesis that the flexural stresses set up by moving traffic ultimately exceeds the flexural strength of the materials, leading to crack formation. It should be pointed out that the flexural strength after repeated bending is considered, and that fatigue phenomena play a role in the process.

A report was published in 1955 on WASHO Road Test (21). One of the conclusions from this report was that cracking and initial failure of the pavement was primarily caused by repeated bending and flexing and was not the result of base failure. Profile measurements emphasized the fact that permanent deformation or shear distortion of the subgrade was not responsible for the initial cracking of the surface.

Extensive work has been reported by Monismith et al. (8, 9, 22) on asphaltic mixture behavior in repeated flexure. In the tests reported in 1958, a constant load or stress amplitude was applied to beam specimens 2 in. X 3 in. X 12 in. supported on a flexible diaphragm mounted on springs to represent the base-subgrade combination [Thomas's base (20)] in an actual road structure. Fatigue was measured by the effect of load repetitions on the static modulus of rupture which was determined by loading a beam at the mid point of a 10 inch span at a rate of 0.25 in./minute until failure occurred, the maximum load being used to calculate the modulus of rupture. In this study beam specimens were compacted by a Triaxial Institute Kneading Compactor. All specimens were made with the same penetration asphalt. A crushed granite aggregate having 3/8 in. maximum size but using two different gradings, dense and open, and various asphalt contents were used. It was concluded from the report that:

(a) The modulus of rupture increased with increase in asphalt content

(b) The dense graded mixes showed better fatigue results than that showed by open-graded mixes.

(c) The decrease in temperature resulted in increase of the modulus of rupture which was accompanied by increased rigidity under dynamic loading.

In another paper reported in 1961, Monismith et al. used the same constant load fatigue machine for further tests on beam specimens made with the same dense aggregate grading but with two different asphalts. The asphalt content was 6% in both cases and three different frequencies of loading 30, 15 and 3 applications per minute, with load application time of one second, were used. The results of these fatigue tests showed that frequency of load applications had no effect on either mixture and there was no real difference between the fatigue behavior of either mix. Monismith et al. also described tests carried out on the same beam type specimens in a constant deformation fatigue machine in which the ends of the beams are clamped and a deformation is applied to the centre of the beam. The machine was arranged to produce stress reversal in the beam, and strain guages were bonded to some of the beams to measure the bending strain. The tests showed that the stress reversal itself has little effect as long as the maximum strains are the same in both directions of bending.

Epps and Monismith (23) reported the results of controlled-stress flexural fatigue tests on asphaltic concrete mixtures. They presented data to illustrate the influence of mixture stiffness, air voids, aggregate gradation, aggregate type, and asphalt content on fatigue life. They reported that:

(a) Increase in air voids resulted in decrease of both fatigue life and dynamic stiffness modulus.

(b) For the mixes investigated, the relationships between fatigue life and air voids are not identical at the same stress level. They explained that "the structure of the voids as well as the obsolute volume of the void content of mixes has an important influence on fatigue life."

(c) Aggregate grading has little effect on fatigue life, and the aggregate type has only a negligible effect on fatigue response for the same asphalt content.

(d) There exists an optimum asphalt content for the best fatigue results.

In 1966, Monismith (10) proposed a design procedure to incorporate the fatigue factor in asphalt-concrete pavement based on laboratory-determined resilient or elastic characteristics of the materials comprising the structural pavement section, the use of elastic theory to estimate the stresses and strains occurring in the various paving elements, and a knowledge of the fatigue response of asphalt-concrete paving materials. He summarized the results obtained in previous works to indicate that pavement deflection can be reasonably predicted within the framework of existing theory. He noted that (10, p. 20):

> Since deflection can be predicted, it would appear logical to assume that stresses and strains within the asphalt-bound layers (at least) can reasonably be estimated...thus if these stresses or strains can be estimated in advance of pavement construction, they could be adjusted through design to a level insuring adequate performance in the field, at least from a cracking standpoint.

He reported that fatigue data for a particular mixture can be established either in terms of stress or of strain, and he termed it appropriate to select the controlled-stress test mode to develop fatigue data for pavements in which thick asphalt-concrete sections are to be used. His design procedure included the estimation of stresses on the underside of the asphalt layer associated with the various wheel loads, from elastic theory, and an estimate of the cycles to failure determined from laboratory-measured fatigue data corresponding to a particular computed stress. Finally, Deacon (16) predicted the fracture life from the combination of stresses.

In 1959, Papazian and Baker (11) carried out essentially constant deformation type tests on beam specimens. The beams were simply supported at the ends with a spring support at the middle. The load was applied in the centre by a cam arrangement through a loading spring at 105 load applications per minute. The resulting stress cycle was non-reversing. A plot of deflection against number of load repetitions indicated that although the deflection is initially constant, cracking and consequential increase in deflection takes place long before the arbitrary point of failure, and once this occurs the test is no longer at constant deformation. It was concluded that stress should be the criterion of fatigue and not deflection.

Pell, with his associates (4, 5, 6) have published some of the most significant data taken from laboratory investigations of the fatigue behavior of bituminous materials. In 1960, a report by Saal and Pell (4) gave results of flexural fatigue tests obtained from the single point loaded rotating cantilever machine. Sandsheet specimens made from a large number of different types of asphalt were used. In each case, a linear relationship (log-log) between stress and number of load repetitions to failure was found. Similar results were also obtained from beam type specimens. Also in that paper and in further publications by Pell, McCarthy, and Gardner (6), and Pell (5), details are given of an extensive fundamental investigation into the fatigue properties of asphaltic mixes. Most of the tests on mixes were carried out on sandsheet specimens having a minimum diameter at the neck, and increasing continuously to either end. The specimens were tested in a temperature-controlled aqueous alcohol solution, in a rotating cantilever machine, but the load was applied in the form of a constant amplitude bending moment resulting in maximum stress at the neck of the specimen situated as far as possible from probable stress concentrations at the ends. Results indicated that the material exhibits fatigue properties over wide ranges of stress and that for a particular temperature and speed of loading the log-log relationship between stress and number of load repetitions to failure is linear between 10^4 and 10^8 cycles. It was also noted that the life under constant stress amplitude is highly dependent on the temperature, a low temperature giving a longer life at a particular stress; it is also dependent to some extent on the speed of loading. Results obtained from the work on the single point loaded cantilever system with various types and grades of asphalt showed that the fatigue life appears to be little dependent upon the types of asphalt except in so far as it affects the stiffness of the mix. The effect of void content on the fatigue life was also investigated. It was found that the overall void content was important at low temperatures. The usual void content of specimens was 1½% to 3½% but with increasing void the life reduced.

Pell and Taylor (7) undertook a study, in 1969, in this field at the University of Notingham and confirmed some of the previous findings; additionally they concluded that:

(a) An optimum asphalt content exists for best fatigue life.

(b) Fatigue life decreases with an increase in air void content.

In 1962 Jimenez (12) reported the details of the apparatus, deflectometer, developed by him, and this report was later extended (13, 14). The deflectometer was intended to be used to produce fundamental fatigue data for the asphaltic mixtures, though it can be used for mixture evaluation purposes as well. It makes possible laboratory investigation of the flexure-fatigue properties of pavement mixtures. The deflectometer also makes possible the determination of relative deflections of various pavement materials under controlled conditions of loading and support. Instead of using simple beam type specimens, he intended to simulate actual road conditions. Slab type specimens were employed for this purpose. The specimen was clamped at the edges, and supported underneath with a uniform pressure. An oil-air system was used to give various supporting pressures. A vibratory-kneading compactor was developed along with this test procedure to compact specimens. Further report of these will be given in later chapters. In this test procedure, failure was defined as the number of applications to cause deviation from a straight line on the log deflection-log number of load repetitions plot. The results obtained showed an increasing number of repetitions to failure for thicker specimens. Similarly, it was found that greater support pressure produced longer life. A linear relationship was found on the log-log scale between the stress, S, and number of load repetitions to failure, N_f. The slope of the S-N_f plots was found to be independent of mixture composition for the 10 mixtures tested. A significant result was that the crack patterns developed on the tension side of the slabs were similar to the surface "alligator" cracking observed in actual pavements. An optimum asphalt content was found to exist corresponding to the maximum fatigue life on a plot of the log of fatigue life versus asphalt content. This asphalt content was different from the optimum asphalt content corresponding to maximum stability. The coarse-textured aggregate produced in general a greater fatigue life than the smooth-textured aggregate. However, the effect was dependent upon asphalt content so that at low asphalt contents, the smooth-textured aggregate appeared superior. The fatigue life was found to be larger for the more viscous binders. The dynamic modulus of elasticity was found to increase with increase in specimen density and binder viscosity. From these studies Jimenez suggested that fatigue life of asphaltic concrete could be increased by increasing the density by compaction (within limits), increasing the asphalt content to an optimum value, increasing viscosity of asphalt (within limits), or by increasing the dynamic modulus of elasticity with the use of mixture additions.

In 1969, Layman and Phillipi (24) studied and extended the work reported by Jimenez and confirmed his findings. In addition they reported that:

(a) The radial stresses within the deflectometer specimens vary approximately in phase with the applied stress.

(b) There is a very slight decrease in the dynamic modulus of elasticity during the stress life of a deflectometer specimen.

(c) For a given test temperature as the radial stress, to which a specimen is subjected, increases, the endurance to repeated flexure decreases.

(d) The radial strain at failure for specimens of a given thickness increased as the test temperature increased because the dynamic modulus of elasticity at failure decreased as the test temperature increased.

(e) For a given specimen thickness the total deflection at failure increases as the test temperature increases.

The last work to be reviewed here was reported in 1972 by Kimambo (25), who extended the work reported previously by Jimenez, and Layman and Phillipi. He used the deflectometer to study the stiffness effects on fatigue life of asphaltic concrete. Variables used by him were asphalt content, temperature and support pressure. He concluded that fatigue life increased as the temperature decreased. Also the influence of temperature on stiffness is non-linear, and varies with asphalt content and initial support pressure; the dynamic stiffness increases with a reduction in air voids.

In the preceding review, a number of experimental observations concerning the fatigue behavior of bituminous materials have been presented. Of particular interest to this writer are some of the observations presented in this section with regard to summarizing the present state of knowledge. This discussion is limited to those data obtained from simple-loading tests of a repeated-flexure nature and emphasizes the relative effects of some of the important variables based on previously reviewed investigators.

1. According to Jimenez and Monismith, a more viscous binder results in a larger (for constant stress) life. The use of more viscous binder tends also to increase the stiffness moduli of the compacted specimens.

2. According to Pell, Epps and Monismith, the fatigue life is increased when the air void content is decreased.

3. According to Monismith, a more dense-graded aggregate results in an increased service life. A more

dense-graded aggregate likewise results in specimens exhibiting larger stiffness modulus.

4. According to Jimenez, a maximum service life exists at some optimum asphalt content. Monismith has found that within certain range, service life increases with increased asphalt contents.

It should be noted that the results found by each individual investigator are meant to be applicable only to the particular test equipment used and the set of test variables employed by the investigator. On the other hand, the desirability of using all available knowledge as a foundation from which to plan new test programs can hardly be questioned. From the literature review, it appeared that the deflectometer offered a promising means of investigating the flexural properties of asphaltic mixtures, because of its ability to best simulate the field conditions. The deflectometer has, therefore, been selected for this study.

CHAPTER 3

MIXTURE DESIGN

In this chapter mix design method of asphaltic concrete will be described. As has been mentioned previously, three different gradings were used in the laboratory study to assess the effect of gradation on the fatigue life of asphaltic concrete.

Aggregate

A 5/8-inch maximum size crushed aggregate was supplied by Sundt Construction Company of Tucson, Arizona. A 3/8-inch maximum size crushed aggregate was obtained from the hot bins at the hot mix plant of New Pueblo Construction Company of Tucson. It was taken from Pit Number 75-500 on the Tucson-Nogales Highway (U. S. Interstate 19). Green Valley sand was used as "fine" aggregate. The last aggregate used was a local "concrete" sand.

The aggregates, as obtained from different sources, were first air dried before being separated into the appropriate size fractions. They were then blended together in the required quantities to yield the desired aggregate gradations.

The coarse gradation was obtained by combining 5/8-inch and 3/8-inch crushed aggregates, and Green Valley sand to meet the design specification IVb of the Asphalt Institute (26). The medium gradation was obtained by blending 3/8-inch crushed aggregate and Green Valley sand. The fine gradation was obtained by washed sieve analysis of concrete sand which was passed through number 4 sieve. A comparison of gradation is shown in Table 1 and Figure 2. Appendix A contains the aggregate blending data.

Specific gravity measurements were made on the aggregates so that theoretical maximum voids could be determined in the mixes. Specific gravity values are shown in Table 2 for the various aggregates used for the laboratory study. Sand equivalent values were also determined.

Surface area determination for the three different aggregate gradings were made in order that the amount of asphalt, based on film thickness according to the Hveem Method of Mix Design (27), could be estimated for each mix. Therefore it was necessary to perform oil equivalent tests on the +#4 aggregates and centrifuge kerosene (C.K.E.) tests on each of the three -#4 fractions of the aggregate gradings.

The surface area of the gradings, based on the surface area constants suggested by Hveem in (27), together with K_c, K_f and K_m factors, which represent the total effect of superficial area, the aggregate's absorptive properties and surface roughness for the coarse fraction, fine fraction

Table 1

Particle Size Distribution of Combined Aggregates

Sieve Number	Percent Passing		
	Coarse Gradation	Medium Gradation	Fine Gradation
3/4"	100	--	--
3/8"	85	100	--
#4	57	64	100
8	47	51	91
16	39	42	67
30	29	31	43
50	18	18.8	19
100	10	10.5	8
200	7	7.3	6

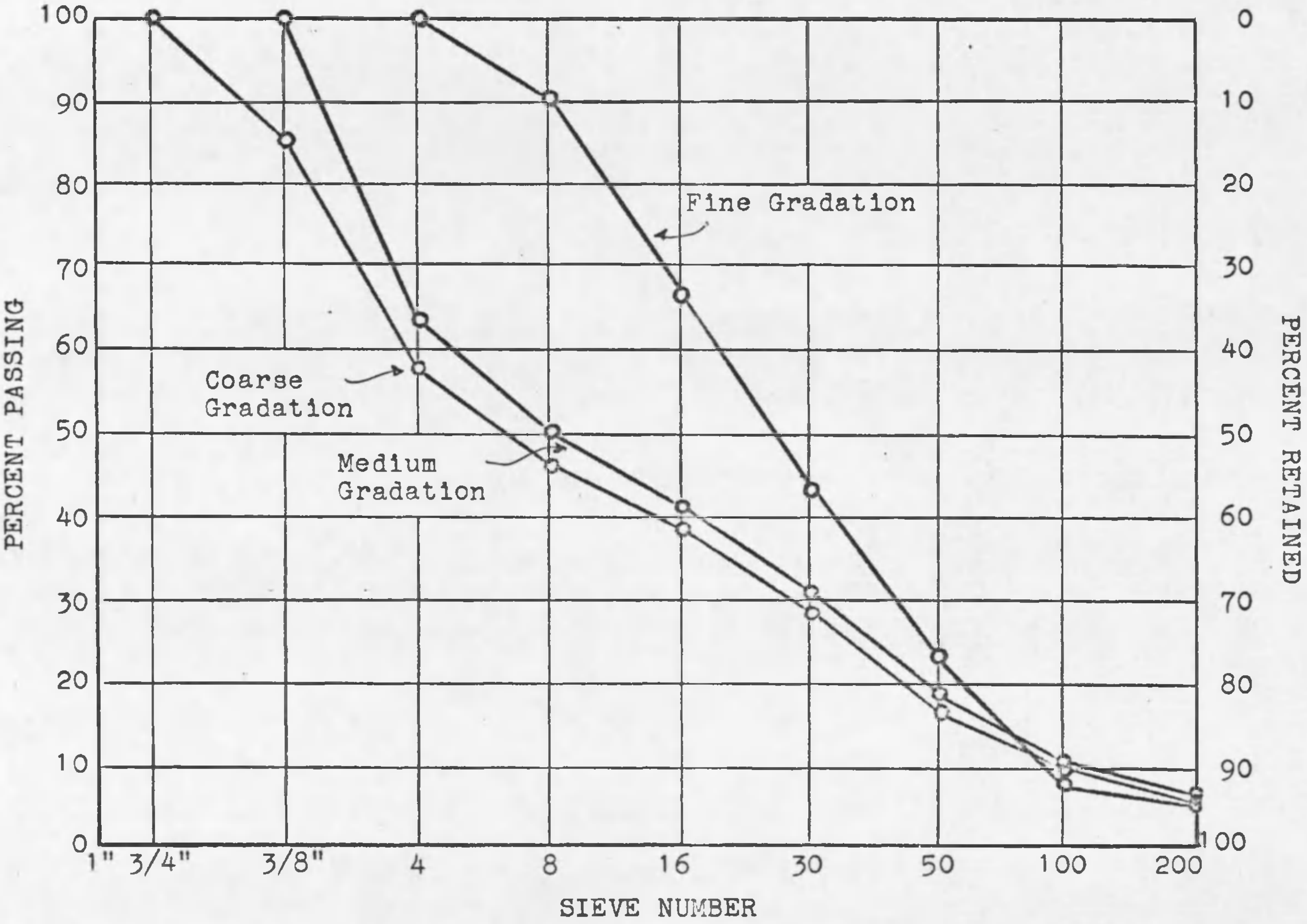


Figure 2. Aggregate Gradation Curves

Table 2

Aggregate Properties

	Coarse Gradation	Medium Gradation	Fine Gradation
Specific Gravity			
◦+#4, Gm/c.c.	2.64	2.56	--
◦-#4, Gm/c.c.	2.58	2.64	2.61
◦Combined, Gm/c.c.	2.61	2.59	2.61
Sand Equivalent, %	44	44	
Surface Area, Sq. ft/lb.	34.5	31.3	37.2
Oil Ratio, % of Dry Aggregate	4.3	4.1	4.2
C.K.E.			
◦Kerosene Equivalent %	3.12	2.60	1.97
◦Oil Equivalent, %	2.75	2.90	--
K_c	1.20	1.28	0.86
K_f	0.99	0.96	1.02
K_m	1.06	1.05	1.02
Asphalt Content % of Total Weight	5.2	5.3	5.7

and combined fraction of aggregate respectively are shown in Table 2.

Asphaltic Mixture

In order to characterize the mix, 4 inch diameter specimens were compacted with a vibratory kneading compactor (14). Since deflectometer specimens were also compacted by this compactor, the compaction procedure will be described in detail in Chapter 4. The specimens were made in triplicate for each asphalt content. Three asphalt contents were used for coarse and medium gradings while the specimens for fine grading were compacted using five asphalt contents, an optimum being estimated in each case by the CKE method (27).

The mixture variables investigated as mentioned earlier are asphalt content, aggregate grading and mixture density. By using the relative amounts and specific gravities of the fine and coarse aggregates (Table 2), the amount and specific gravity of the asphalt and density of the compacted mix, the theoretical volume of air voids can be calculated. The density of the mix was calculated for each specimen using the resulting weights of the specimens determined from weighing the specimens in air and in water.

Hveem stability and cohesiometer values were determined in the manner described in Reference (27). The design characteristics of each mix are presented in Table 3.

Table 3

Design Characteristics of Coarse, Medium and Fine Mixtures with 60 - 70 Penetration Asphalt Molded by Vibratory Kneading Compaction Method.

Asphalt Content %	Specimen Density %	Theoretical Sp. Gr. Gm/c.c.	Total Void Content %	Hveem Stability %	Cohesiometer Value Gm/in.	Film Thickness Micron
			Coarse Gradation			
5.0	2.26	2.42	6.5	54	295	6.9
5.5	2.29	2.40	5.0	59	220	7.6
6.0	2.32	2.39	3.0	57	306	8.3
			Medium Gradation			
5.0	2.24	2.40	6.6	56	201	7.7
5.5	2.27	2.39	4.9	55	176	8.4
6.0	2.26	2.37	4.6	56	320	9.2
			Fine Gradation			
5.0	2.08	2.42	14.3	41	132	--
5.5	2.12	2.41	13.3	39	108	--
6.0	2.09	2.39	12.4	39	168	7.7
6.5	2.14	2.37	9.8	41	--	8.4
7.0	2.16	2.36	8.4	39	--	9.0

CHAPTER 4

SPECIMEN COMPACTION PROCEDURE

Flexural-fatigue specimens were compacted to have a uniform thickness of 2 inch, and the diameter was fixed at 17½ inches. Duplicate specimens were made for each testing condition.

Material Preparation

Asphalt contents used for these specimens were the same as those used for Hveem specimens for each gradation except that for fine gradation--6.0%, 6.5% and 7.0% asphalt were used to obtain required air void contents.

The aggregate was combined in proper proportion and weighed out for each specimen to be compacted. The batched aggregate was thoroughly hand mixed, and placed overnight in an oven maintained at 300°F. The asphalt cement, which was stored in 1200 gm. containers, was placed in another oven for approximately 3 hours at 285° prior to mixing.

Mixing

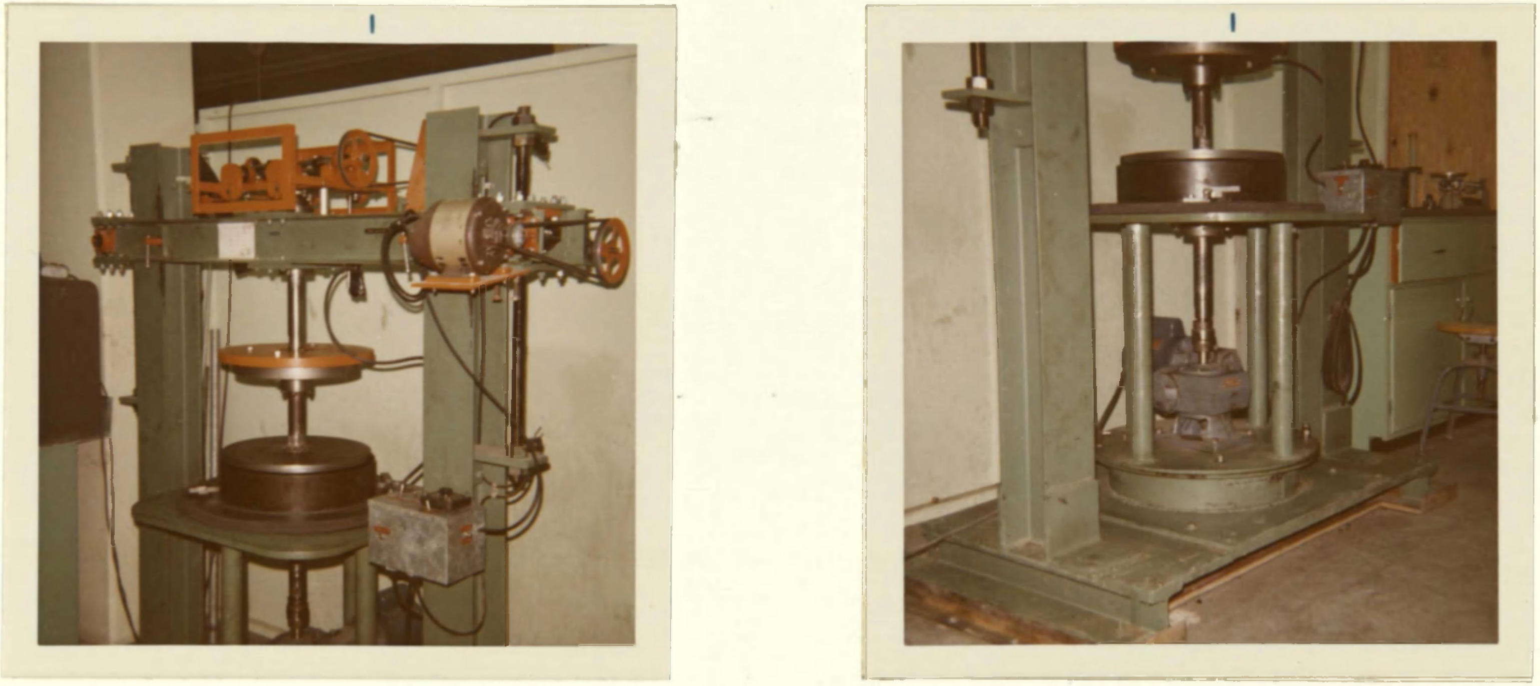
Aggregate for each specimen was mixed in three parts due to the limited capacity of the Hobart Mixer, (C-10), which was used in the laboratory. It can mix up to 7000 gm. of aggregate.

A calculated quantity of asphalt was weighed into each batch of aggregate and both ingredients were transferred immediately to the mechanical mixer. The mixer bowl was already heated so that the temperature of the mix could be maintained at approximately 285°F. throughout the mixing operation. Mixing proceeded for that period necessary to assume adequate coating of the aggregate but such that aggregate degradation would be minimized. Normally this required approximately three minutes.

Upon completion of the mixing operation, mixture for each specimen was transferred to pans and placed in a 300°F. oven for about 30 minutes prior to compaction.

Vibratory Kneading Compaction

The mix was compacted using a vibratory kneading compactor into circular specimens. For a detailed discussion on the development of this device the reader is referred to Reference 12. The photograph of Figure 3 illustrates the compactor. This device provided the kneading compaction to the loose mix when it was initially placed into the mold. The turntable of the kneading compactor was tilted to impose horizontal forces on the asphalt-aggregate mixture. These forces were required to obtain desirable particle orientation and density in the 17½ inch specimen. The compaction procedure followed is set forth below:



(a) Loading System

(b) Turntable

Figure 3. Vibratory Kneading Compactor

(a) A dead load of 283 lb. was used.

(b) A load of 400 lbs. caused the dynamic force due to rotation of eccentric masses at a frequency of 1200 revolution per minute.

(c) Prior to molding, the mold, the 17½ inch diameter and 1/4 inch thick steel bottom plate, and the 6 inch diameter tamper were heated.

(d) A transfer board was set on turntable and the mold was set on it. The steel bottom plate was inserted in the mold. A 1/4 inch plywood, and a paper disc each 17½ inches in diameter were placed on the steel bottom plate. Kerosene was applied on the paper disc to avoid sticking.

(e) The hot and loose asphaltic mixture was placed into the mold. The edge of a metal trowel was used with a chopping action to spread and knead the mixture into a uniform thickness, and the 6 inch diameter tamper was used over the surface.

(f) A paper disc was placed on the top surface, and the mold assembly was placed on the turntable of the kneading compactor. The compaction head, ballast, and loading system were lowered, and the mold was centered on and secured to the turntable. The turntable was tilted to one degree. The positioning cross bar was lowered away from the loading system to insure that no load was applied to the cross bar during compression of the mixture. The cross bar was locked to the vertical posts.

(g) The timer was set for two minutes and the loading motor was started. During this period, the turntable was rotated.

(h) At the end of the two minute period, the cross bar was released, and the loading head was raised and secured. The mold was slid onto transfer board. The above operations were repeated until the necessary number of layers were obtained. Interfaces were scarified prior to compaction.

(i) When the last layer was compacted, the one degree tilt was removed from the turntable. The loading motor was started and levelling compaction was continued for 30 seconds.

(j) The loading system was raised and then the mold was removed from the kneading compactor and rested on the extruder so that the mold could be pushed down free of the specimens and discs.

(k) The specimen and 1/4 inch plywood was slid off the steel plate. The upper paper disc was removed and the specimen was marked on the upper face for identification and allowed to cool to room temperature before transferring to storage.

Compaction Effort

Three compaction efforts were used so that variable densities could be obtained in order to study the effect of voids on the fatigue life of asphaltic concrete.

For high compaction effort, the specimens were compacted for two minutes. The specimens for regular compaction effort were compacted in two layers while compaction time was set to two minutes for each layer. Low compactive effort was achieved by compacting the samples in two layers with compaction time reduced to one minute for each layer.

Height and density for all specimens were measured and recorded. These specimens were cured in 77°F. testing room for a minimum period of three days before testing.

Same compaction procedure was used to prepare Hveem specimens of 4 inch diameter and $2\frac{1}{2}$ inch thickness. These specimens were compacted in one layer only.

CHAPTER 5

DEFLECTOMETER TESTING PROCEDURE

Deflectometer

The deflectometer developed by Jimenez (12) is a relatively new device for testing asphaltic concrete mixtures. In 1968 Layman (28) worked with the deflectometer for his doctoral thesis and noted that (28, p. 15, 16):

> As a result of this evaluation, it is thought that the deflectometer device provides a repetitive flexural-fatigue test which is sensitive, accurate and reproducible ...The test also offers a means of measuring the relative fatigue life of both flexible and semi-rigid systems under the test conditions selected.

The deflectometer, as shown in Figure 4, consists primarily of a loading system and a reaction unit. In this apparatus, a circular specimen with 17½ inches diameter is used. The specimen is bolted to a rigid peripheral support so that its effective diameter is 14 inches. This is done by means of a steel ring and 16 bolts. The steel ring has an internal diameter of 14 inches. In addition to this rigid support, a uniform pressure is applied to the lower surface of the specimen during repeated loading by means of a reaction unit. It consists of a cylinderical chamber containing oil and air, and covered at the top with a rubber membrane. The amount of oil and air is controlled to give a standard support pressure to the specimen. The support pressure is normally set at one pound per square inch initially and gradually increases as the specimen deflection accumulates during a test. The support pressure is recorded on a bourdon pressure gauge mounted on the side of oil chamber. The loading system provides a constant load over which is superimposed a sinusoidally varying load of smaller magnitude. This is produced by the counter rotation of eccentric and mirror-positioned masses. These loads are used to damage the specimens through a circular loading foot with 5.0 square inch area. (A loading foot of 3.14 (π) square inch can be used for higher stresses.) The loading foot is placed at the center of the upper surface of the specimen. Deflection measurements are made by means of gauges mounted on a rigid steel bar which is secured onto the oil chamber.

In this study all deflectometer specimens were tested at a constant temperature of 77°F., with initial support pressure of one pound per square inch.

Before testing, the deflectometer was calibrated. The reaction unit was checked for the proper amount of air and oil in accordance with the following procedure:

(a) A one inch thick plywood plate and two 1/4-inch thick steel plates, each having $17\frac{1}{2}$ inch diameter, were used. The plywood plate was sandwiched between the steel plates and secured to the reaction unit. All 16 bolts were tightened and were drawn to the tension controlled by the spacer sleeves and springs.

(b) The valve between the reaction unit and the oil pump was opened. The position of the pump was adjusted so that the pressure gauge recorded 1.0 psi.

(c) The pump piston was displaced 2 inches inwards to cause an increase of pressure in the oil chamber. With the proper amount of air and oil in the system a pressure of 2.5 psi was recorded on the gauge. If the equipment is not in calibration, oil and air are added to or removed from the chamber. The air was added or removed by means of an air valve connected to the oil chamber. This process was repeated until the deflectometer was calibrated.

Testing Procedure

After deflectometer was calibrated for the test temperature of 77°F. the specimens were tested in the following manner:

(a) A $17\frac{1}{2}$ inch diameter paper disc with four radial slits was placed on the rubber membrane. The specimen was then centered and secured into position.

(b) The clamping ring (20 inch external diameter and 14 inch internal diameter) was placed on top of specimen. The bolts were tightened in such a manner as to apply the clamping force as uniformly as possible around the periphery of the specimen. The bolts were tightened sufficiently to bring the spacer sleeves into contact with the shoulder of the oil chamber.

(c) The dial carriage was secured to the reaction unit and the gauges were set to zero (see Figure 5).

(d) A load disc with contact area of 5.0 square inch was used.

(e) The loading system was lowered to the surface of the specimen until a paper inserted between the loading disc and specimen indicated very slight contact.

(f) An initial support pressure of 1.0 psi was applied in the reaction unit. The valve connecting the pump and reaction unit was closed. The counter indicating the number of load applications had been set to zero. (One reading recorded in the counter indicates 20 load applications.)

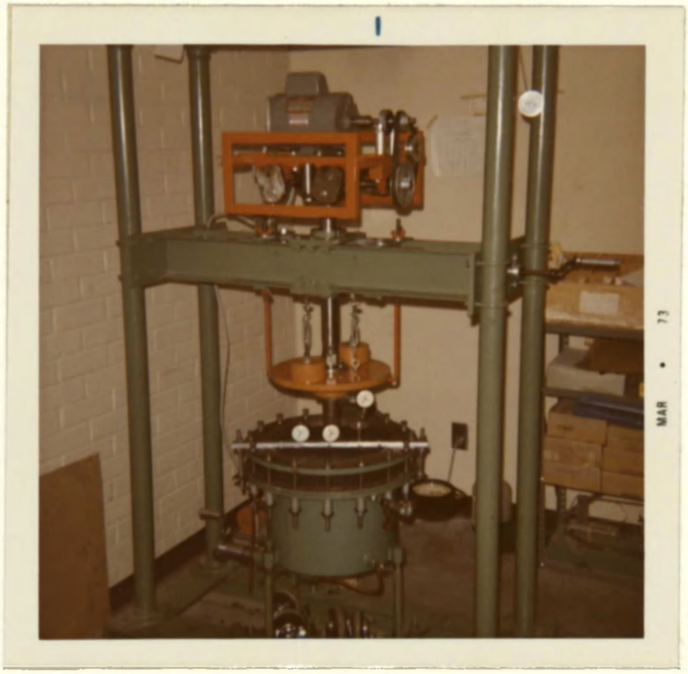


Figure 4. Deflectometer

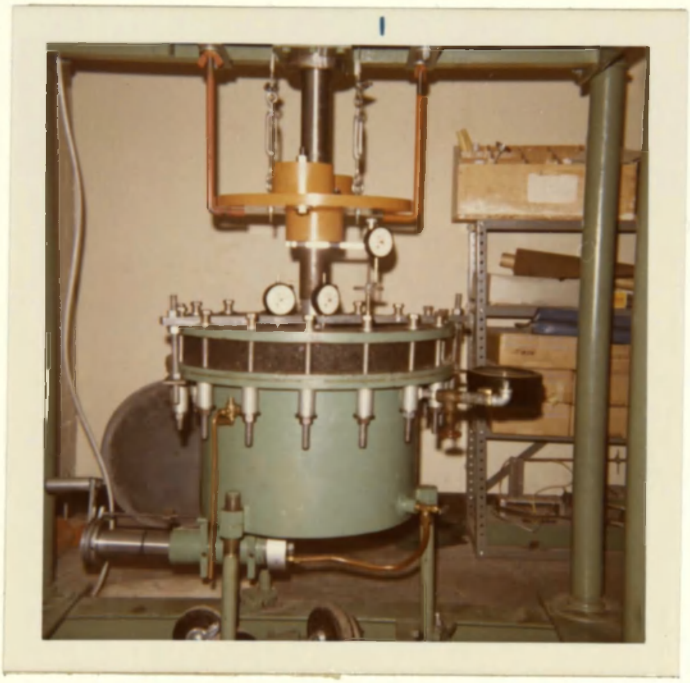


Figure 5. Reaction Unit

(g) The dead load was applied by releasing the elevating cable and the electric motor was started.

(h) Readings of deflections and pressure were taken at various intervals of time. These intervals were based on number of load applications. A running plot was kept of the load disc dial reading versus the number of load applications on log-log scale. A typical data sheet and plot is shown in Appendix B.

(i) The loading of the specimen was continued and the plot of the accumulated deflections against the number of load applications was kept. This plot was linear. According to Jimenez (12), the failure occurs when the plot of loading disc deflection versus number of load repetitions deviates from a straight line. When the readings deviated for at least three consecutive points from the straight line plot, the loading was stopped.

(j) At the end of the test the loading system was elevated from the specimen and secured. The specimen was removed from the reaction unit. It was examined for cracks, and these were marked with chalk. Figure 6 shows a typical crack pattern of a specimen.

Figure 6. Typical Crack Pattern
of a Failed Specimen

(k) The number of load applications causing failure were determined for each specimen from the running plot of load disc deflections against number of load applications. The point of tangency between the straight line and the curve establishes the number of load applications causing failure. To insure the accurate location of the point of tangency, enough data was obtained during the test.

In this study, all the specimens were tested by the standard loads, employed as follows:

1. Dead load of 175 lbs.
2. Load frequency of 740 revolutions per minute.
3. Live load, due to rotation of masses, 150 lb.
4. Load contact area of 5.0 square inches.
5. Initial support pressure of 1.0 psi.

Stress Computation

Radial stresses and dynamic moduli of elasticity were computed for all specimens. This was done by using Grashof's equations. These equations as simplified by Jimenez (12) are set out below:

(1) Expression for radial surface stress, S, at the center of a circular disc fixed about its periphery and supported from below, and loaded centrally on top:

$$S = \frac{3(m+1)W}{2\pi mt^2} (\ln \frac{r}{r_o}) - \frac{3(m+1)r^2}{8mt^2} P$$

where m = the reciprocal of Poisson's ratio assumed

= 0.2

therefore m = s

W = dead load + load of rotation (F_{LL}) + load of translation (F_T)

r = effective specimen radius = 7 inches

r_o = radius of loaded area = 1.596 inches

p = support pressure at failure, psi

t = specimen thickness, inches

now W = dead load + (F_{LL} + F_T)

where dead load = 175 lbs.

F_{LL} = 150 lbs.

The equation for load of translation is given as:

$$F_T = M \frac{d}{2} \omega^2$$

M = mass

d = repeated deflection, feet

ω = angular velocity of the eccentric masses

= 77.5 radians per second

Substituting the values into the expression for F_T,

F_T = 1.362 d (d in thousandths of an inch)

When all the indicated values are substituted into the expression for S, it reduces to:

$$S = \frac{1}{t^2} (319 + 1.337d - 22.05p)$$

or $S = \frac{1}{t^2}$ (286 + 1.337d), at 1.5 psi support pressure

(2) Expression for Modulus of elasticity at the center of a circular disc fixed about its periphery and supported from below, and loaded centrally on top:

$$E_D = \frac{3(m^2-1)}{4dm^2t^3}\left[\frac{W^1r^2}{\pi} - \frac{r^4}{4}P\right]$$

where $W^1 = 2(F_{LL} + F_T)$

The other variables are as defined in equation for radial stress.

When the indicated values are substituted into the above expression for E_D, it reduces to:

$$E_D = \frac{10^3}{dt^3}\ (3369 + 30.6d - 432.2\ P)$$

or $E_D = \frac{10^3}{dt^3}$ (2720.7 + 30.6d), at 1.5 psi support pressure

The above mentioned equations were used for computing the radial stresses and dynamic moduli of the specimens. These are computed at failure and at a mean pressure of 1.5 psi for each specimen. The results obtained will be discussed in Chapter 6 and the data are presented in Appendix C.

CHAPTER 6

TEST RESULTS AND DISCUSSION

It was stated in a previous chapter that the resistance of asphaltic concrete to repetitive flexural stresses is affected by many factors such as those listed by Epps and Monismith (23).

It has been generally agreed that the air void within the compacted asphaltic mixture is an important factor that influences the behavior of bituminous mixtures. For this reason, this investigation was planned to study the effect of air voids on the fatigue response of such materials.

The influence of a mixture variable on the fatigue response of asphaltic concrete is difficult to assess as it is difficult to alter one mixture variable while holding the other variables constant. In this study voids were varied by changing the following factors:

(a) asphalt content
(b) aggregate gradation
(c) compaction effort

Tests were all performed at a constant initial support pressure of 1.0 psi, with a constant load disc area of 5.0 square inches, a temperature of 77°F., and a constant load.

Radial stresses and dynamic moduli were computed at two points during the test life of the specimens. First at an average support pressure of 1.5 psi, and second at failure. Analyses of the test results were made for average support pressure case.

In this chapter the writer will discuss the influence of air voids on the fatigue response of those asphaltic mixtures which were used in this study. Hence air void effects will be investigated initially. The influence of dynamic stiffness, asphalt content and aggregate gradation on the fatigue behavior will then be discussed using the effect of air void content. Appendix C contains individual fatigue test results (Tables 7 to 10).

Effect of Air Voids

The effect of air void content on the fatigue behavior of asphaltic mixtures has been reported by Pell and Taylor (7), Epps and Monismith (23), and others. In general the results indicate that decrease of air voids in a mixture results in increase in fatigue life. However these results point out the importance of proper compaction to produce mixtures with long fatigue lives. It has been found that variation in air void content for different mixtures creates changes in fatigue life with different magnitudes.

Figure 7 shows the effect of air voids on the fatigue life of the medium graded mixture used in this study. In this figure for the same asphalt content, fatigue life increases with the decrease in air void content. The above variation in air voids was achieved by changing the compactive effort. Curves for each of the three compactive efforts indicate that the fatigue life increased when the voids were reduced and then started decreasing after a certain air void content. A peak fatigue life line was found between 9.6% to 10.6% of air voids to establish a fatigue life line based on optimum asphalt content. This shows the interaction between asphalt content and compactive effort. Increasing compactive effort resulted in increased fatigue life at a lower asphalt content, whereas the air voids increased from 9.6% to 10.6%. Hence it is suggested that fatigue life of asphaltic mixtures could be effectively increased by increased compactive effort.

The air voids produced by three gradations varied. However the trend followed by these (Figure 8) was the same, that is, fatigue life increased with decreasing air voids then started decreasing at some point. For both coarse and medium graded mixtures a peak fatigue life was found, but it was not well defined for fine graded mixture.

The results of the effect of air void content on the fatigue life reported by other investigators (27, 7) showed the dependency of fatigue life on air void content

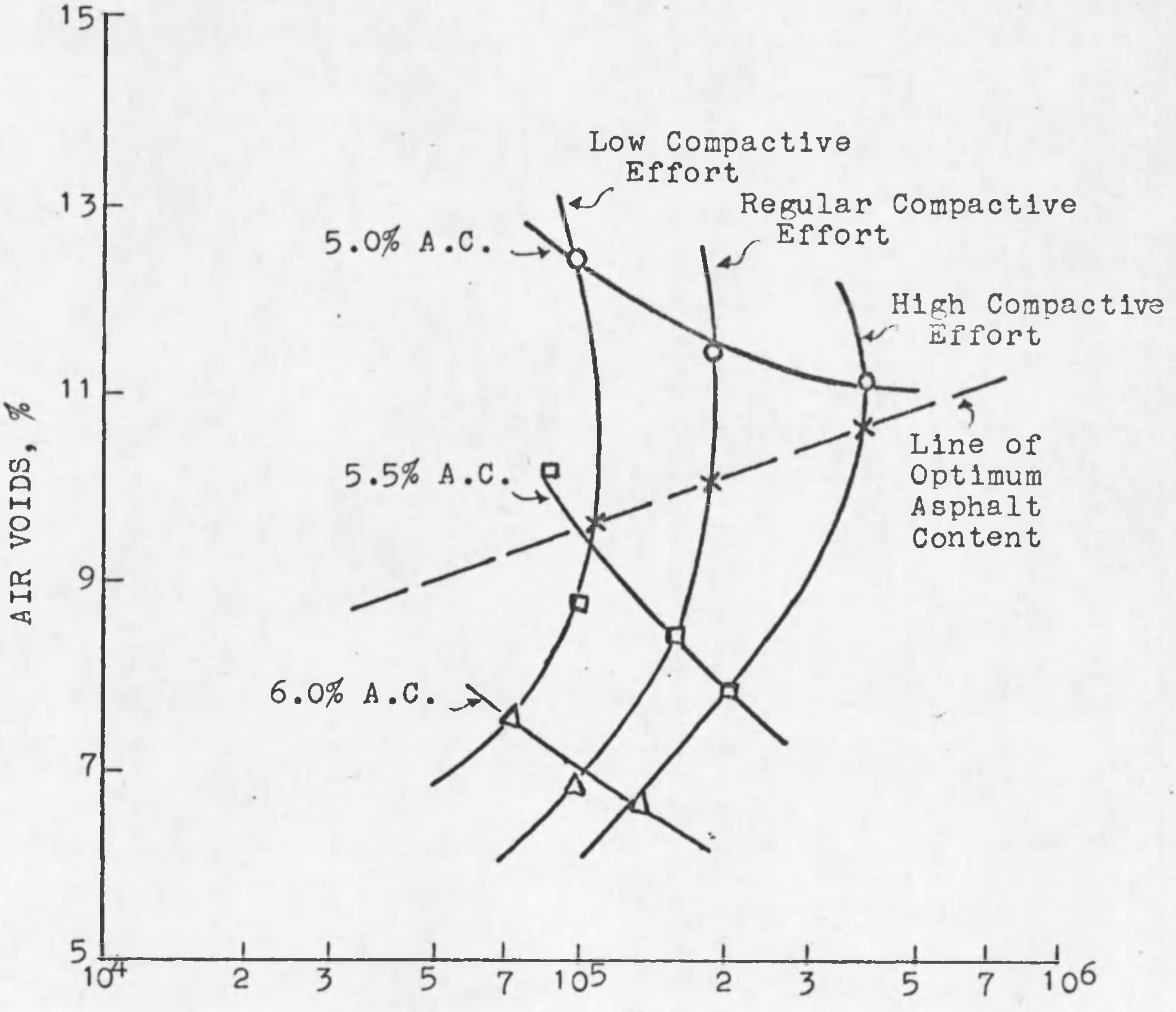


Figure 7. Effect of Air Voids on the Fatigue Life of Medium Gradation Mixture

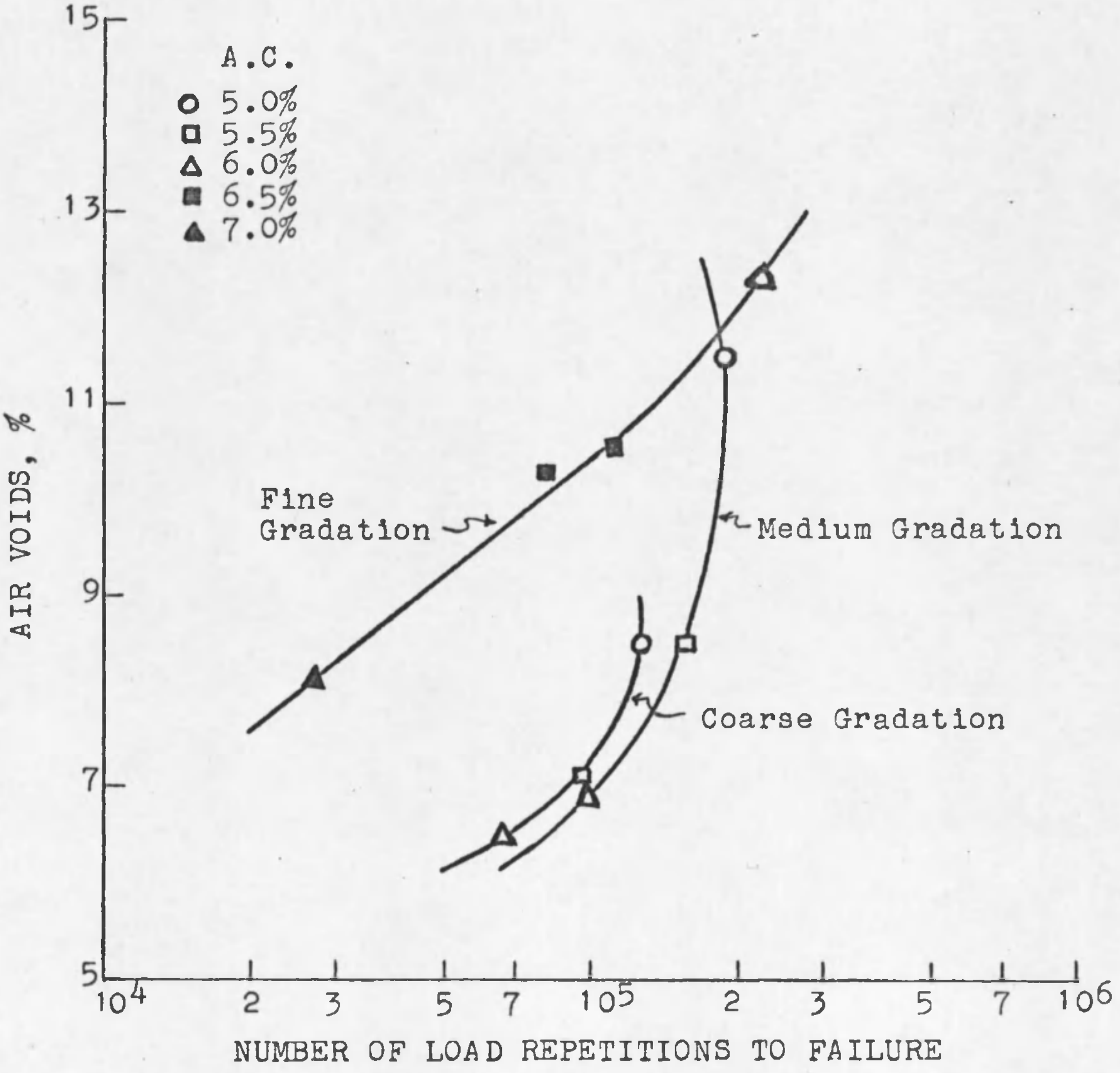


Figure 8. Effect of Air Voids on the Fatigue Life of Coarse, Medium, and Fine Mixtures

for their mixtures. Nevertheless, air void content-fatigue life relationships are not the same for all mixtures at the same stress level. It was suggested by Epps (29) that the structure of the voids in addition to absolute volume of the voids is important. It was explained that (29, p. 84):

> ...for mixes with the same absolute volume of voids, the size of the void is important in that the presence of a very large void will produce a greater reduction in the load carrying solid cross section of the specimen than several smaller voids which are more likely to be scattered throughout the specimen.

It should be pointed out that specimens could not be visually examined for shape and size of voids.

The effect of voids in connection with dynamic stiffness modulus will be discussed in the next section.

Effect of Stiffness

Mixture stiffness or dynamic modulus of stiffness depends both on rate of loading and temperature. In addition to this, mixture stiffness is also dependent upon air void content. Deacon (16) presented data suggesting that mixture stiffness is reduced with decrease in mixture density. Pell and Taylor (7) also agreed that stiffness modulus decreases with increased void content.

For this study effect of voids on stiffness is shown in Figure 9. The curves in this figure were plotted for medium gradation mixture. They indicate the compactive effort (low, regular and high), and three asphalt contents

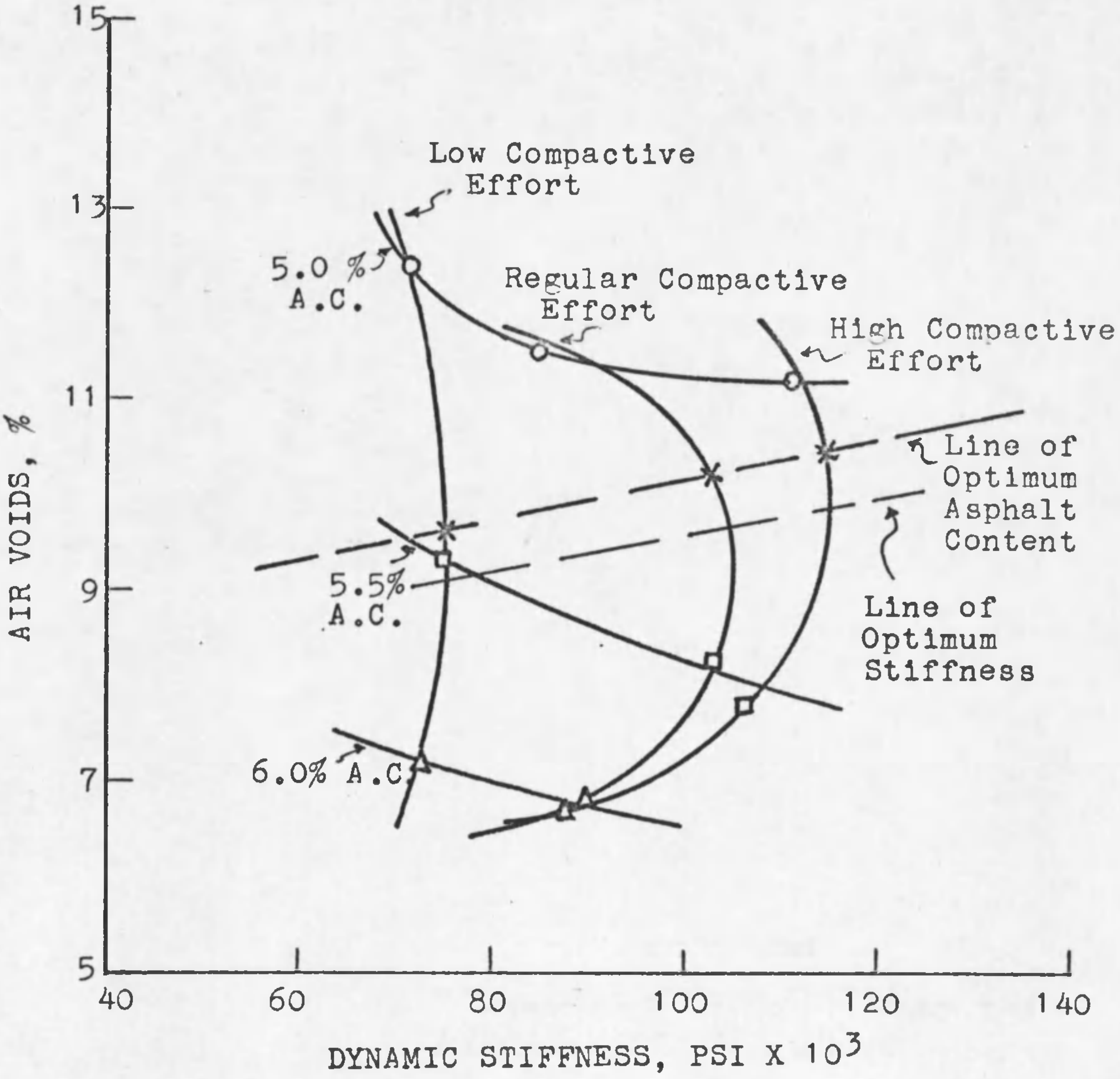


Figure 9. Effect of Air Voids on Stiffness of Medium Gradation Mixture

for each effort employed. The results agree with the previous works, that is the stiffness increases with the decrease in air voids (for the same asphalt content). However the curves for each compactive effort indicate that the dynamic stiffness first increased and then decreased at some air void content when the air voids were reduced. Again the maximum stiffness was found to vary between 9.0% to 10.0% of air void content. This indicates that maximum fatigue and optimum stiffness lines are parallel on air void-fatigue life-stiffness relationships.

Stiffness of asphaltic concrete is also dependent upon aggregate gradation, and asphalt amount (23).

Effect of asphalt content on stiffness will be discussed in another section. Figure 10 shows the effect of void content on the dynamic stiffness of coarse, medium and fine asphaltic mixtures. As before a peak stiffness value corresponds to certain air void content as in the case of air void content-fatigue life relationships. The air void content for both these conditions is not the same but very close.

Figure 11 indicates the effect of stiffness on fatigue life for the coarse, medium and fine graded mixtures. It indicates the peak stiffness value for each of the three mixtures.

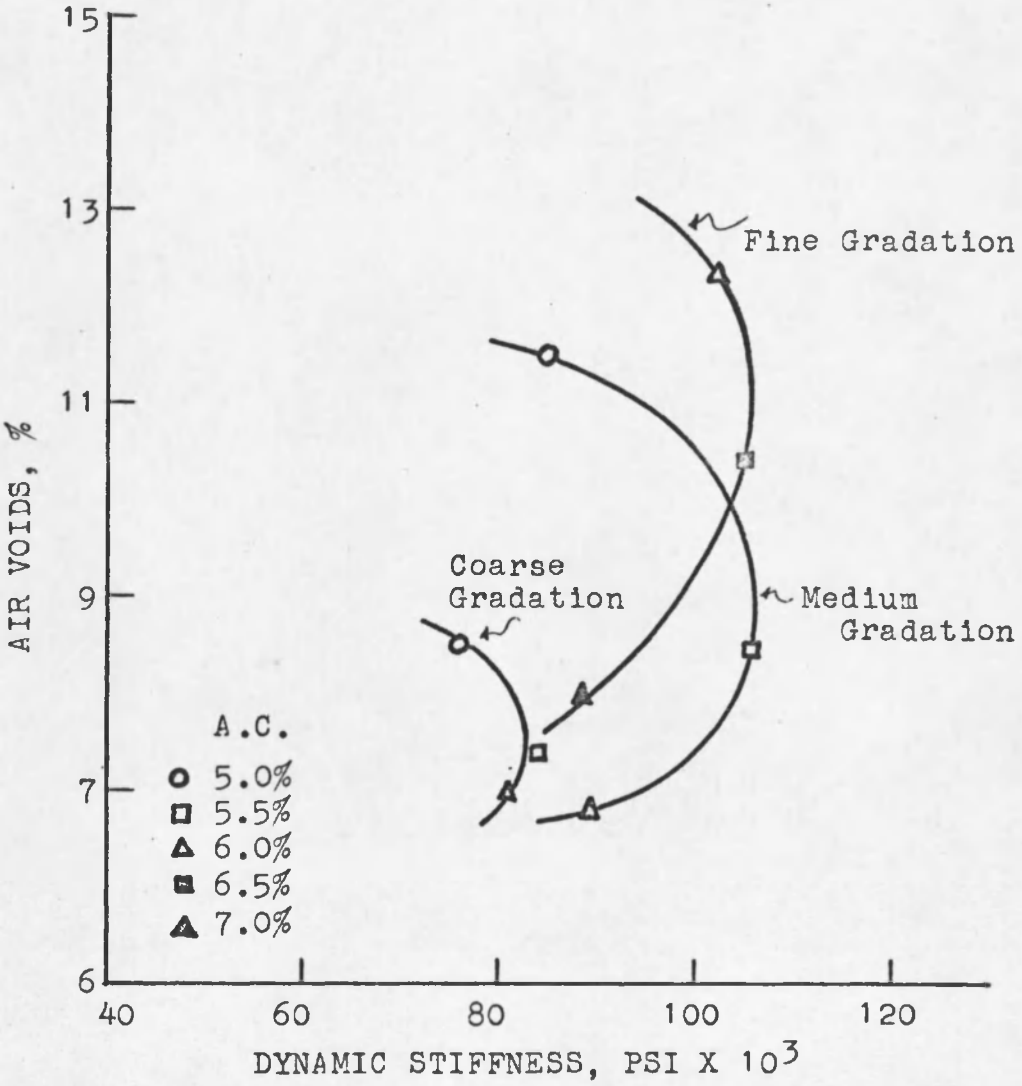


Figure 10. Effect of Air Voids on Stiffness of Coarse, Medium and Fine Mixtures

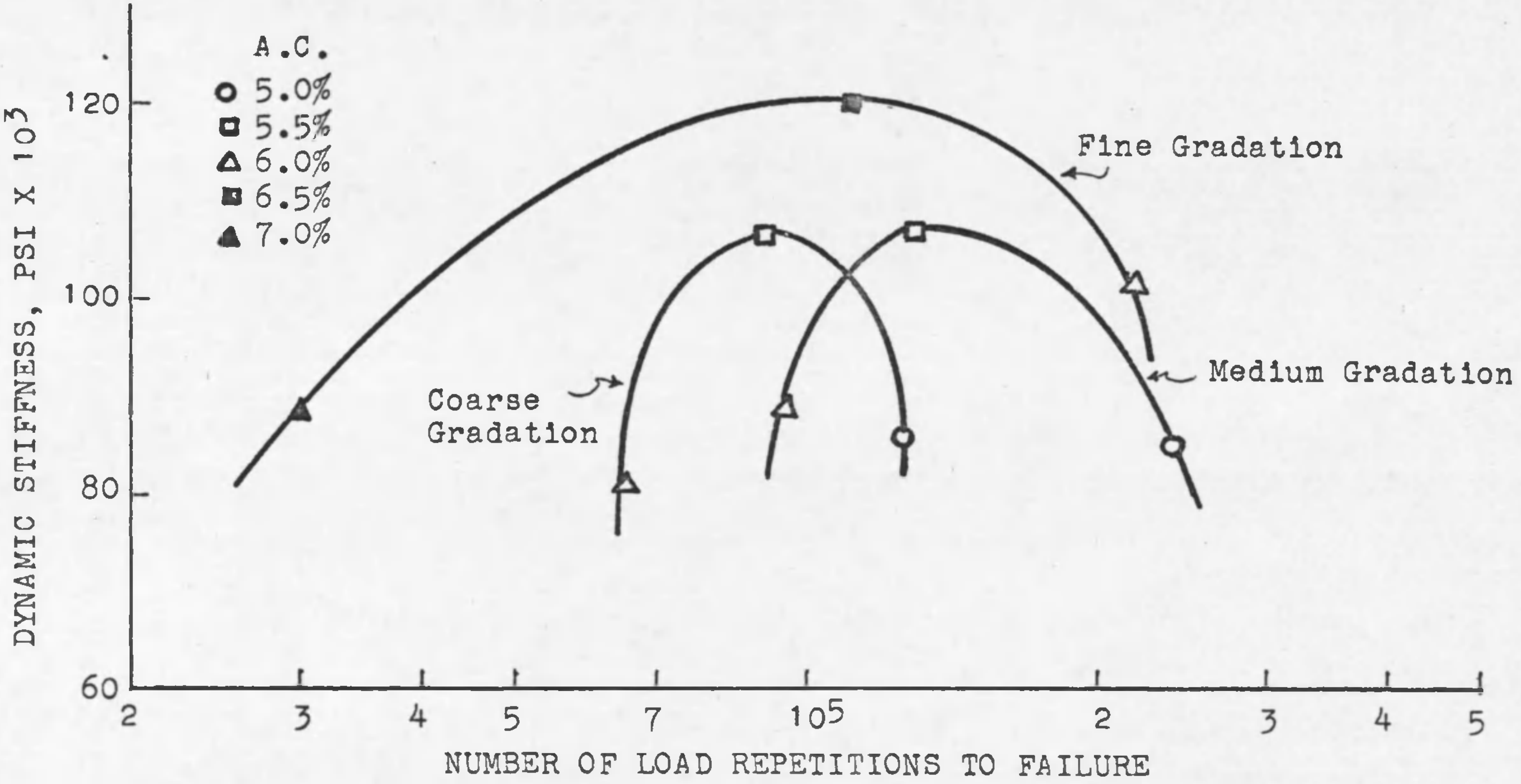


Figure 11. Effect of Stiffness on the Fatigue Life of Coarse, Medium, and Fine Mixtures

Effect of Asphalt Content

Asphalt content effects on fatigue life were investigated by Jimenez (12), Pell and Taylor (7), and Epps and Monismith (23). They all have agreed that a peak asphalt content exists for optimum fatigue life. However, Jimenez has shown that the optimum asphalt content is function of the type of aggregate used.

Figure 12 shows that an optimum asphalt content exists for coarse and medium gradations used in this study. The figure indicates a maximum fatigue life resulting at approximately 5.1% asphalt content for both gradations. However, this peaking effect is not very evident because samples were not compacted below 5% asphalt content. It should be noted that the binder content estimated by CKE method for coarse and medium gradation was found to be 5.2% and 5.3% respectively. It appears that optimum binder content for best fatigue life is little lower than the optimum asphalt for CKE method.

To evaluate this behavior film thicknesses for all mixtures were computed (Table 3). According to Jimenez (12), excessive film thickness reduces the frictional resistance between the aggregate particles and hence reduces the fatigue life. It was also stated that asphalt mixtures with film thicknesses of 6 to 8 microns are most suitable for pavement surfaces. For coarse gradation film thickness ranged between 6.9 and 8.3 microns while medium graded mixture produced film thickness of 7.7 to 9.2 microns. It is thought that for both gradations fatigue life will be lower at an asphalt content just below 5% (see Figure 12).

Figure 12 also shows the fatigue life curve for fine gradation. The samples for fine grade mixture were compacted at 6.0%, 6.5%, and 7.0% to control the air voids. The optimum binder content estimated by CKE method was 5.7%. As seen, the peak point in this curve is not evident, but would be expected at less than 6.0% asphalt content.

Effect of compaction effort and asphalt content on the fatigue life is shown in Figure 13. For this purpose medium grade mixture was used. It is clearly indicated that increasing the compactive effort and hence density, results in increased number of load repetitions to failure.

Epps and Monismith (23), and Jimenez (14) have also indicated that the optimum asphalt content which produces best fatigue life also produces mixture with highest stiffness. A plot of asphalt content against stiffness for the three gradations is shown in Figure 14. In this figure maximum stiffness is obtained at an asphalt content which is little higher than the optimum asphalt content.

Effect of Gradation

Layman and Phillipi (24), and Epps and Monismith (23) performed fatigue tests on specimens using various types of aggregate gradations. However, they could not

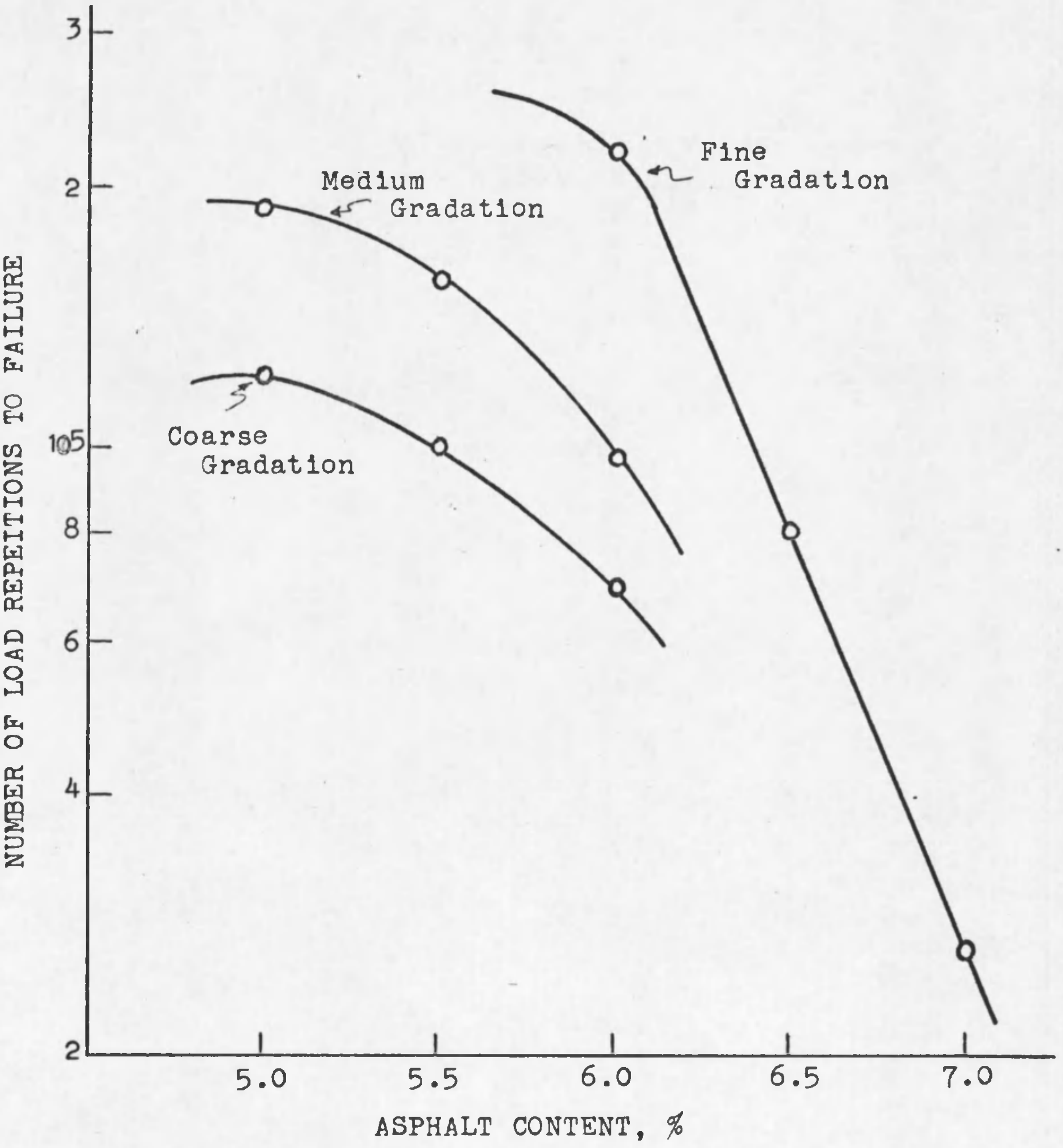


Figure 12. Asphalt Content Versus Number of Load Repetitions to Failure for Coarse, Medium, and Fine Mixtures

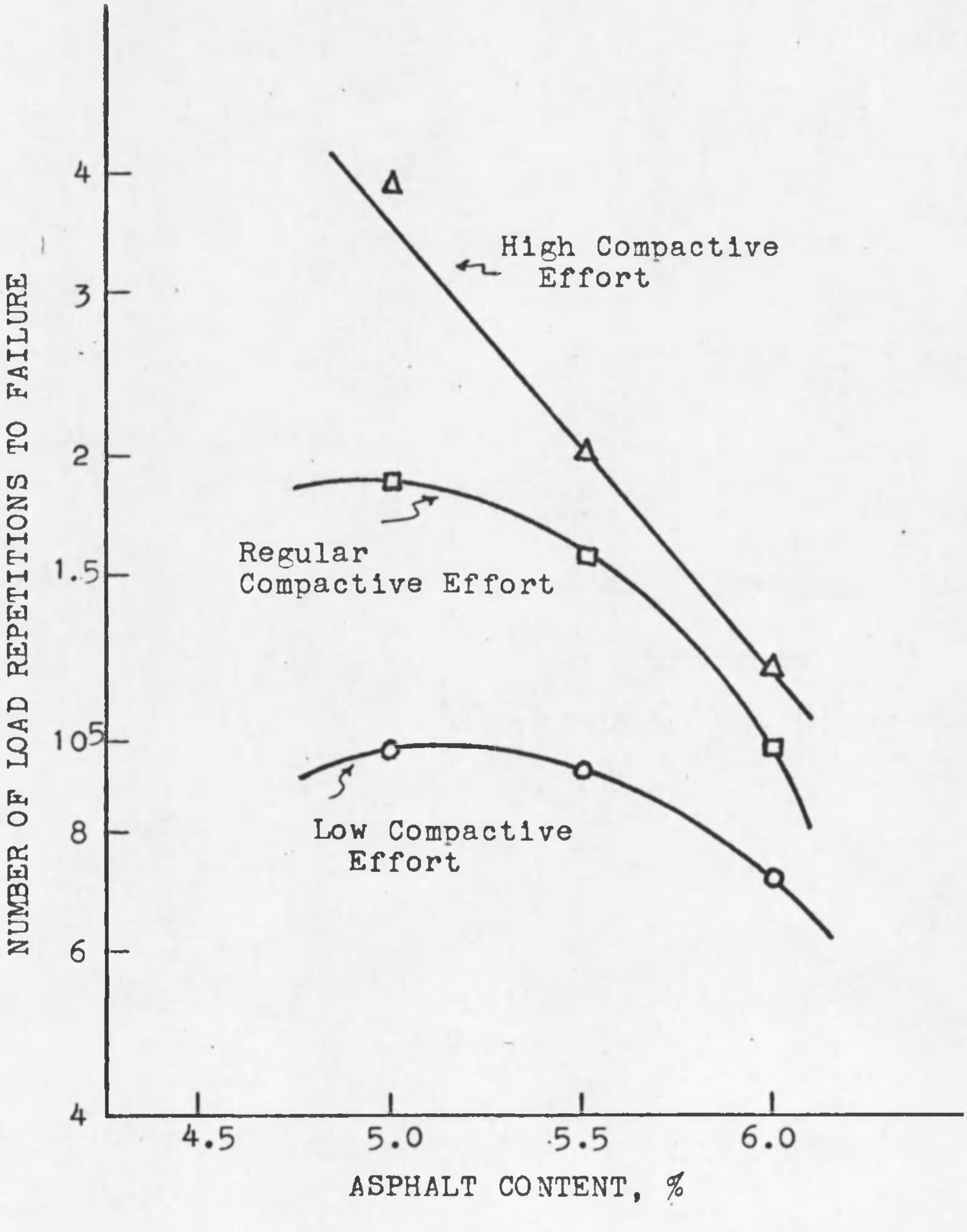


Figure 13. Asphalt Content Versus Number of Load Repetitions to Failure for Medium Gradation

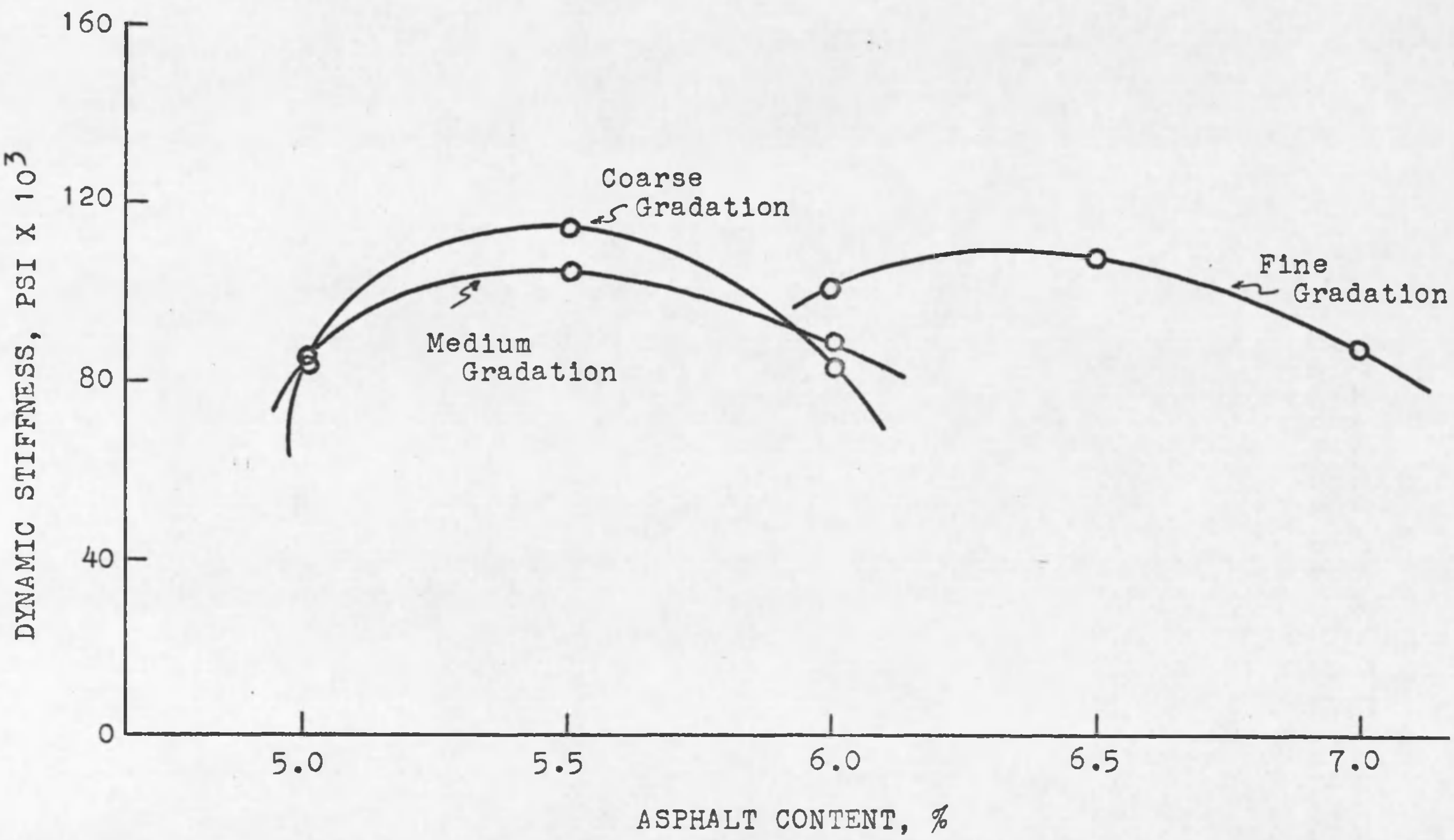


Figure 14. Effect of Asphalt Content on Stiffness of Coarse, Medium, and Fine Mixtures

determine any significant effect of gradation on the fatigue life of asphaltic concrete.

In this study the use of three gradations was mainly to have variability in air void content and hence to evaluate the air void-fatigue life relationships. As can be seen from the testing program, samples for each gradation were made with three asphalt contents. Also, the aggregates used in these gradations were not the same (see Mixture Design). The air void content obtained from each of the gradations varied, lower in the case of coarse gradation and higher for fine gradation. The effect of gradation in that term has already been discussed in previous sections.

An effect of surface texture of the three gradations was found. Medium and course gradations had coarse particle surface texture, while fine gradation had particles of smooth surface texture. The behavior of the coarse and medium gradation was similar and the fine gradation behaved differently for the air voids, stiffness and asphalt effects on fatigue life (see Figures 8, 10, 12 and 14).

CHAPTER 7

SUMMARY AND CONCLUSIONS

Results of the fatigue tests performed are reported in this study. A controlled-load type testing method was employed for the investigation of mixture variables. In particular, the air void effects on fatigue behavior of three asphaltic mixtures were investigated. All data reported in this thesis were obtained at 77°F.

It should be remembered that a limited number of specimens were used for this report and therefore only general trends could be deduced in the following conclusions:

(1) Results of the tests performed on medium gradation mixtures with various air voids are in agreement (in parts) with other investigators (23, 7). These results indicate that decreasing air voids result in increased fatigue life (for the same asphalt content). However, the results for three compactive efforts show that fatigue life increases and then decreases when the air void content is reduced. Maximum fatigue life being obtained between 9.6% to 10.6% of air voids. The

results also show the interaction between asphalt content and compactive effort. Increase in compactive effort results in increased fatigue life at lower asphalt content (see Figure 7).

(2) Results of the tests performed on two gradations, coarse and medium, indicate the same trend. That is fatigue life increased and then decreased when the air voids were decreased. In the case of fine gradation, peaking effect was not evident (see Figure 8).

(3) Air voids affect the stiffness in the same way as it affects fatigue life. Air void content-stiffness-fatigue life relationships indicate that, for medium gradation, maximum fatigue life and optimum stiffness lines will be parallel. Again, for the same asphalt content, stiffness increases when the air voids decrease by compaction (see Figure 9).

(4) Results of the tests performed on three gradations show that a peak stiffness value is present in each case of void-stiffness plots (see Figure 10).

(5) A peak stiffness exists for each of the three gradations on stiffness-fatigue life plots (see Figure 11).

(6) An optimum asphalt content appears to exist for maximum fatigue behavior for coarse and medium mixtures (see Figure 12).

(7) Results of the tests performed on medium gradation indicate that increasing compactive effort (density) increases the fatigue life on asphalt content-fatigue life plots (see Figure 13).

(8) Effect of asphalt content on stiffness could not be found in agreement with other investigators (23, 14), that is, the optimum asphalt content (for the best fatigue life) also produces the mixtures with the highest stiffness. Maximum stiffness, for each of the three mixtures, was obtained at an asphalt content which was higher than the optimum (see Figure 14).

(9) Effect of gradations on air voids-fatigue life, and asphalt content-fatigue life plots show that medium gradation mixtures exhibit higher resistance to fatigue than the coarse or fine mixtures.

CHAPTER 8

SUGGESTIONS FOR FURTHER RESEARCH

Fatigue test results reported in this study require continued work on void effects on fatigue life of asphaltic concrete mixtures. It is desirable to investigate, in detail, the interaction between asphalt content and compactive effort for various mixtures. A statistical analysis will be more suitable.

Variability in the compactive effort was achieved by changing the compaction time in this study. Other methods, as listed by Jimenez (14), should, also, be employed to control density.

APPENDIX A

MIXTURE DESIGN

Table 4

Blending Materials for Coarse Gradation

Sieve Size	Material: Sundt-5/8" % Pass	25% Sundt-5/8"	Material: I-19 % Pass	20% I-19	Material: G.V. Sand % Pass	55% G.V. Sand	Total Comb. % Pass	Spec. Limits
3/4"	100	25	100	20	100	55	100	100
3/8	45.6	11.4	98.5	19.7	98.7	54	85.4	70-90
# 4	8.7	2.2	21.9	4.4	92.3	51	57.4	50-70
8	1.9	0.5	1.2	0.24	83.4	46	46.6	35-50
16	1.3	0.3	0.3	0.06	69.5	38	38.6	--
30	1.3	0.3	0.3	0.06	51.8	28.5	29	18-29
50	1.3	0.3	0.2	0.04	31.0	17	17.3	13.23
100	1.3	0.3	0.2	0.04	17.5	9.6	10	8-16
200	1.3	0.3	0.2	0.04	12.1	6.7	7	4-10

Table 5

Blending Materials for Medium Gradation

Sieve Size	Mat: I-19 % Pass	40% I-19	Mat: G. Valley Sand % Pass	60% G.V. Sand	Total Combination % Pass
3/4"	--	--	--	--	--
3/8	100	40	100	60	100
# 4	21.9	8.8	92.3	55.4	64
8	1.2	0.5	83.4	50.1	51
16	0.3	0.12	69.5	41.7	42
30	0.3	0.12	51.8	31.0	31
50	0.2	0.10	31.0	18.6	18.7
100	0.2	0.10	17.5	10.5	10.5
200	0.2	0.10	12.1	7.2	7.3

APPENDIX B

DEFLECTOMETER TESTING

Table 6

Deflectometer Data Sheet

Mix. Coarse A.C. 5.0% Thick. 2.05 in. D.L. 175# L.L. 150# Mass 4 disc
Speed 740 rpm Press. 1.0 psi Cont. Area 5.0 in^2 Temp. 77°F. Spec. 5.0B

Date:
Mold 2/8/72
Test 3/23/72

Density	Counter	Reps.	4" L D	2 1/4C D	Load Disc	Press Gage	Time and Remarks
Before Test	0	0	300	600	0	1.00	test began at 11:35 a.m.
Wt. (air) 17,845 gm	50	1,000	323.5	557.0 -558.0	83.0 -88.0	1.70	
Wt. (H_2O) 9,750 gm	100	2,000	25.5	52.0 -53.0	93.0 -99.5	1.81	
Vol. 8,095 cc	200	4,000	27.5	48.0	103.0 -109.5	1.92	
Density 2.204 gm/cc	500	10,000	29.5	43.5 -44.5	114.5 -120.0	2.12	
Max. S.G. 2.416 gm/cc	1,000	20,000	30.0	42.0 -43.0	120.0 -126.5	2.20	
Void 8.8 %	2,500	50,000	30.5	40.5 -41.5	127.5 -134.5	2.30	
	5,000	100,000	31.5	40.5 -41.5	135.0 -141.5	2.29	
	7,500	150,000	31.5	37.0 -38.0	143.0 -149.0	2.20	
	10,000	200,000	32.0	35.0 -36.0	151.0 -157.0	2.17	test stopped at 6:30 p.m.

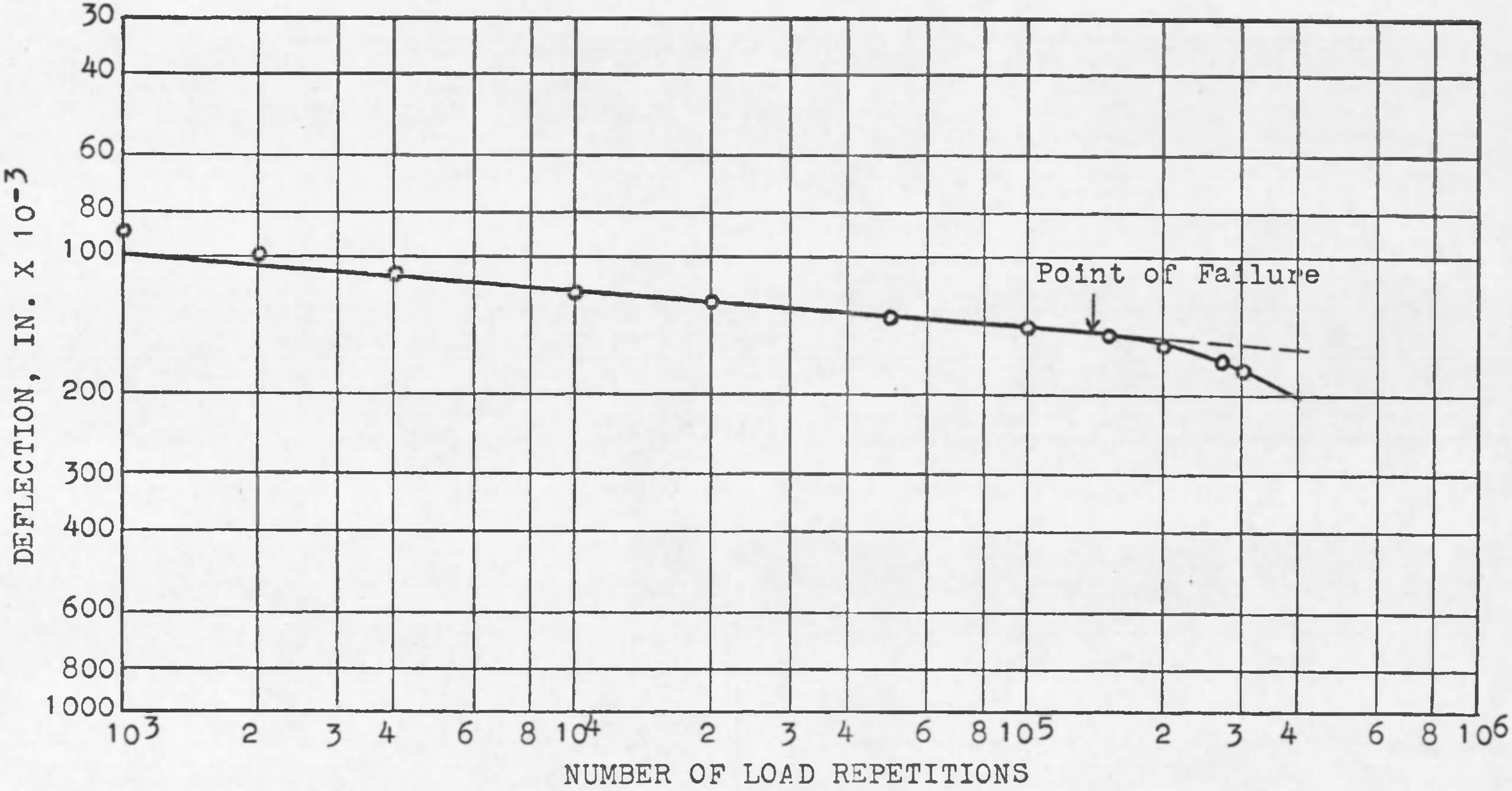


Figure 15. Total Deflection Versus Number of Load Repetitions

APPENDIX C

DEFLECTOMETER DATA

Table 7

Mixture Characteristics of Deflectometer Specimens

Asphalt Content %	Compaction Effort	Thickness in.	Density Gm/c.c.	Total Air Voids %
Variable Coarse Gradation				
5.0 A	Regular	2.02	2.219	8.2
B	"	2.05	2.204	8.8
5.5 A	"	1.97	2.267	5.7
B	"	2.06	2.203	8.4
6.0 A	"	2.07	2.231	6.5
B	"	2.06	2.210	7.4
Variable Medium Gradation				
5.0 A	Low	2.13	2.125	11.6
B	"	2.16	2.085	13.2
5.5 A	"	2.10	2.142	10.2
B	"	2.07	2.176	8.8
6.0 A	"	2.06	2.195	7.3
B	"	2.09	2.181	7.9
5.0 A	Regular	2.13	2.127	11.5
B	"	2.11	2.130	11.4
5.5 A	"	2.08	2.186	8.4
B	"	2.06	2.183	8.5
6.0 A	"	2.05	2.202	7.0
B	"	2.08	2.207	6.8
5.0 A	High	2.07	2.134	11.2
B	"	2.14	2.137	11.1
5.5 A	"	2.04	2.204	7.6
B	"	2.06	2.198	7.9
6.0 A	"	2.05	2.210	6.7
B	"	2.14	2.211	6.7

Table 7, Continued

Asphalt Content %	Compaction Effort	Thickness in.	Density Gm/c.c.	Total Air Voids %
Variable Fine Gradation				
6.0 A	Regular	2.00	2.087	12.6
B	"	1.99	2.106	11.9
6.5 A	"	1.98	2.122	10.5
B	"	1.92	2.135	10.0
7.0 A	"	1.93	2.169	7.9
B	"	1.93	2.160	8.3

Table 8

Summary of Deflectometer Load Test Data
(D.L. = 175#, F_{LL} = 150#, Frequency = 740 rpm, Temperature = 77°F
Initial Support Pressure = 1.0 psi, Disc Area = 5.0 sq. in.)

			Supp. Press.		Repeated Deflect.			
Spec. No.	Thick. In.	Compac. Effort	At Mean, P_m psi	At Fail. P_f psi	At Mean, d_m In. x 10^{-3}	At Fail. d_f In. x 10^{-3}	Reps. to Fail. N_f x 10^3	Total Defl. At Fail. D_F In.
1	2	3	4	5	6	7	8	9
				Variable <u>Coarse Gradation</u>				
5.0 A	2.02	Regular	1.50	2.07	4.0	4.5	110	0.151
B	2.05	"	"	2.22	5.0	6.0	140	0.147
5.5 A	1.97	"	"	2.02	3.0	4.5	100	0.150
B	2.06	"	"	2.20	3.0	4.5	95	0.150
6.0 A	2.07	"	"	2.04	1.0	4.0	65	0.114
B	2.06	"	"	2.10	4.0	5.0	85	0.144
				Variable <u>Medium Gradation</u>				
5.0 A	2.13	Low	1.50	2.20	4.0	5.0	85	0.161
B	2.16	"	"	2.10	4.0	3.5	110	0.104
5.5 A	2.10	"	"	2.41	8.5	9.0	85	0.192
B	2.07	"	"	2.00	4.5	6.5	100	0.129
6.0 A	2.06	"	"	2.29	3.5	4.5	58	0.196
B	2.09	"	"	2.11	2.5	3.5	85	0.140

Table 8, Continued

1	2	3	4	5	6	7	8	9
Variable Medium Gradation								
5.0 A	2.13	Regular	1.50	2.47	3.5	5.0	220	0.140
B	2.11	"	"	2.20	3.5	4.5	150	0.172
5.5 A	2.08	"	"	2.54	3.0	4.5	180	0.163
B	2.06	"	"	2.20	3.0	4.5	130	0.130
6.0 A	2.13	"	"	2.08	2.0	4.0	100	0.140
B	2.08	"	"	2.10	3.5	4.0	95	0.124
5.0 A	2.07	High	1.50	2.06	2.5	3.0	390	0.095
B	2.14	"	"	2.21	3.0	3.5	390	0.190
5.5 A	2.04	"	"	2.10	2.5	3.5	160	0.141
B	2.06	"	"	2.08	4.0	4.0	200	0.118
6.0 A	2.05	"	"	2.10	3.5	3.5	120	0.129
B	2.14	"	"	2.12	3.5	4.0	150	0.160
Variable Fine Gradation								
6.0 A	2.00	Regular	1.50	2.40	3.5	5.5	250	0.227
B	1.99	"	"	2.12	3.5	4.0	190	0.152
6.5 A	1.98	"	"	2.32	3.0	6.5	110	0.220
B	1.92	"	"	2.40	5.0	6.0	50	0.249
7.0 A	1.93	"	"	2.51	4.5	4.5	30	0.180
B	1.93	"	"	2.48	4.5	5.5	23	0.190

Table 9

Deflectometer Data Analysis
(Temperature = 77°, Initial Support Pressure = 1.0 psi.,
Disc Area = 5.0 sq. in.)

Spec. No.	Compac. Effort	Thick. In.	Reps. to Failure, $N_f \times 10^3$	Dynamic Stiff. at Mean, E_D psi	Rad. Stress at Mean, S_R psi
		Variable Coarse Gradation			
5.0 A	Regular	2.02	110	86,280	71.4
B	"	2.05	140	66,770	69.7
5.5 A	"	1.97	100	122,750	74.7
B	"	2.06	95	107,420	68.4
6.0 A	"	2.07	65	310,660	67.1
B	"	2.06	85	81,440	68.7
		Variable Medium Gradation			
5.0 A	Low	2.13	85	73,520	64.2
B	"	2.16	110	70,390	62.4
5.5 A	"	2.10	85	37,870	67.4
B	"	2.07	100	71,710	68.2
6.0 A	"	2.06	58	92,570	68.5
B	"	2.09	85	122,590	66.2
5.0 A	Regular	2.13	220	83,580	64.0
B	"	2.11	155	86,070	65.3
5.5 A	"	2.08	180	104,080	67.0
B	"	2.06	130	107,420	68.4
6.0 A	"	2.05	100	161,610	68.7
B	"	2.08	95	89,700	67.1
5.0 A	High	2.07	390	126,330	67.6
B	"	2.14	390	95,690	63.3
5.5 A	"	2.04	160	131,830	69.5
B	"	2.06	200	81,440	68.7
6.0 A	"	2.05	120	93,860	69.2
B	"	2.14	150	82,470	63.5

Table 9, Continued

Spec. No.	Compac. Effort	Thick. In.	Reps. to Failure $N_f \times 10^3$	Dynamic Stiff. at Mean, E_D psi	Rad. Stress at Mean, S_R psi
		Variable	Fine Gradation		
6.0 A	Regular	2.00	250	101,020	72.7
B	"	1.99	190	102,540	73.4
6.5 A	"	1.98	110	120,820	74.0
B	"	1.92	50	81,220	79.4
7.0 A	"	1.93	30	88,380	78.4
B	"	1.93	23	88,380	78.4

Table 10

Deflectometer Load Test Data
(Temperature = 77°, Disc Area = 5 sq. in.,
Support Pressure = 1.0 psi.)

Spec. No.	Compac. Effort	Thick. In.	Dynamic Stiff. at Failure, E_D psi	Rad. Stress at Failure, S_R psi	Rad. Strain at Failure, ε_R In./In.
Variable Coarse Gradation					
5.0 A	Regular	2.02	70,470	68.5	.00097
B	"	2.05	50,210	66.2	.00132
5.5 A	"	1.97	76,630	72.3	.00094
B	"	2.06	65,070	65.2	.00100
6.0 A	"	2.07	73,660	65.3	.00089
B	"	2.06	59,910	65.9	.00110
Variable Medium Gradation					
5.0 A	Low	2.13	53,190	61.0	.00115
B	"	2.16	72,680	59.4	.00082
5.5 A	"	2.10	31,230	63.0	.00202
B	"	2.07	46,950	66.3	.00141
6.0 A	"	2.06	64,080	64.7	.00101
B	"	2.09	80,260	63.4	.00079
5.0 A	Regular	2.13	50,780	59.7	.00118
B	"	2.11	60,500	62.1	.00103
5.5 A	"	2.08	59,430	62.1	.00105
B	"	2.06	65,070	65.2	.00100
6.0 A	"	2.05	75,300	66.3	.00088
B	"	2.08	71,720	64.2	.00090
5.0 A	High	2.07	96,740	64.9	.00067
B	"	2.14	73,520	60.0	.00082
5.5 A	"	2.04	86,450	66.7	.00077
B	"	2.06	74,260	65.7	.00088
6.0 A	"	2.05	85,250	66.0	.00077
B	"	2.14	65,710	60.6	.00092

Table 10, Continued

Spec. No.		Compac. Effort	Thick. In.	Dynamic Stiff. at Failure, E_D psi	Rad. Stress at Failure, S_R psi	Rad. Strain at Failure, ε_R In./In.
6.0	A	Regular	2.00	56,830	68.4	.00120
	B	"	1.99	81,710	70.1	.00086
6.5	A	"	1.98	50,850	70.5	.00139
	B	"	1.92	59,240	74.4	.00126
7.0	A	"	1.93	74,890	72.4	.00097
	B	"	1.93	62,370	72.9	.00117

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