MECHANICAL CHARACTERIZATION OF FIBER-REINFORCED BITUMINOUS CONCRETE

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Prepared for

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INTRODUCTION

For decades engineers have recognized that the low tensile strength of asphalt concrete is a serious weakness and often the source of performance problems that develop in asphalt concrete pavements. To answer this need, research has been directed toward improving the tensile properties of asphalt concrete. One method with demonstrated merit involves reinforcement of the paving mixture with fibers and fabrics. Potential advantages of improving tensile strength include the following:

1. Reduced cracking due to repeated traffic loads (fatigue cracking),
2. Reduced cracking due to thermal stresses (thermal cracking),
3. Reduced cracking of overlays due to reflection of old cracks from the original pavement,
4. Reduced cracking due to volume changes occurring in the base, subbase and/or subgrade,
5. Increased acceptable performance life and
6. Significant economic benefits.

If pavement performance is to be improved as identified above, the following asphalt concrete mechanical properties will have to be optimized:

1. Tensile strength,
2. Tensile strain at failure,
3. Stiffness and creep compliance,
4. Stability,
5. Shear strength and
6. Shear strain at failure.

It should be noted that these properties are highly dependent upon the temperature and deformation rate used to define the mechanical property being investigated.

LITERATURE REVIEW

The value of fiber reinforcement of construction materials was recognized more than 3000 years ago when Egyptian building specifications required the Hebrews to add straw during the fabrication of their bricks (1). Early attempts in the United States to reinforce bituminous concrete were made in the mid-1930's when cotton fibers were incorporated into test pavements in North and South Carolina (2).

Busching, Elliott and Reyneveld (2) have prepared an extensive review of the literature associated with reinforced asphalt concrete paving mixtures. To date most of the reinforcement used has been continuous rather than particulate. Particulate fibers used to date include asbestos (3-9), cotton (2) and fiberglass (2). Continuous reinforcement in the form of welded wire, synthetic yarns and fabrics has been used sporatically and in modest amounts in the United States for over 30 years.

Busching and Antrim (10) performed a limited series of tests on sand asphalt mixtures containing randomly oriented chopped fiberglass roving and yarn. Data from these tests indicated that randomly oriented chopped strand fiberglass, in amounts up to one percent by weight of the mixture, decreased mixture stiffness and caused cracks to propagate. Busching and Antrim (10) indicated that the release of strain energy from the elastic fiber to the sand asphalt matrix was responsible for the resulting deterioration. Figure 1 shows comparative results from Busching's unconfined compression tests while Figure 2 shows results from his rupture test (10).

Puzinauskas (3) reported that asphalt cement viscosity and hence mixture stiffness can be improved by the addition of randomly dispersed asbestos fibers (Figures 3 and 4). The effect of asbestos fibers on Marshall stability is shown in Figure 5 (3). In addition, asbestos fibers have a demonstrated effectiveness to improve the low temperature cracking properties of asphalt concrete mixtures.

Based on the above rather limited literature review, it is apparent that certain types of fibers may be successfully used as a reinforcement in asphalt concrete mixtures. The selected fibers and asphalt concrete must, however, have compatible mechanical, chemical and thermal properties. Asbestos is a natural fiber with suitable properties; however, the Environmental Protection Agency considers asbestos fibers a health hazard, hence, these fibers are used sparingly. Synthetic fibers offer promise as an asphalt concrete reinforcement as their properties can be tailored to needs of the paving mixture.

STUDY OBJECTIVES AND APPROACH

Because of the potential benefits of polypropylene fibers in asphalt concrete, Hercules Incorporated sponsored a research program at Texas A&M University with the following objectives:

1. Establish the relative mechanical characteristics of various fiber reinforced asphalt concrete materials,
2. Determine the stability of fiber reinforced asphalt concrete,
3. Determine the resilient modulus (elastic modulus) of fiber reinforced asphalt concrete over a range of temperatures,

4. Determine the tensile stress-strain behavior of fiber reinforced asphalt concrete,
5. Define low temperature properties of fiber reinforced bituminous concrete and
6. Determine the ability of fiber reinforced asphalt concrete to resist repeated load applications (fatigue behavior).

Laboratory tests were used to characterize asphalt concrete mixtures containing fibers. Tests used by state departments of transportation to specify properties of asphalt paving mixtures were employed to determine relationships between different fiber characteristics and the ability of mixtures containing the fibers to meet acceptable criteria. These tests are concerned with mixture stability at higher temperatures. Test methods designed to simulate field loading conditions were also utilized. These tests concentrated primarily on tensile properties of mixtures at low temperatures and relatively slow loading rates.

The tests performed includes Marshall stability, Hveem stability, resilient modulus, direct (uniaxial) tension, and overlay tests (resistance to thermal or reflection cracking).

DESCRIPTION OF EXPERIMENTAL PROGRAM

The test program was conducted in three phases which are described in Appendix E. Phase 1 (Table E1) included Marshall and Hveem stability and resilient modulus testing. Phase 2 (Table E2) involved uniaxial tensile testing. Phase 3 (Table E3) involved overlay testing. These tests will be described in more detail later in the body of this report.

Marshall and Hveem stability tests were conducted to verify the optimum asphalt contents for various fiber contents and to provide assurance that paving mixtures containing fibers could meet state specifications. Direct tension and cracking resistance tests were conducted to determine the ability of fibers to provide additional tensile strength to paving mixtures.

All of these tests should be related to field performance and were performed to provide input data for the pavement design engineer who may be considering the use of polypropylene fibers.

MATERIALS

ASPHALT

The asphalt selected for use in this study is a Texas A&M University materials laboratory standard asphalt (11). It is an AC-10 produced in 1976 by American Petrofina at their Mt. Pleasant Texas, refinery. Properties of this asphalt are given on Table A1, Appendix A.

AGGREGATE

The aggregate used throughout this test program to fabricate specimens was a subrounded, siliceous river gravel which has been selected as a Texas A&M University laboratory standard aggregate (11). Standard sieves were employed to separate the aggregate into fractions sized from 3/4 inch to minus number 200 mesh. Then the various sizes were recombined according to the ASTM D 3515-77 (5A) dense grading specification. Properties of this aggregate are given on Table A2 and a gradation chart is presented in Figure A1, Appendix A.

FIBERS

The chopped polypropylene fibers utilized in this study were furnished by Hercules, Incorporated. They ranged in length from 3 to 15 millimeters and ranged in size from 5 to 15 denier. The fibers will be referred to as length by denier. For example, a 3 x 5 fiber is one that is 3 millimeters in length and sized 5 denier.

Three types of fibers were used in this study. 1) conventionally processed fibers 2) washed fibers and 3) Pulpex P™. Selected 15 x 10 fibers were supplied after being washed in a solvent to remove the "spin finish". Washed fibers were used in this program with selected mixtures in the Marshall and Hveem stability study; all other mixtures contained unwashed fibers.

Pulpex P is a short fiber-like material formed by spurting rather than spinning the polypropylene.

LABORATORY MIXTURES

Mixtures of the three previously mentioned materials were prepared in the laboratory by the methods described in the next section. Control specimens containing no fibers are described in some detail on Table A3, Appendix A.

FIELD MIXTURES

Mixtures were prepared using a conventional hot-mix batch plant in Maryland to produce specimens for the overlay test (to be discussed later). The asphalt was an AC-20 produced by American Oil. The aggregate was crushed limestone with the gradation as shown on Table A4. Ten different types of samples were fabricated using 4 different fibers at fiber contents ranging from 0 to 2 percent as shown on Table A5. Mixing was performed in the batch plant at approximately 275°F (135°C). Compaction of slabs was completed at approximately 265°F (130°C). Samples of appropriate size were sawed from a slab sample and shipped to Texas A&M University for testing.

PREPARATION AND TESTING OF SPECIMENS

MIXING

Sized fractions of aggregates were recombined to meet specifications. Prior to mixing, the asphalt cement and the aggregate were heated to 280°F (138°C). A predetermined quantity of fibers was added to the dry aggregate but not blended. The appropriate quantity of asphalt cement was added and then the mixture was manually blended for about two minutes using the back side of a large preheated metal spoon. When blending was completed (all aggregate particles coated with asphalt cement), the mixture was placed in an oven at 260°F (127°C) for about 20 to 30 minutes to bring it to the appropriate compaction temperature.

When fibers are introduced into an asphalt paving mixture, additional asphalt is necessary to coat these fibers. (This is similar to the addition of very fine aggregate). The proper quantity of asphalt for consistent coating of all particle for different fiber contents was estimated on a volumetric basis and converted to a weight basis for convenience in the laboratory. The values were then verified by conducting Marshall and Hveem stability tests over a range of asphalt contents.

MARSHALL TESTS

The Marshall test was developed in the late 1930's and early 1940's by the Mississippi State Highway Department and the U. S. Army

Corps of Engineers. The test is used by a large number of States as well as several foreign countries. Marshall stability and flow values of an asphalt concrete material are measures of the materials ability to resist plastic flow. Normally, mixtures with high Marshall stability and low flow do not shove, corrugate or rut under field traffic.

Marshall specimens were compacted at 280°F (137°C) by applying 50 blows per face with the standard Marshall hammer. The cylindrical specimens are 4-inches in diameter and approximately 2.5 inches in height. Testing was conducted at 140°F (60°C) in accordance with ASTM D 1559.

Mixtures containing 0.0 (control), 0.2 and 0.4 percent washed and unwashed 15 x 10 fibers, each at 5 different asphalt contents, were tested. Mixtures containing 0.2 and 0.4 percent unwashed 3 x 5 fibers, each at 3 different asphalt contents were also tested. Test plan is shown in Table E1, Appendix E.

HVEEM STABILITY

The test was developed in the late 1930's by the California Division of Highways and is presently used by approximately 15 state departments of transportation for asphalt concrete mixture design. The Hveem stability value of asphalt concrete is a measure of the material's ability to resist plastic flow. Normally, mixtures with adequate Hveem stability will not shove, corrugate or rut.

Hveem specimens were compacted at 250°F (121°C) using the Texas gyratory compactor in accordance with test method TEX-206-F, Part II. The cylindrical specimens are 4-inches in diameter and approximately

2.0-inches in height. Hveem stability of the specimens was determined at 140°F (60°C) in accordance with the Texas State Department of Highways and Public Transportation test method TEX-208-F, "Test for Stabilometer Value of Bituminous Mixtures", which is a modification of ASTM D 1560.

Mixtures containing 0 (control), 0.2 and 0.4 percent washed 15 x 10 fibers, each at 5 asphalt contents, were tested. Mixtures containing 0.2 percent of unwashed 3 x 5 fibers at 3 asphalt contents were also tested in accordance with the test plan given in Table E1.

RESILIENT MODULUS

Resilient modulus is a measure of the mixtures ability to distribute traffic load, and is approximately equal to the elastic modulus. Resilient modulus was determined at 5 temperatures using the Mark III Resilient Modulus Device developed by Schmidt (12). A diametral load of approximately 72 pounds (33 kg) is applied for a duration of 0.1 seconds while monitoring the lateral deformation of the specimen. The load is normally reduced somewhat for M_R tests at higher temperatures to prevent specimen damage.

The resilient modulus test program is outlined in Table E1. Mixtures containing 0 (control), 0.2 and 0.4 percent washed 15 x 10 fibers, each at 5 asphalt contents and 0.2 percent 3 x 5 fibers at 3 asphalt contents were tested at 77°F. Three of these mixtures were tested at additional temperatures of -13, 33, 68 and 104°F (-25, 1, 20, and 40°C).

DIRECT TENSION

In an effort to determine the effects of fibers on the tensile properties of asphalt concrete, uniaxial tensile tests (Figure 6) were conducted on specimens containing fibers as well as control specimens at constant deformation rates of 2, 0.02 and 0.002 inches per minute (51, 0.51 and 0.0051 mm/min) and a temperature of 32°F (0°C).

The first step was to compact a 1.5 x 3 x 15-inch (50 x 75 x 375 mm) beam using a modified Soil-Test Model CN-425 kneading compactor with a 3 x 4-inch (75 x 100 mm) tamping foot. Following extrusion from the mold, the beams were allowed to cool to room temperature. The specific gravity of each specimen was determined gravimetrically in air and water, and the air void content was computed. Each of the six beams was cut in half longitudinally. Then each half was sawed into three pieces which were trimmed to ultimately produce test specimens approximately 1.25 x 1.25 x 5-inches.

Aluminum end caps (Figure 1) were epoxied to each end of the specimens. These end caps are specially prepared to fit the Instron Universal Testing Machine, which was used to apply the uniaxial load at a constant rate of displacement. Load was measured by a load cell. Two linear variable differential transformers (LVDT), fastened directly to the specimen by a small test frame, were used to monitor specimen deformation during a test.

RESISTANCE TO THERMALLY INDUCED REFLECTION CRACKING

The "overlay tester" developed at Texas A&M University, is essentially a displacement controlled fatigue testing machine designed to initially produce a small initial crack (due to tension) in a test specimen and then continue to induce repetitive longitudinal displacements at the base of the crack which causes the crack to propagate upward through the specimen (Figure 7).

An asphalt concrete beam with dimensions of approximately 3 x 3 x 15 is attached by epoxy to a set of rigid aluminum plates on the overlay tester, one fixed, the other regulated to oscillate at a displacement of ostensibly 0.07-inches and a rate of 6 cycles per minute. (The displacement during a given test ranged from some minimum value at the start, say about 0.05-inches, to a maximum of 0.07 near the end of a test. This device is in the developmental stage and this shortcoming is being resolved.) The initial movement is outward which causes tensile stresses at the center of the base of the specimen.

Tests were conducted at 77°F (25°C) and 32°F (0°C). Load was measured by a strain gage load transducer and displacement of the moving plate was monitored by a linear variable differential transformer (LVDT). Load as a function of displacement was recorded on an X-Y recorder. An example of recorded data is given in Figure 8. The length of the crack in the specimen was periodically measured on the two sides. The machine was allowed to oscillate until complete specimen failure. Failure is defined as that cycle at which the load supported by the specimen showed no further decrease after an additional approximately 200 displacement cycles. This usually occurred about the same time the crack propagated completely through the specimen. Ideally, complete failure would be defined as the cycle at which the load approached zero, however, with those specimens containing fibers, a measurable load was supported by the fibers even after the asphalt concrete specimen was completely cracked.

This process is intended to simulate the cyclic stressing of a pavement due to periodic thermal variations. Results obtained with this apparatus should prove very useful in predicting pavement service-life extension produced by systems purported to reduce reflection cracking.

Ten different types of test specimens were fabricated by Hercules personnel using asphalt concrete containing fibers mixed in a conventional hot-mix batch plant. A description of these specimens is shown on Table A5. The mixtures were compacted at approximately 265°F (130°C) in a wood mold. Beams approximately 3 x 3 x 16-inches in size were sawed from the compacted specimens and shipped to Texas A&M University for testing.

TEST RESULTS AND DISCUSSION

The relative laboratory performance of different fiber variants (denier, length, and content in mixture) are evident from the results of the tests described below. It is difficult, if not impossible, to directly predict field performance from these tests results; however, the laboratory tests are an attempt to realistically simulate field loading conditions. The relative performance of fabrics in the field is in all probability correlatable to their relative laboratory performance.

MARSHALL STABILITY AND FLOW

Results from the Marshall stability study are tabulated in Table B1, Appendix B. Selected data are presented graphically in Figures) through 19.

The addition of 0.2 or 0.4 percent of the particular fibers tested resulted in a decrease in Marshall stability of the asphalt-aggregate mixture. This is in agreement with published literature (13). Marshall stability was, however, above acceptable levels. Marshall flow was not appreciably or consistently affected by the addition of fibers.

The addition of fibers increases the amount of asphalt cement required to achieve maximum stability. Mixtures containing 0.2 and 0.4 percent fibers exhibited about the same maximum Marshall stabilities but the maximum stability occurred at a higher asphalt content (Figures 9 and 11).

Slightly higher stabilities and lower flows were obtained with mixtures containing washed fibers (Figure 15) as compared to unwashed fibers. However, field tests have shown that washed fibers will tend to cling together, thus causing difficulties in mixing. Washed fibers are no longer considered for use in asphalt concrete applications. Therefore, only unwashed fibers were used for all successive tests.

Although the data are incomplete, it appears that the mixtures containing the smaller (3 x 5) fibers will yield lower Marshall stabilities than the mixtures containing the larger (15 x 10) fibers (Figure 15). This indicates that the longer fibers with the larger diameter may be more desirable if Marshall stability is the acceptance criterion.

Bulk specific gravity of the Marshall compacted specimens decreased in proportion to the quantity of fibers added at comparable asphalt contents (Figures 16 and 18). The use of washed fibers also resulted in notably lower specific gravity specimens. Air voids at asphalt contents near optimum (for Marshall stability) are not greatly increased upon the addition of fibers (Figures 17 and 19). At asphalt contents above optimum, air voids may show a decrease upon the addition of fibers.

HVEEM STABILITY

Results from the Hveem stability study are given in Table B2, Appendix B. Selected data are presented graphically in Figures 20 through 22.

Hveem stability of an asphalt paving mixture can increase or decrease upon the addition of synthetic fibers, depending on the quantity and the size of the fibers (Figure 20). It appears that proper utilization of fibers in asphalt paving mixtures can significantly improve Hveem stability.

The limited data indicate that smaller quantities (0.2 percent) of the larger fibers (15 x 10) produce specimens with greater Hveem stability than specimens containing no fibers (control specimens). On the other hand, 0.4 percent of the 15 x 10 fibers or 0.2 percent of the 3 x 5 fibers did not appreciably affect the maximum Hveem stability value obtained for a given mixture. However, the inclusion of the fibers produced mixtures which are more tolerant of increases in asphalt content that is, the rate of decrease in Hveem stability with asphalt content is lower. Thus, the inclusion of fibers will allow higher asphalt contents (while maintaining acceptable stability values) and thus may improve durability.

Bulk specific gravity of the gyratory compacted specimens decreased in proportion to the quantity of 15 x 10 fibers added, when compared at equal asphalt contents (Figure 21). Those specimens containing 0.2 percent of the unwashed 3 x 5 fibers, which have a larger surface area per unit weight, exhibited consistently lower bulk specific gravities and slightly higher air void contents than comparable mixtures containing 0.2 percent of the washed 15 x 10 fibers. Generally, air void content of the gyratory compacted mixtures was not increased appreciably until the fiber content exceeded 0.2 percent (Figure 22).

RESILIENT MODULUS

Results from resilient modulus tests at 77°F (25°C) are included in Table B2, Appendix B and Figure 23. Data from resilient modulus tests at -13, 33, 68, 77 and 104°F (-25, 1, 20, 25 and 40°C) are contained in Table B3 and Figure 24.

Figure 23 shows that resilient modulus at 77°F, like Hveem stability, can be increased significantly by the addition of fibers. At higher asphalt contents the resilient modulus of the fiber filled asphalt concrete exceeds that of the control. The optimum asphalt content based on resilient modulus increases with fiber content. Addition of the shorter 3 x 5 fibers is detrimental to resilient modulus at lower asphalt contents. The resilient modulus increase as the asphalt content is increased.

Figure 24 shows that resilient modulus of an asphalt paving mixture over a large temperature range will increase uniformly upon the addition of 0.2 percent 15 x 10 fibers. One encouraging aspect of this plot is the larger increase in resilient modulus for the specimens containing fibers at the higher temperatures. This indicates that the addition of fibers will aid in preventing instability of paving mixtures at the higher temperatures occuring during summer service.

DIRECT TENSION

Data from the uniaxial tensile tests are given in Table C1, Appendix C. A summary of these data is presented in Table 1 and graphically depicted in Figures 25 through 31.

Tensile tests were conducted on specimens containing 0, 0.2, 0.4 and 0.8 percent fibers. Based on results from Marshall and Hveem stability tests and engineering judgement, optimum asphalt contents were selected for each fiber content (regardless of fiber type) and utilized throughout this experiment. The asphalt contents utilized are given below:

Fiber Content, %	0	0.2	0.4	0.8
Asphalt Content, %	3.8	3.9	4.0	4.1

The effects of fiber type (diameter and length) and fiber content on tensile strength and tensile strain at failure are shown for displacement rates of 2.0, 0.02 and 0.002 inches per minute at 32°F (0°C) in Figures 25 through 30. There are no consistent relationships between fiber diameter or length and tensile strength or tensile strain at failure at any of the displacement rates. Increasing the fiber content above 0.2 percent is shown to decrease the mixture strength. However, tensile strain at failure is shown to increase substantially with increased fiber content when tested at 0.002 inches per minute. This is likely due in part to additional asphalt in these high fiber content mixtures. Most of the fibers tested have the ability, at some fiber content, to increase tensile strain at failure at displacement rates of 0.02 and 0.002 inches per minute. In general, a fiber content of 0.2 percent improved tensile properties of this asphalt paving mixture more often than the higher fiber contents.

Figure 31 depicts tensile strain at failure of specimens containing 0.2 percent fibers. At high displacement rates fibers appear to decrease tensile strain at failure of asphalt concrete. However, at very low displacement rates (as expected in thermal variations) the addition of fibers generally causes a marked increase in tensile strain at failure.

Figure 32 shows that tensile strengths of those specimens containing 0.2 percent fibers are significantly lower than the strengths of those specimens with no fibers.

The large top size of the laboratory standard aggregate in conjunction with the comparatively small size of the tensile test specimens may have contributed to these unfavorable results regarding tensile strength. The extreme denseness of gradation of the aggregate utilized in this study may not have allowed the fibers to function as well as one might expect, particularly if the grading were more open.

It may be necessary to increase compactive effort in proportion to the quantity of fibers added in order to properly densify an asphalt mixture containing fibers. This is in agreement with earlier work of Puzinauskas (3) whose tests indicated that a good correlation exists between binder viscosity and the compactive effort needed to densify a paving mixture. And further, his tests suggest that a substantial increase in temperature may be needed when compacting paving mixtures containing high-viscosity filler-asphalt binder. Softer asphalts may be used with fibers as the fibers (filler) will increase the effective viscosity of the binder system (3). This may be particularly desirable in colder climates. Additionally, softer asphalt will allow the use of lower mixing temperature thus reducing the probability of damage to the fibers. Polypropylene fibers should not be exposed to temperatures above 290°F (144°C).

RESISTANCE TO THERMALLY INDUCED REFLECTIVE CRACKING

Properties of the overlay test beams at 77 and 32°F are furnished in Table D1, Appendix D. Data obtained during experimentation on the overlay tester are listed on Table D1 and D2. Plots of crack height versus number of deformation cycles for individual specimens are presented in Appendix D.

Based on these tests results, fiber reinforced asphalt concrete is more resistant to reflection cracking than conventional asphalt concrete mixtures. Table 2 is a summary of all tests conducted on the overlay tester. Several times more load cycles were required to produce failure in the specimens containing fibers as compared to those containing no fibers (see also Figure 33).

Figure D1, when compared to Figures D2 through D10, illustrates that crack propagation through the control specimens was much faster than crack propagation through the specimens containing fibers.

Figure 33 shows that the number of cycles to failure at 77°F increases in proportion to fiber content when one observes samples containing similar fibers. The reader is reminded that asphalt demand increases with fiber content and the higher asphalt content may very well be partly responsible for the improved performance. However, air void content also usually increases with fiber content (assuming constant compactive effort) which will negatively affect tensile properties of asphalt concrete. This figure also indicates that generally the number of cycles to failure increases with fiber diameter. Performance of the specimens containing the Pulpex^{P} was not good when compared to those containing the other fibers. All the fibers used for overlay testing except the Pulpex^{P} fibers were 5 mm in length.

Figures 34 and 35 are presented to illustrate the reinforcing characteristic of the fibers at 77°F which sustains the load supporting ability of the asphalt concrete specimens for approximately 30 times more deformation cycles than the control specimens. The initial peak load during cycle one was essentially the same for all specimens including the control specimens. However, the peak load for the control specimens during all succeeding cycles decreased at much faster rate than those specimens containing fibers. For those specimens containing 1.0 percent or more fibers, a flattening out of the curves occurs at peak loads between 10 and 20 pounds. This phenomenon is not readily explicable, but may be associated with the load bearing capacity of the fibers that span the cracks as these cracks propagate through the specimen. Figure 35 shows the relatively poor performance of Pulpex^{P} when compared to the other specimens containing fibers.

Figure 36 shows typical cracking patterns of specimens with and without fibers. Specimens containing fibers cracked over a wider area than those without fibers. This is attributed to the load spreading ability of the fibers.

Fracture mechanics theory developed by Schapery (14) and refined for use with the overlay tester by Lytton (15) were applied to compute fracture toughness. Fracture toughness is also called the "crack extension force" in some fracture mechanics applications. Fracture toughness is defined here as the initial rate of change of work per unit of increased crack surface area. Larger values of fracture toughness (smaller absolute values) are desirable.

Two sets of fracture toughness values are given in Table 2. One set was computed using all valid data points collected periodically throughout the duration of the overlay test. These data show no appreciable difference in fracture toughness of the control specimens and those containing fibers. A second set of fracture toughness values was computed using only the first few data points collected, where cracking rate was fairly rapid, in order to emphasize the initial cracking resistance of the overlay specimens. These data show significantly greater toughness for those specimens containing fibers. Similar results were obtained using this test procedure with specimens containing engineering fabrics applied to prevent reflective cracking (15). That is, fracture toughness was significantly greater for specimens containing a fabric as compared to specimens with no fabric.

A limited number of overlay tests were conducted at 32°F (Table 2). This marked the first time this relatively new apparatus had ever been used at any temperature other than 77°. Only a few specimens were available for testing at 32°F and the control specimens available were only 1.5-inches in height. This makes comparisons to the 3-inch fiber reinforced specimens difficult. However, it appears evident from these few tests that the number of cycles to failure at 32°F will increase when fibers are included in the mix. At this temperature some of the larger aggregates within the failure plane were actually pulled in half, indicating the tensile strength of the matrix equaled or exceeded that of the aggregates. Future tests at 32°F would likely employ a displacement of considerable less than 0.070-inches as used throughout this study. This would allow more time for observations between test initiation and specimen failure.

This experimental technique, employing cyclic constant displacement tensile loading, which simulates the action responsible for thermal reflective cracking, demonstrates several important features of fibers when applied to retard reflective cracking in asphalt concrete overlays:

1. Fibers will retard reflective cracking in asphalt concrete.

2. Fibers will span small cracks in asphalt concrete and support a small load. These asphalt coated fibers will probably retard the intrusion of moisture into successive pavement layers.

3. Fibers will allow additional asphalt in paving mixtures which will improve tensile properties, promote "healing" of cracks and improve mixture durability.

CONCLUSIONS

Based on analysis of laboratory test results and the literature reviewed the following conclusions are warranted:

1. Small quantities of certain polypropylene fibers will improve tensile properties and retard reflective cracking in asphalt concrete when the asphalt content is increased to satisfy the requirements of the fibers,

2. Tensile strain at failure and resistance to crack propagation increase with fiber content, whereas, mixture stability and tensile strength decrease with fiber content. The optimum fiber content for a mixture depends on the field application of the mixture,

3. Based on tensile test results, appropriate types and quantities of polypropylene fibers will increase the extensibility of asphalt concrete paving mixtures,

4. Stiffness and resistance to cracking of an asphalt concrete paving mixture were shown, in general, to increase in proportion to fiber length and diameter,

5. Depending on the test temperature and the rate of deformation, the tensile strength of a fiber reinforced mixture may be larger or smaller than a conventional mixture. The magnitude of the strength increases noted in this study are not enough to sufficiently alter the low temperature cracking characteristics of pavements (16),

6. Marshall or Hveem stability appear to be acceptable tests for use in selecting optimum asphalt contents for asphalt paving mixtures containing fibers, therefore, state highway departments can use standard mixture design test procedures,

7. The addition of fibers will decrease Marshall stability of asphalt concrete but appropriate quantities of fibers will not decrease Marshall stability below acceptable levels,

8. The addition of fibers to asphalt concrete may either increase or decrease the Hveem stability depending upon the size and amount of the fibers. The inclusion of fibers reduces the rate of decrease in Hveem stability with increase in asphalt cement content, i.e., the stability remains at a high value as asphalt content increases.

9. Resilient modulus of asphalt concrete is increased by the addition of fibers. Large increases are apparent at high temperatures,

10. The addition of fibers to low stability mixtures may alter properties sufficiently to minimize shoving, corrugation and rutting types of failures and

11. From the stand point of flexibility, the fact that small quantities of polypropylene fibers allow a significant increase in asphalt content of conventional paving mixtures is an important consideration. The additional asphalt will improve tensile properties and reduce reflection cracking. Although no positive evidence is provided herein, it follows that the additional asphalt would also improve fatigue properties, reduce water susceptibility and promote healing of cracks without flushing or bleeding.

RECOMMENDATIONS

The study reported herein should be considered only as a first stage program. Additional testing programs should be formulated and conducted to investigate the influence of fiber reinforcement on the following:

1. Permanent deformation,
2. Flexural fatigue resistance,
3. Reflection cracking at low temperatures and small displacements,
4. Water susceptibility,
5. Resistance to flushing or bleeding,
6. Properties of maintenance and materials and
7. Resistance to shearing or punching loads (mixture tenderness).

Mixtures containing different aggregates should be included in the program, especially those with gap and open gradations and smaller maximum sizes than those used in this study. In addition, different types of fibers should be investigated as well as the cost effectiveness of the use of fiber reinforced asphalt concrete mixtures.

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11. Button, J. W., Epps, J. A. and Gallaway, B. M., "Test Results on Laboratory Standard-Asphalt, Aggregate and Mixtures," Research Brief No. 1, Materials Division, Texas Transportation Institute, January 1977.

12. Schmidt, R. J., "A Practical Method for Measuring the Resilient Modulus of Asphalt-Treated Mixes," Highway Research Record No. 404, Highway Research Board, 1972.

13. Martinez, P. B., Mills, D. R., Steininger, B., "Synthetic Fibers Reduce Reflection Cracking," Public Works, April 1979.

14. Schapery, R. A., "A Theory of Crack Growth in Viscoelastic Media," Office of Naval Research, Department of the Navy, MM-2764-73-1, Mechanics and Materials Research Center, Texas A&M University, March 1973.

15. Button, J. W., Epps, J. A., Lytton, R. A., "Laboratory Evaluation of Fabrics Designed to Reduce Reflection Cracking," RR3424-3 for Celanese Fibers Marketing Co., Texas Transportation Institute, Texas A&M University, August 1979.

16. Haas, R. C. G., "A Method for Designing Asphalt Pavements to Minimize Low-Temperature Shrinkage Cracking," RR-73-1, The Asphalt Institute, January 1973.

Table 1. Summary of Results from 32°F Direct Tension Tests.

Type Fibers	Fiber Content, wt. percent	Air Voids, percent	Deformation Rate, in/min	Tensile Strength, psi	Strain @ Failure, in/in	Secant Modulus. psi
3 x 5	0.2	9.3	2	470	0.0017	276,000
			0.02	240	0.0013	185,000
			0.002	69	0.0013	64,000
	0.4	-	0.02	122	0.0021	58,000
			0.002	102	0.0013	78,000
3 x 10	0.2	-	0.002	117	0.0008	146,000
3 x 15	0.2	9.9	2	334	0.0007	798,000
			0.02	110	0.0046	27,000
			0.002	58	0.0042	30,000
15 x 5	0.2	-	2	359	0.0022	177,000
			0.02	250	0.0017	157,000
			0.002	152	0.0018	97,000
	0.4	7.6	0.02	213	0.0028	81,000
			0.002	104	0.0023	46,000
	0.8	12.1	0.02	114	0.0043	27,000
			0.002	53	0.0021	31,000
15 x 10	0.2	7.7	2	520	0.0004	910,000
			0.02	107	0.0024	47,000
			0.002	72	0.0039	22,000
	0.4	9.4	0.002	54	0.0006	106,000
15 x 15	0.2	8.5	2	370	0.0005	893,000
			0.02	140	0.0015	183,000
			0.002	80	0.0047	18,000
Control	None	10.0	2	489	0.0028	174,000
			0.02	231	0.0018	133,000
			0.002	103	0.0022	58,000

Table 2. Summary of Data From Overlay Tests on Specimens Supplied by Hercules.

Test Temp., °F (°C)	Sample Number	Type Fiber	Fiber Content, wt. %	Asphalt Content. wt. %	Sample Height, inches	Sample Width, inches	Bulk Specific Gravity	Air Voids, vol. %	No. Cycles @ Failure	Peak Load During First Cycle, lbs.	Fracture Toughness All Points	Fracture Toughness Initial Points
	1	None	0	5.8	2.25	3.19	2.29	7.1	30	634	-3.7	-31
	2	15 x 5	0.2	6.0	3.15	3.10	2.31	5.7	550	700	-5.8	-11
	3	15 x 5	0.8	6.7	3.13	3.14	2.25	7.5	800	653	-6.9	-14
77	4	6 x 5	0.8	6.8	3.14	3.08	2.22	8.5	450	787	-	-
(25)	5	3 x 5	1.0	7.0	3.17	3.10	2.18	9.7	780	706	-5.4	-14
	6	Pulpex[P]	1.0	7.0	3.21	3.10	2.05	14.4	350	578	-1.6	-21
	7	15 x 5	1.4	7.5	3.16	3.13	2.13	9.6	890	657	-	-
	8	6 x 5	1.4	7.5	3.19	3.14	2.08	12.1	730	562	-5.0	-14
	9*	3 x 5	2.0	8.4	1.65*	3.10	2.10	12.7	230	227	-3.2	-21
	10	15 x 5	2.0	8.4	3.16	3.17	2.07	10.0	1230	565	-5.9	-17
	1	None	0	5.8	1.5	3.0			1	1264	-	-
32	5	3 x 5	1.0	7.0	3	3			4	1446	-	-
(0)	7	15 x 5	1.4	7.5	3	3			4	1785	-	-
	10	15 x 5	2.0	8.4	3	3			14		-	-

*These specimens were damaged and had to be trimmed to the smaller height in order to salvage them for testing.

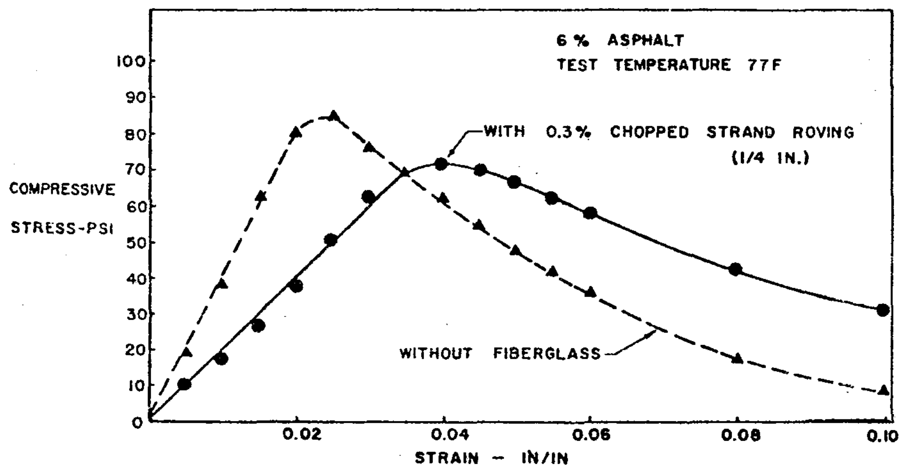


Figure 1. Stress-Strain Diagram for Sand Asphalt Cylinders, 6% Asphalt (After Reference 10).

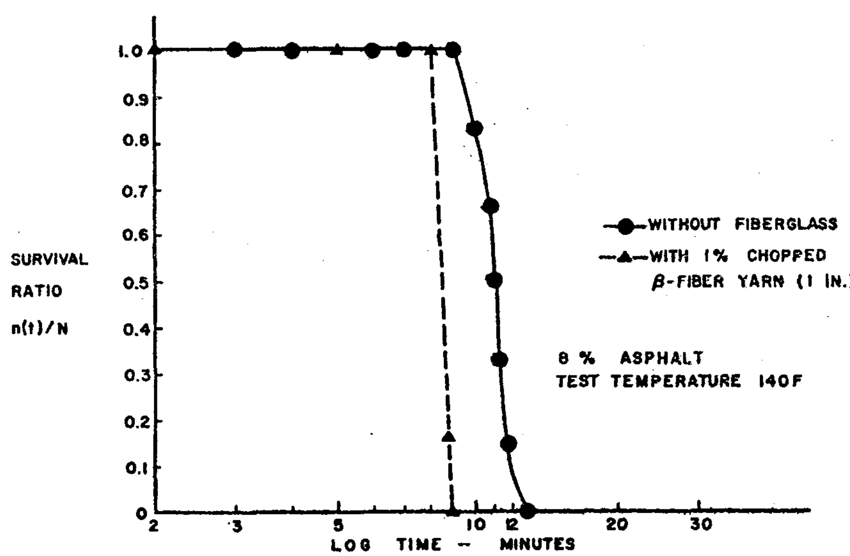


Figure 2. Survival Ratio vs. Log Time for Cylindrical Specimens, 8% Asphalt (After Reference 10).

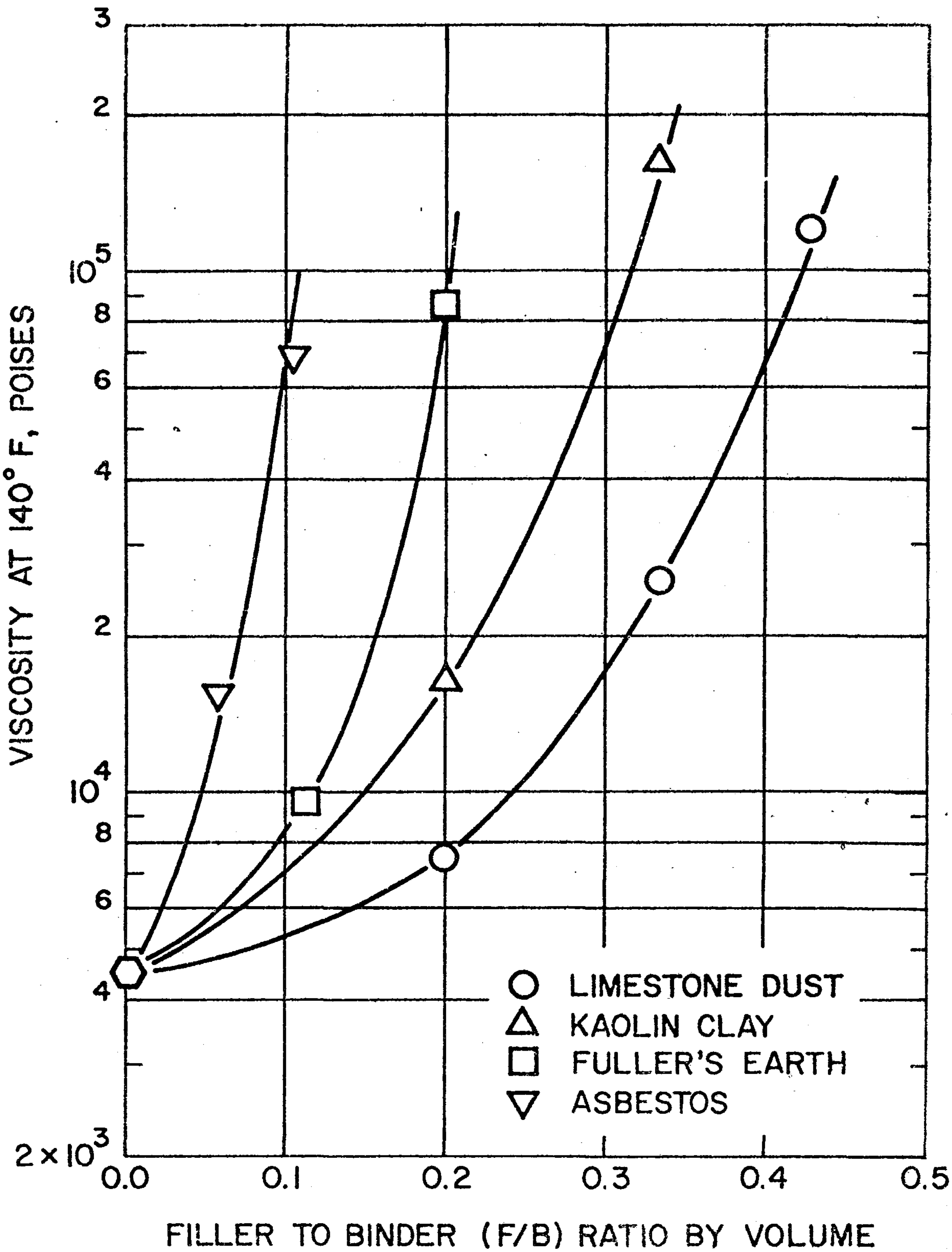


Figure 3. Effect of Filler Concentration on Viscosity at 140°F of Filler-Asphalt Mixtures. (After Reference 3)

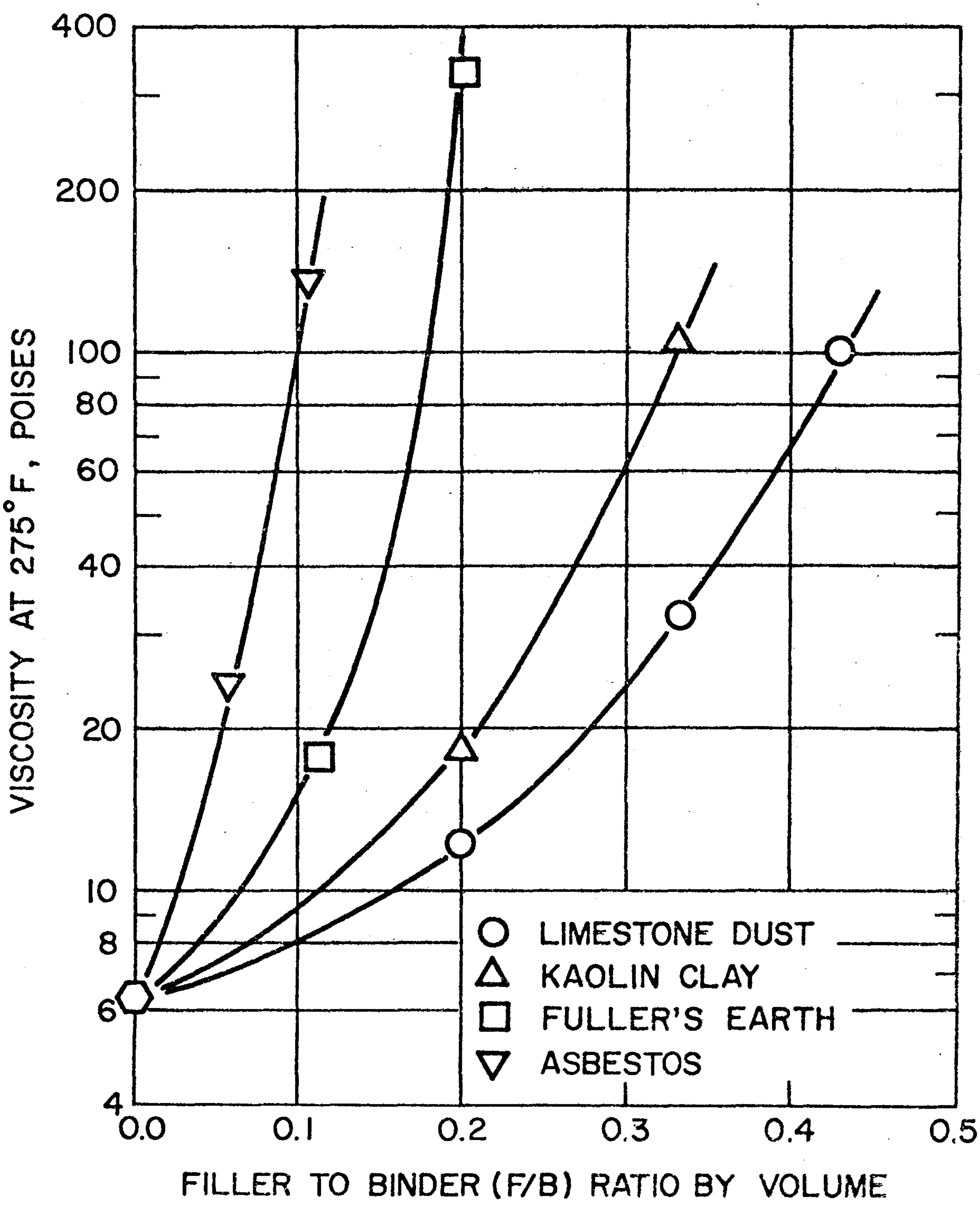


Figure 4. Effect of Filler Concentration on Viscosity at 275°F of Filler-Asphalt Mixtures. (After Reference 3)

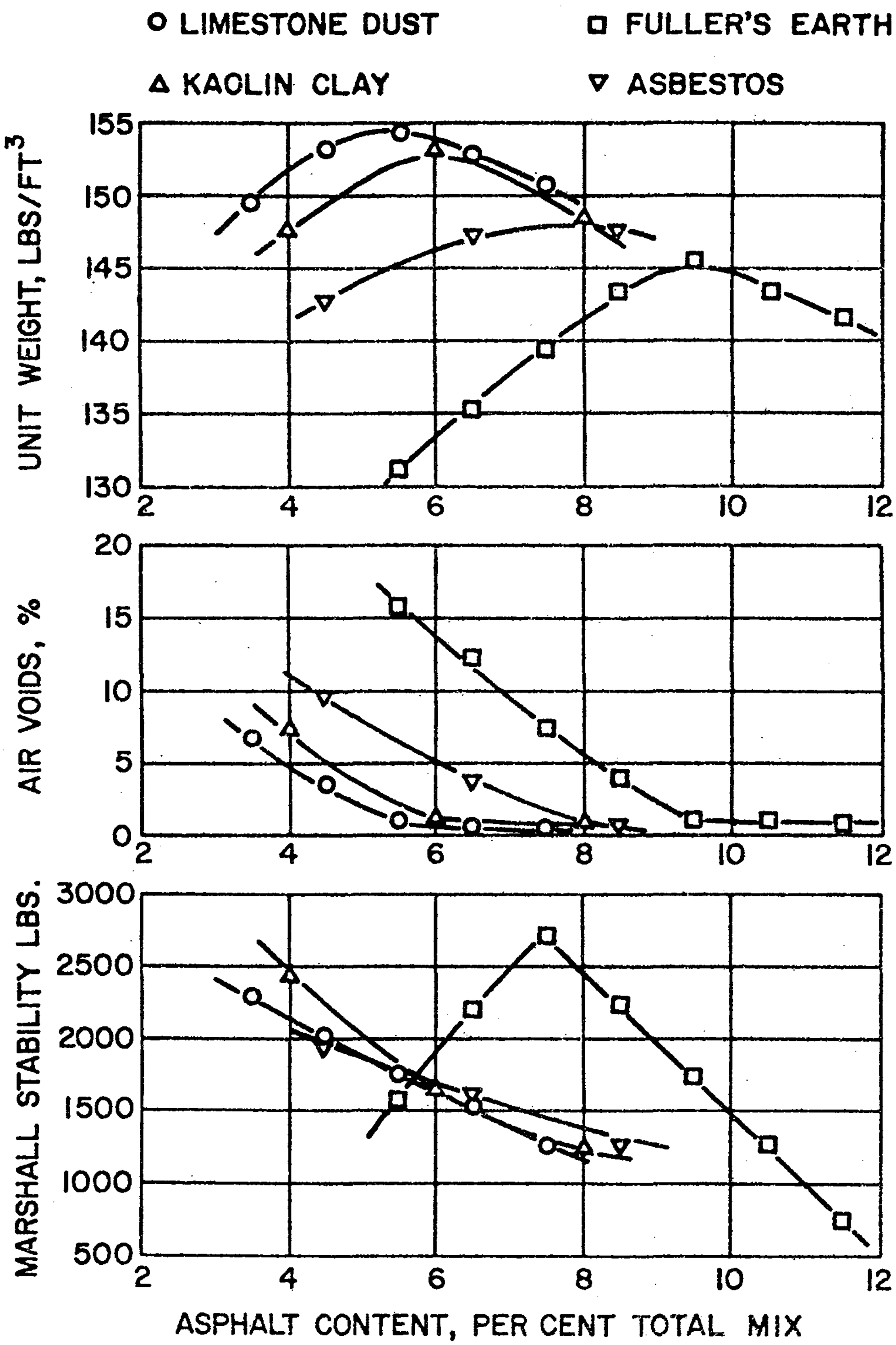


Figure 5. Effect of Various Fillers on Marshall Design Properties of Asphalt Concrete. (After Reference 3)

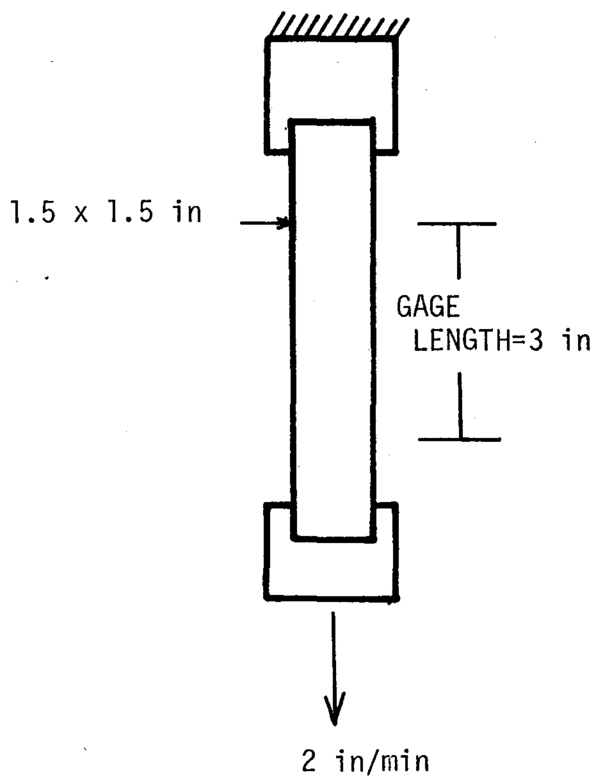


Figure 6. Direct Tension Test Apparatus.

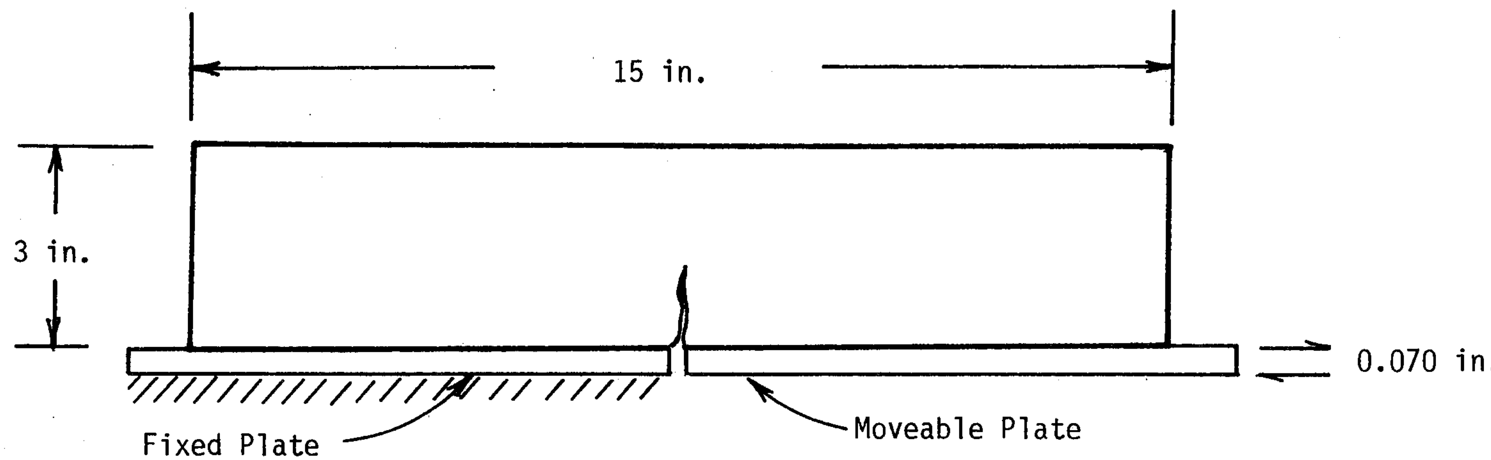


Figure 7. Schematic diagram of test specimen and TTI Overlay Tester.

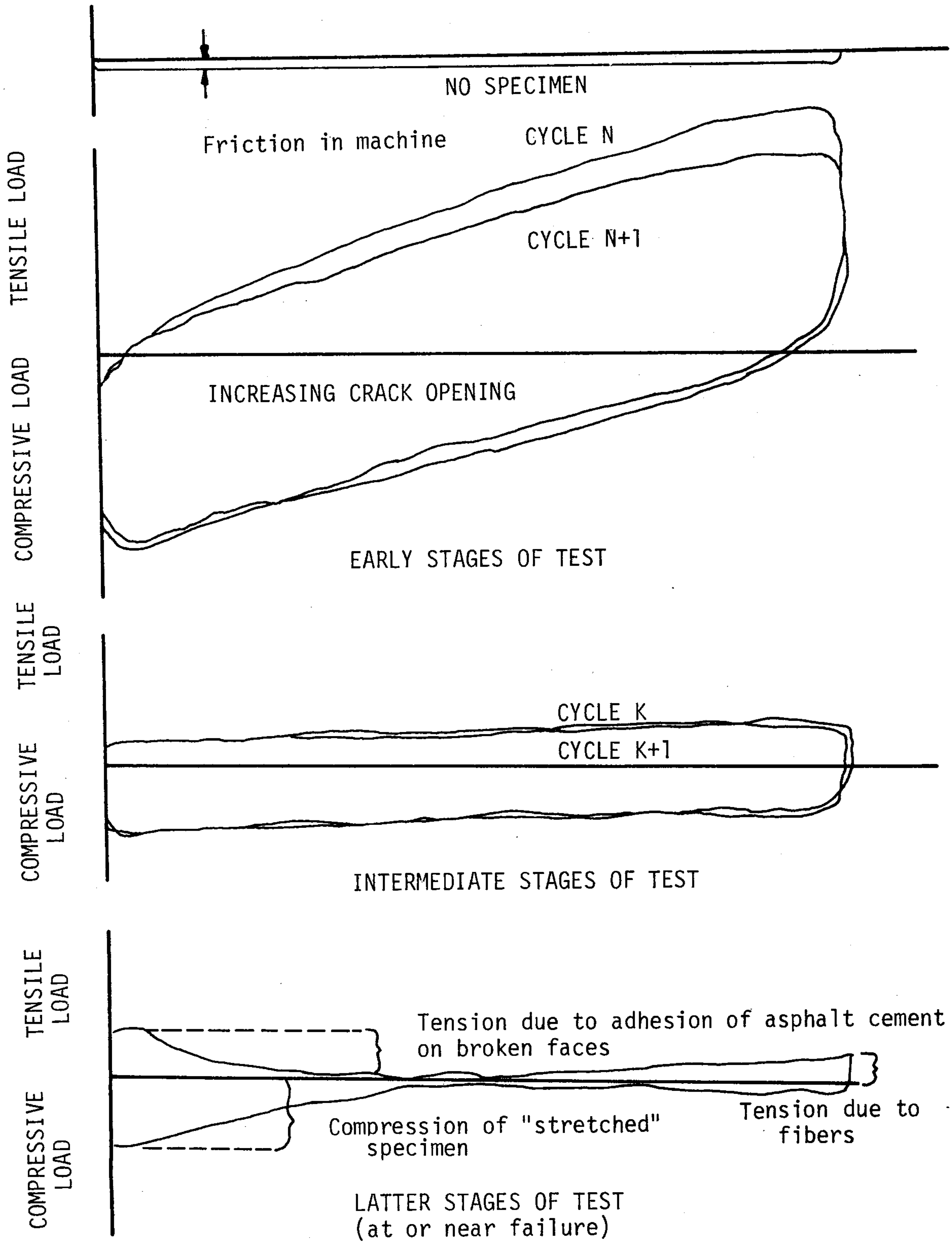


FIGURE 8. Typical Recordings of Load versus Deformation at Various Phases During a Test.

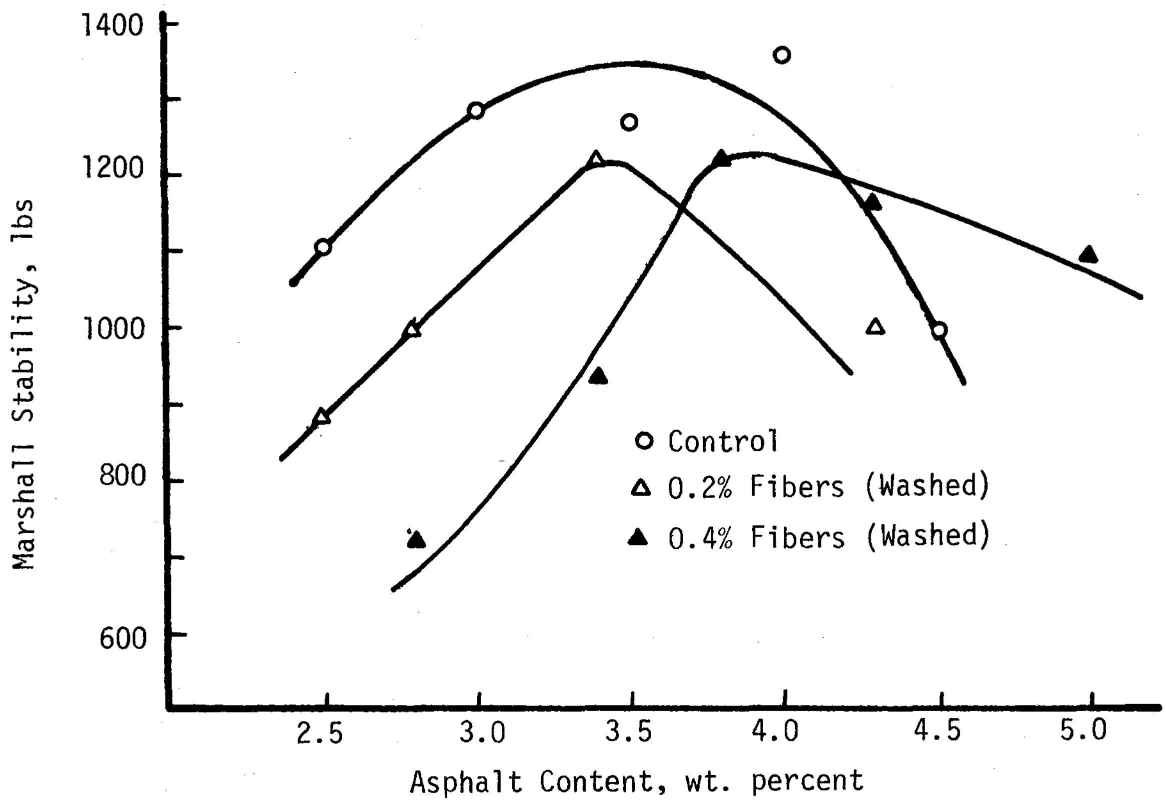


Figure 9. Marshall Stability as a Function of Asphalt Content of Marshall Specimens (15 x 10 Fibers).

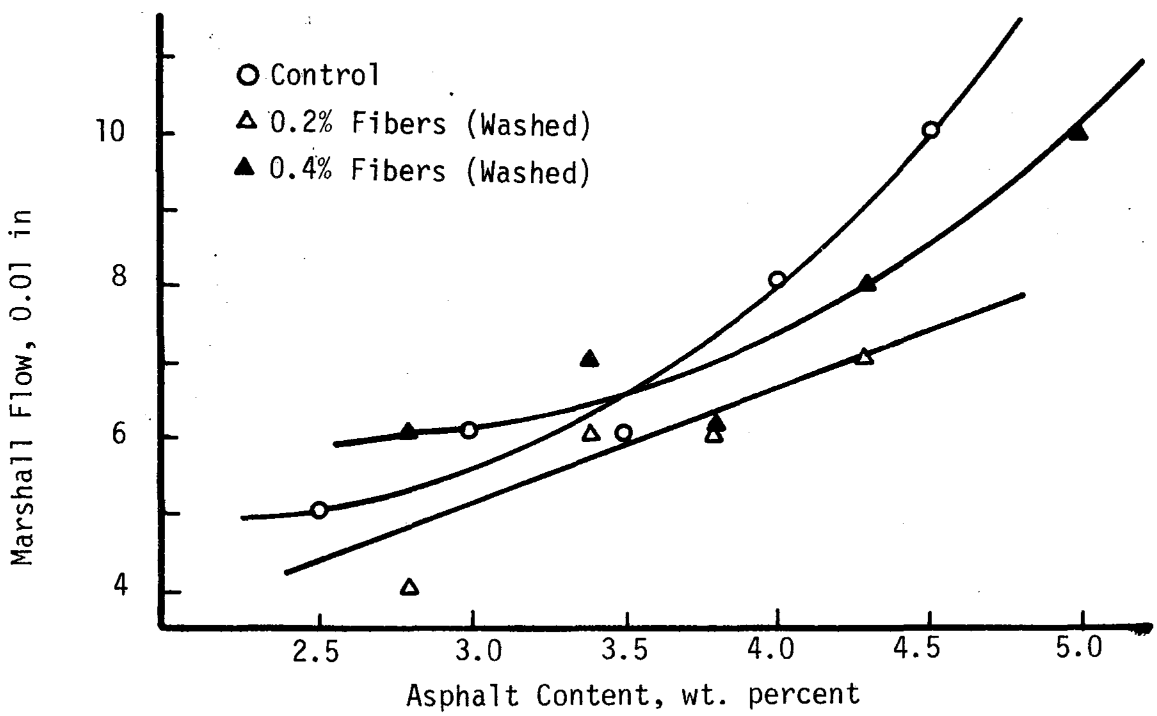


Figure 10. Marshall Flow as a Function of Asphalt Content of Marshall Specimens (15 x 10 Fibers).

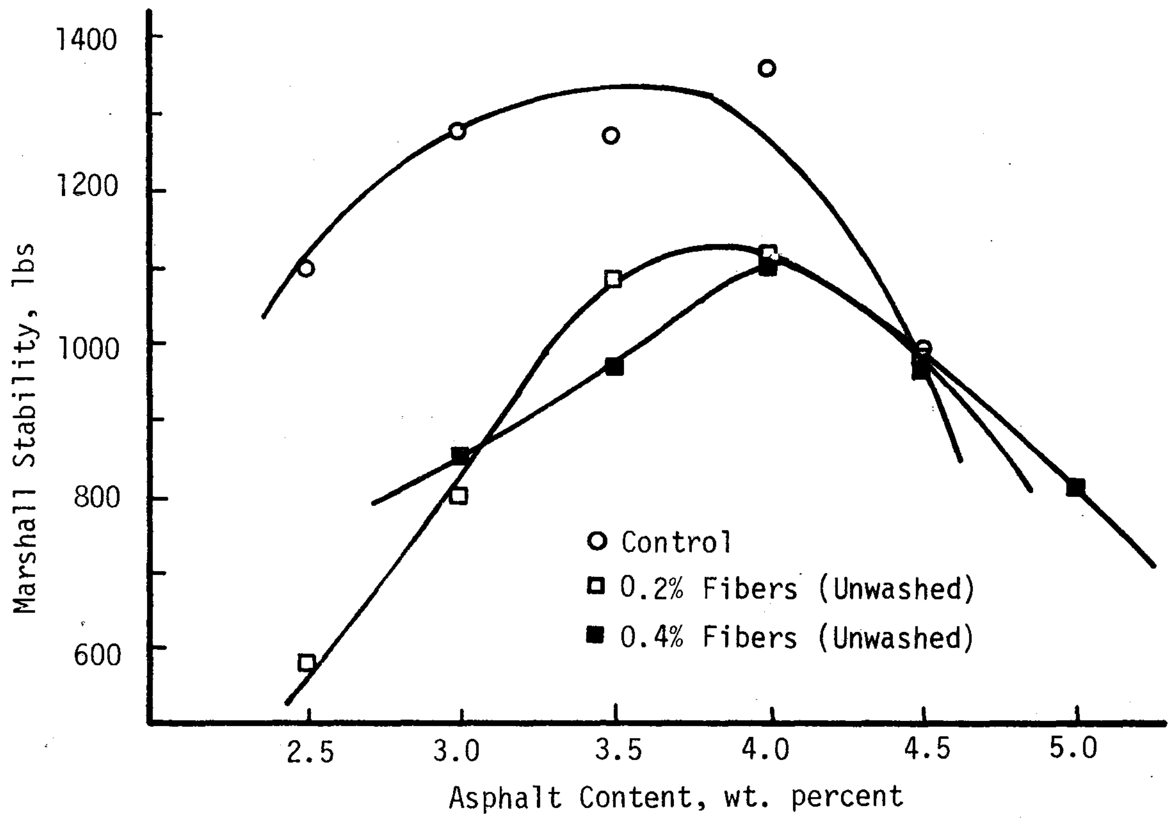


Figure 11. Marshall Stability as a Function of Asphalt Content of Marshall Specimens (15 x 10 Fibers).

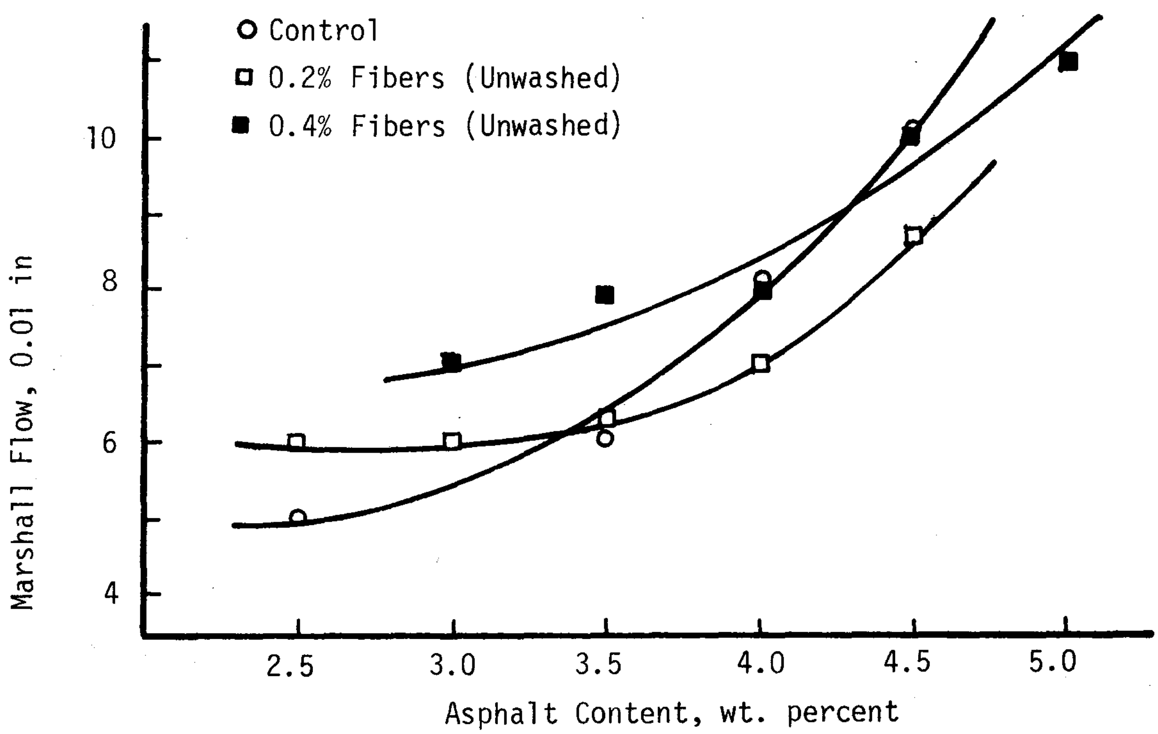


Figure 12. Marshall Flow as a Function of Asphalt Content of Marshall Specimens (15 x 10 Fibers).

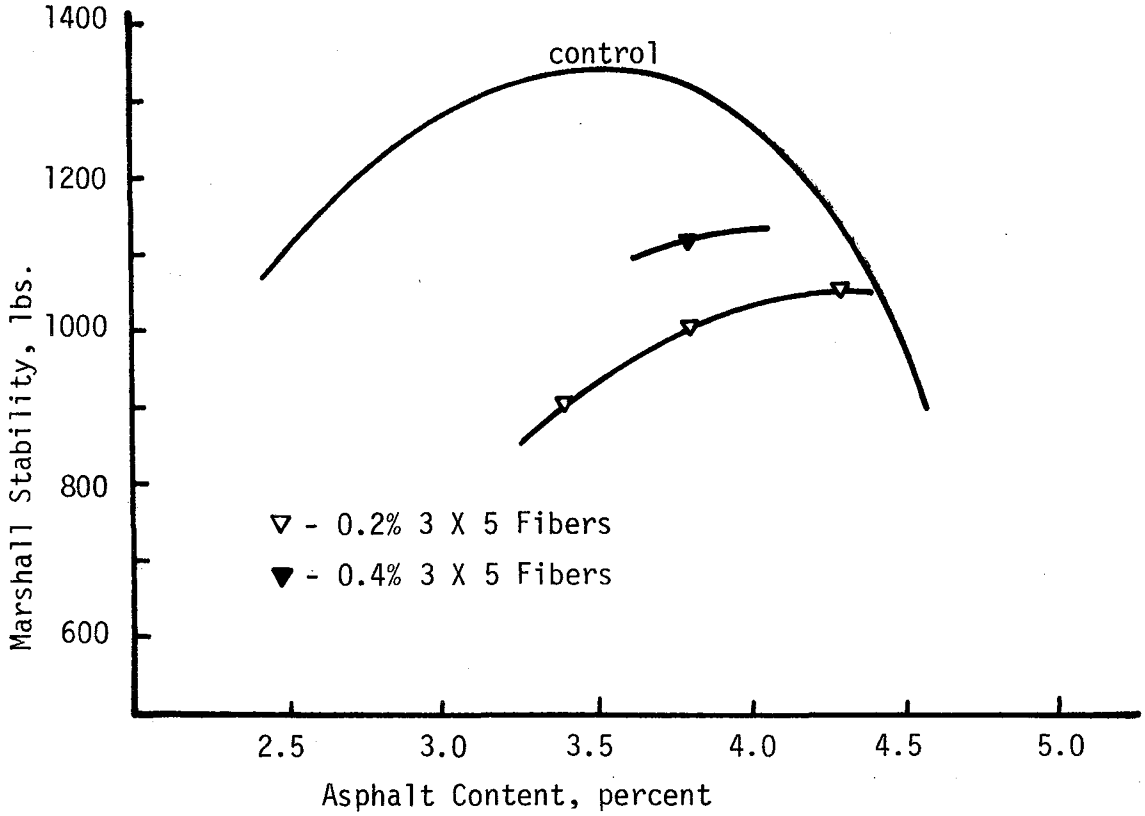


Figure 13. Marshall Stability vs. Asphalt Content for Specimens Containing 3 X 5 Fibers

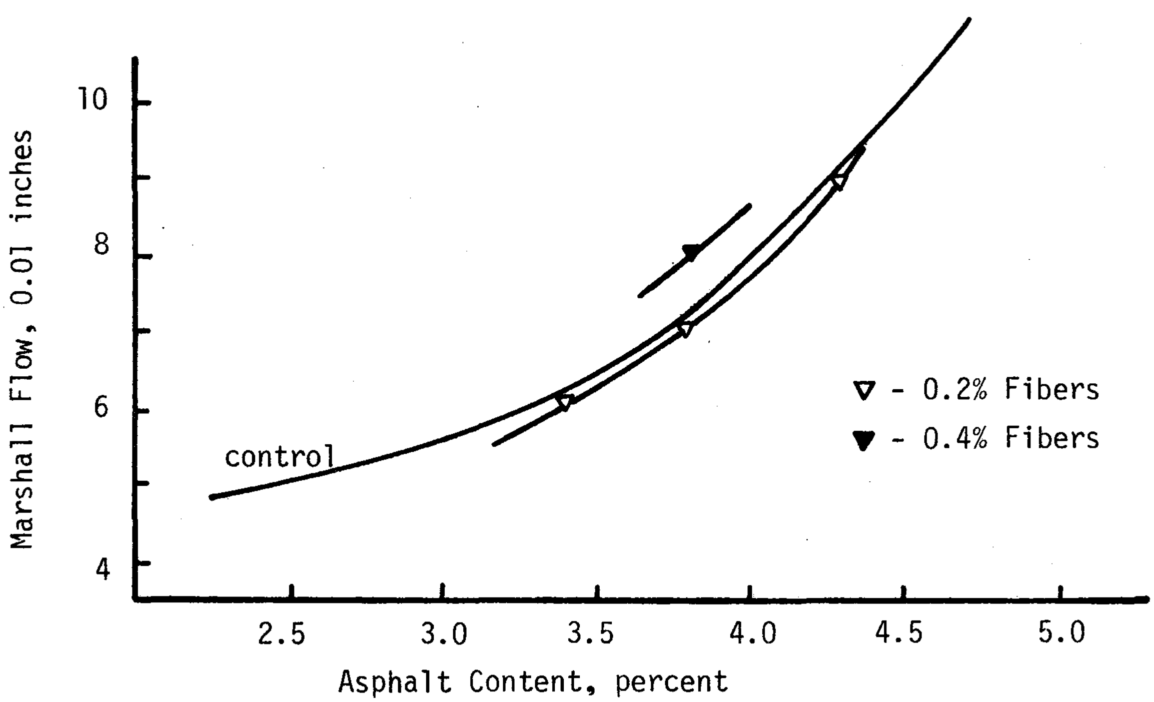


Figure 14. Marshall Flow vs. Asphalt Content for Specimens Containing 3 X 5 Fibers.

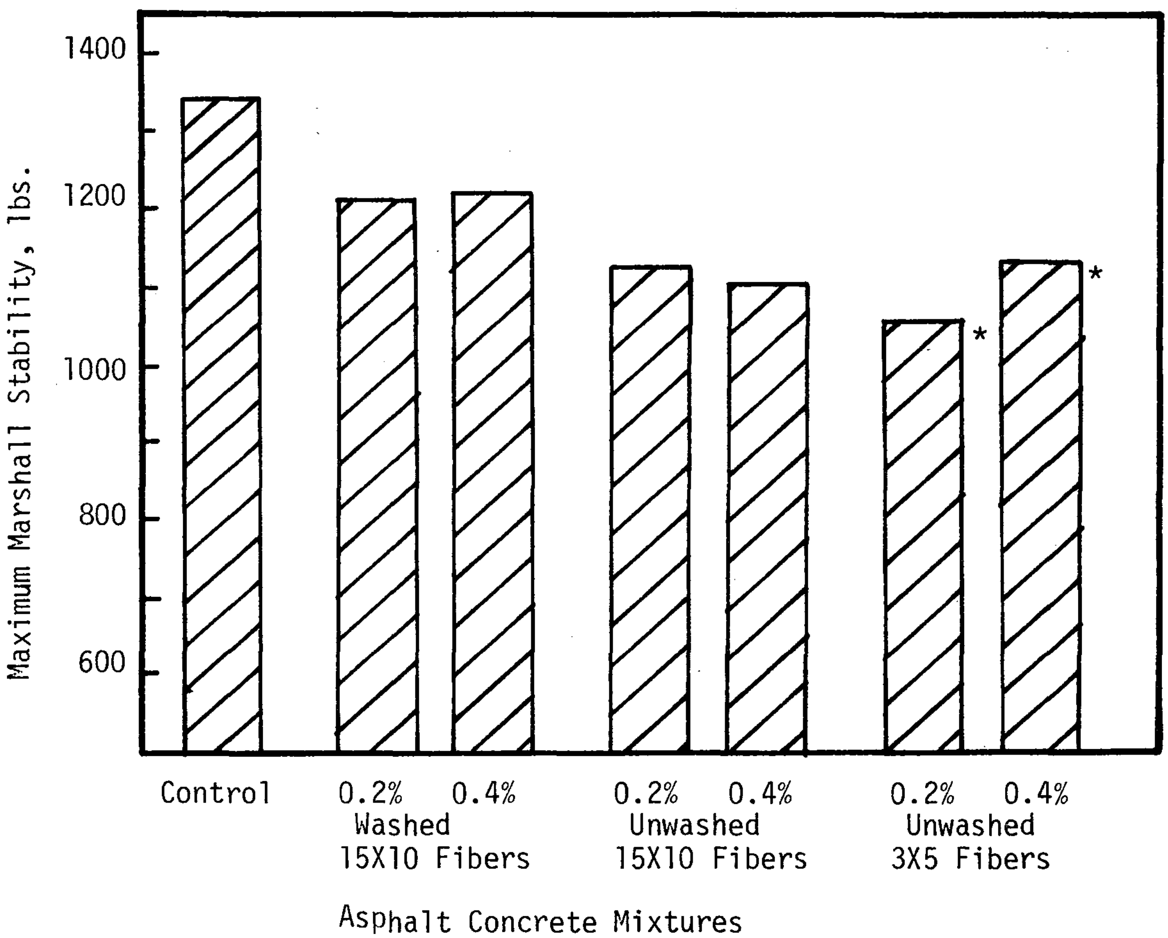


Figure 15. Maximum Marshall Stability for the Seven Different Asphalt paving Mixtures

*These values are estimated based on data not sufficient to define the maxima.

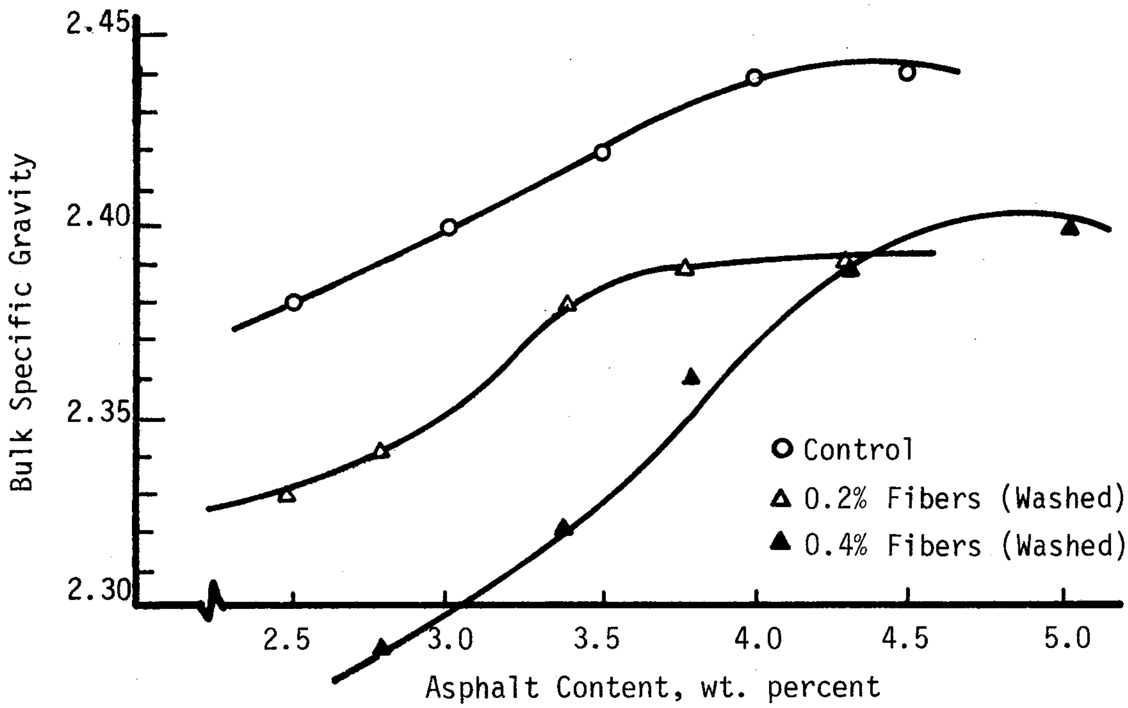


Figure 16. Bulk Specific Gravity as a Function of Asphalt Content of Marshall Specimens (15 x 10 Fibers).

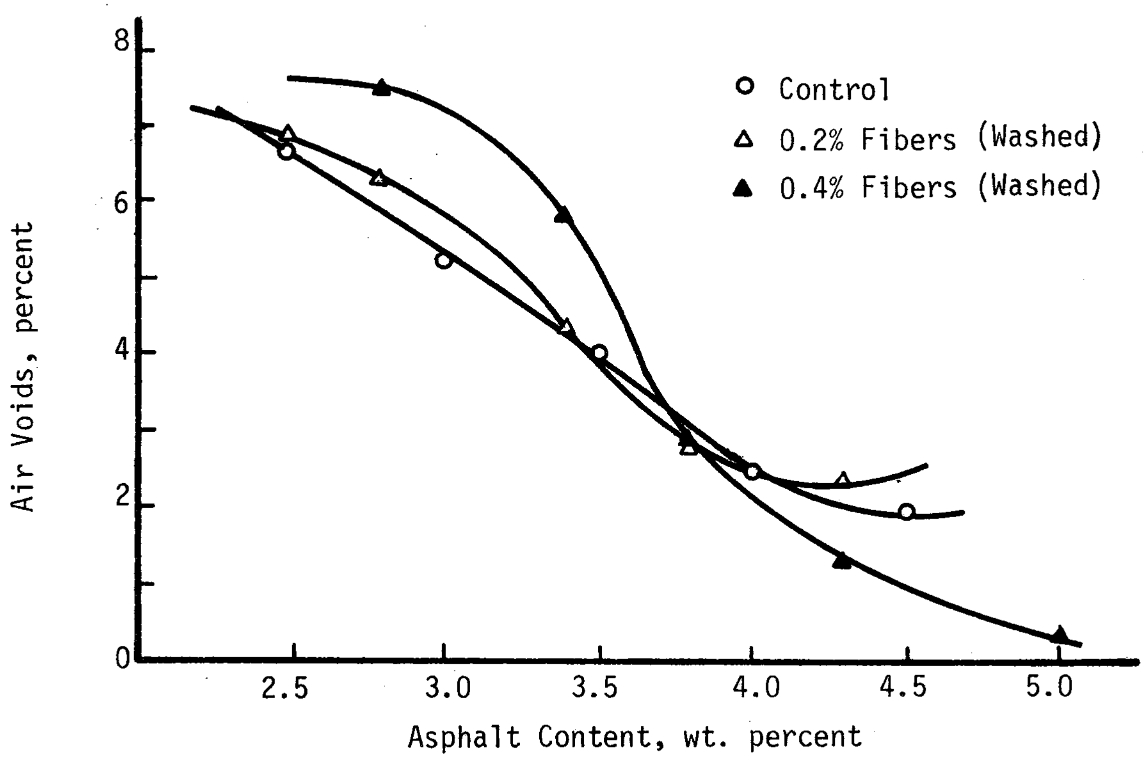


Figure 17. Air Voids as a Function of Asphalt Content of Marshall Specimens (15 x 10 Fibers).

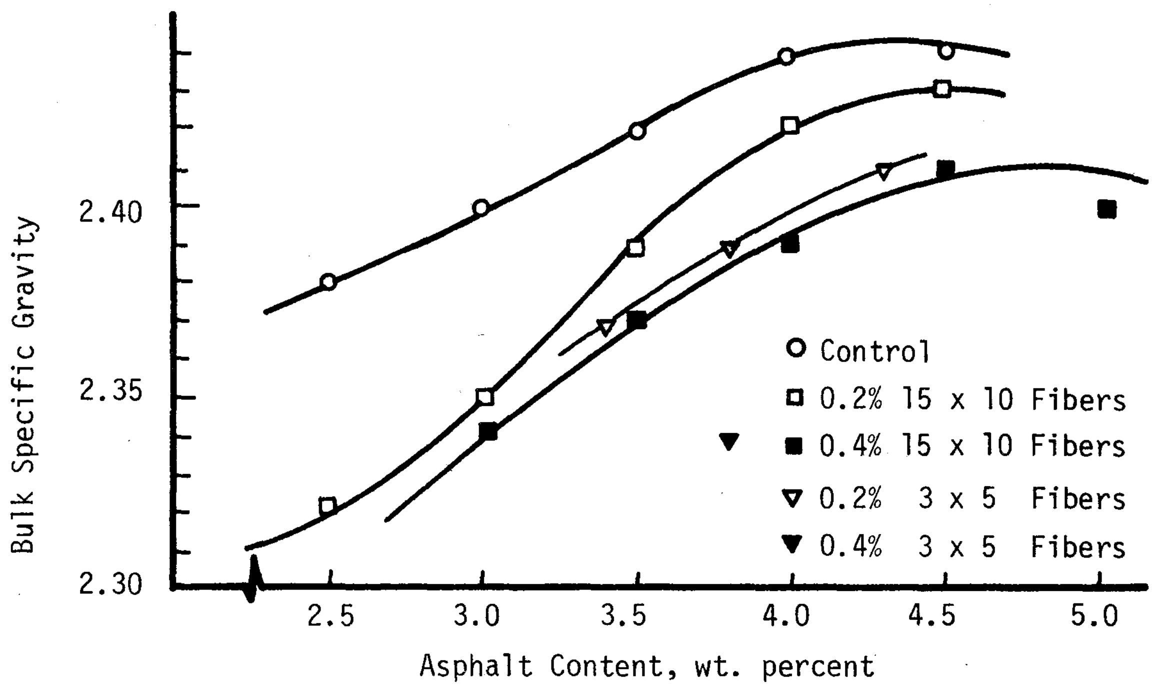


Figure 18. Bulk Specific Gravity as a Function of Asphalt Content of Marshall Specimens With and Without Unwashed Fibers.

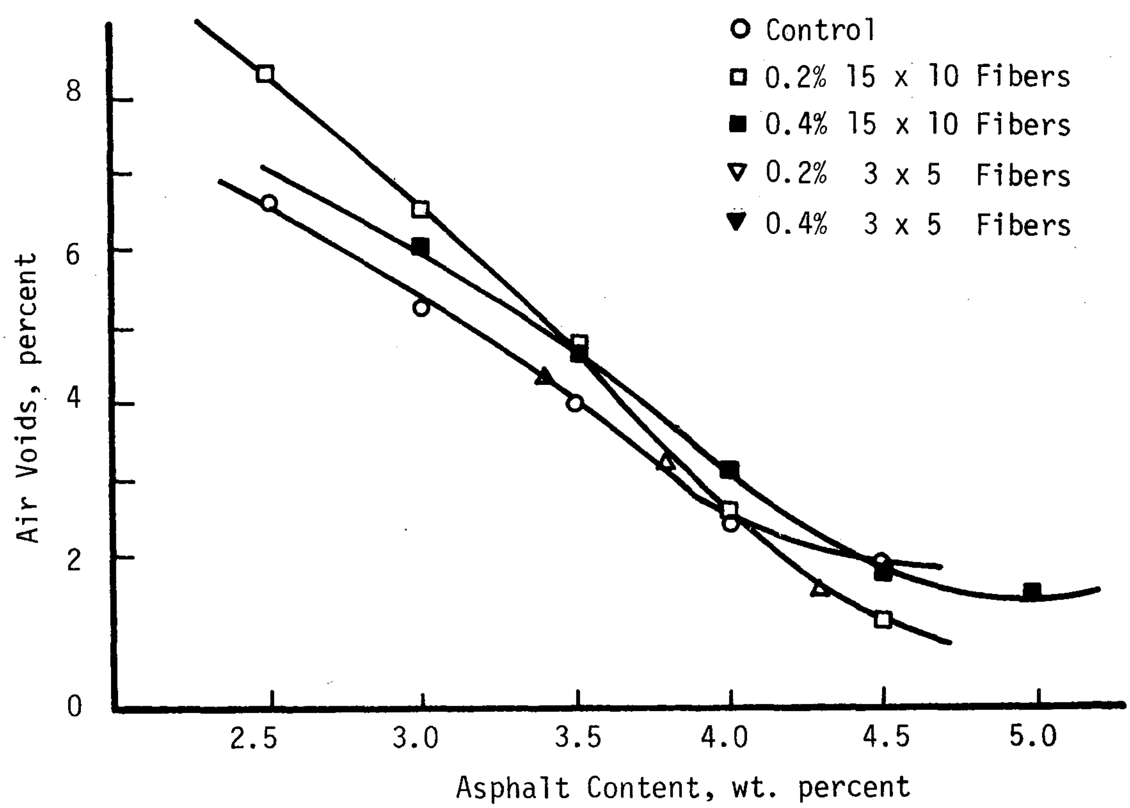


Figure 19. Air Voids as a Function of Asphalt Content of Marshall Specimens With and Without Unwashed Fibers.

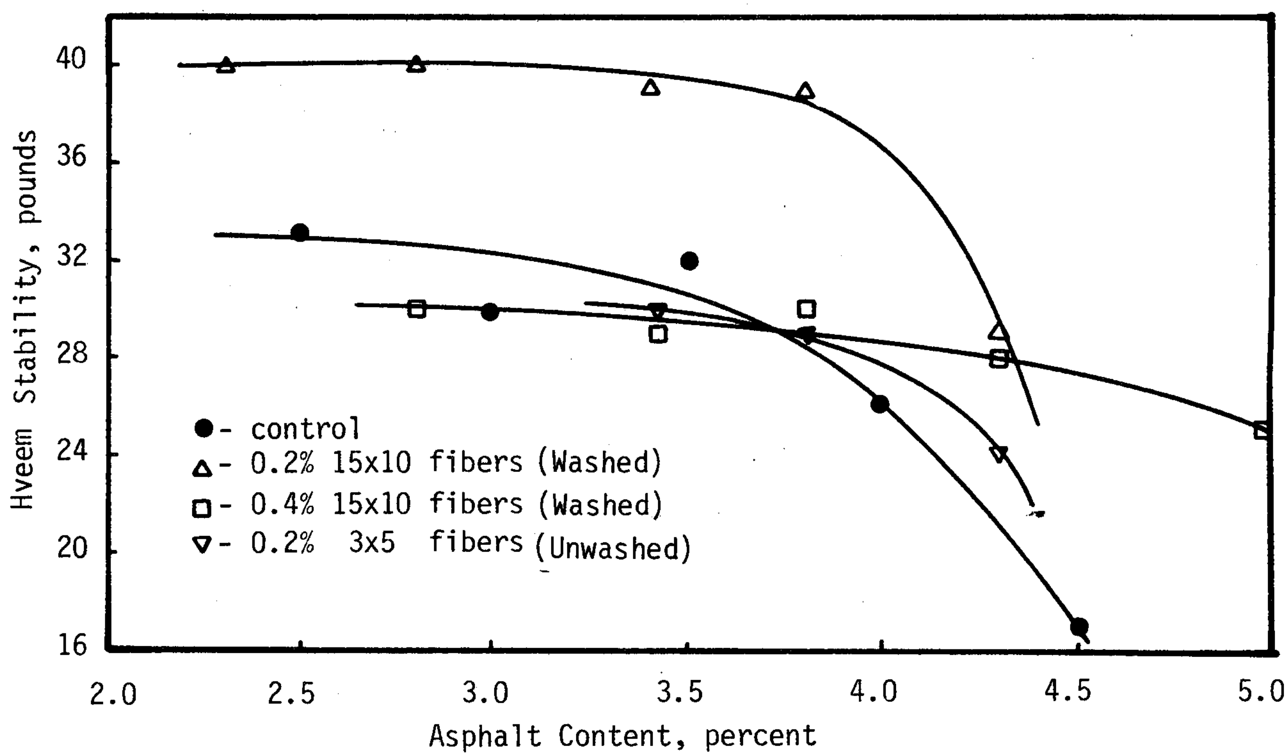


Figure 20. Hveem Stability as a Function of Asphalt Content for Gyratory Compacted Specimens.

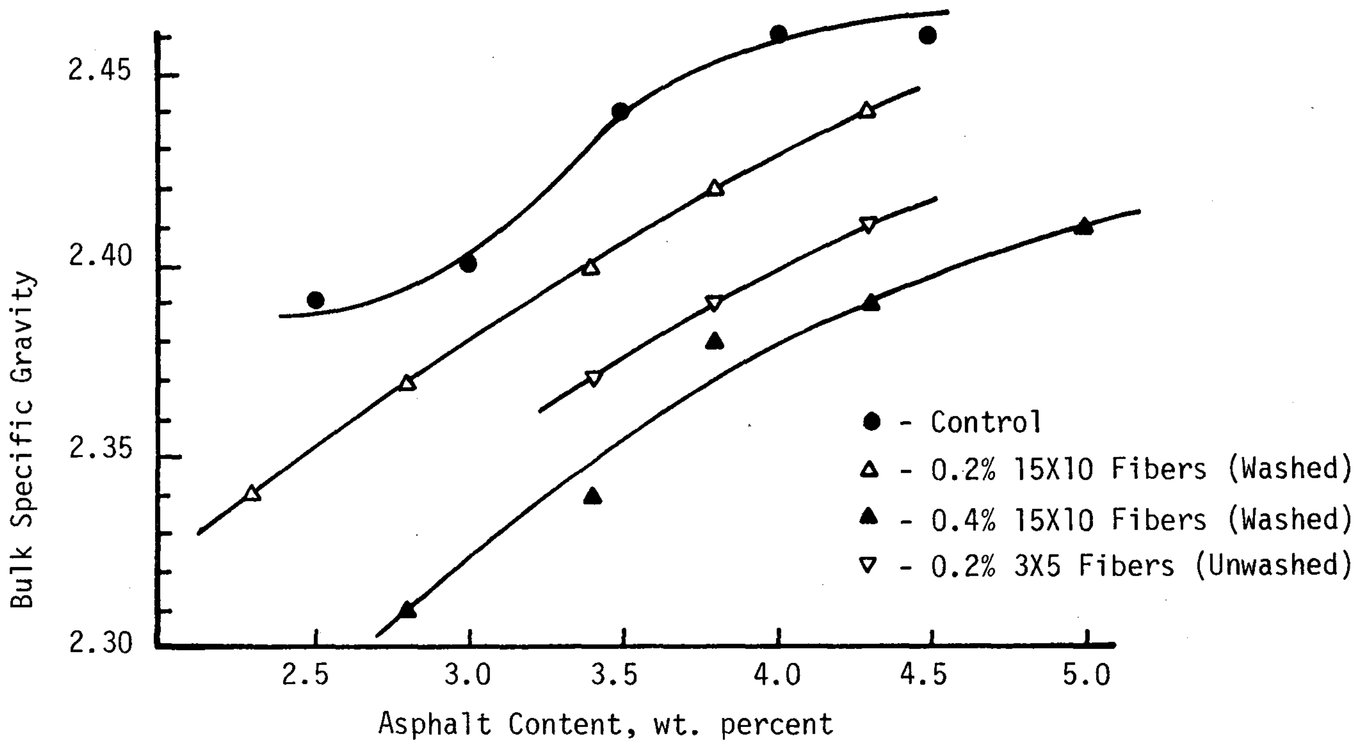


Figure 21. Bulk Specimen Gravity as a Function of Asphalt Content of Gyratory Compacted Specimens.

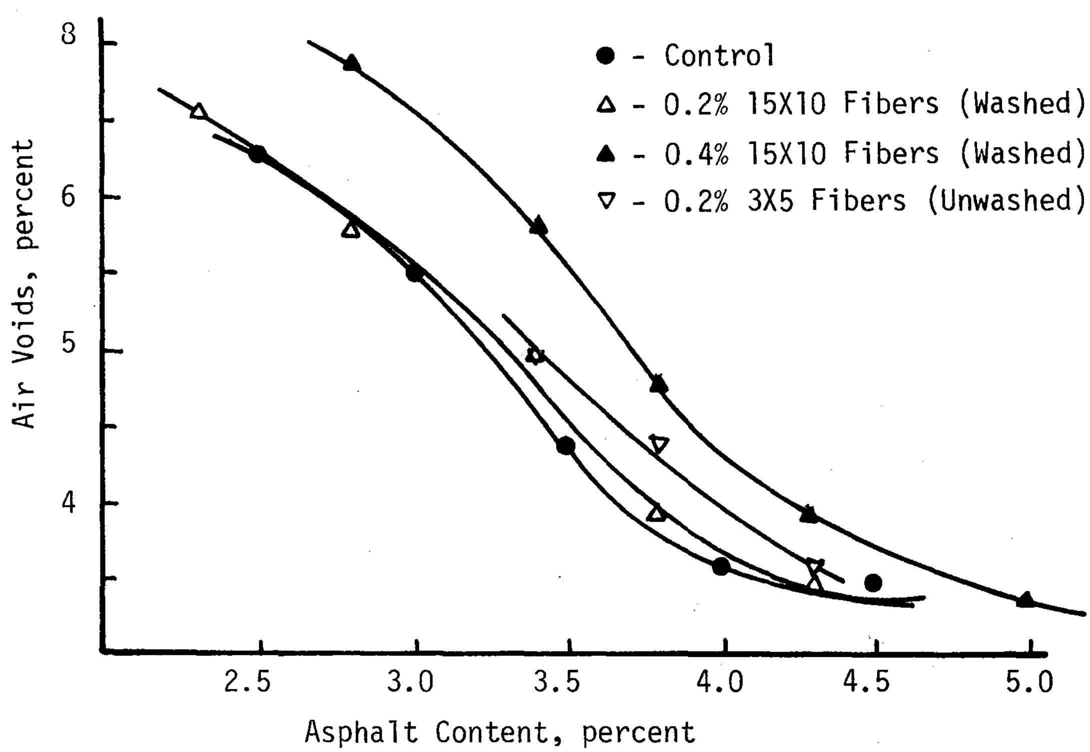


Figure 22. Air Void Content as a Function of Asphalt Content of Gyratory Compacted Specimens.

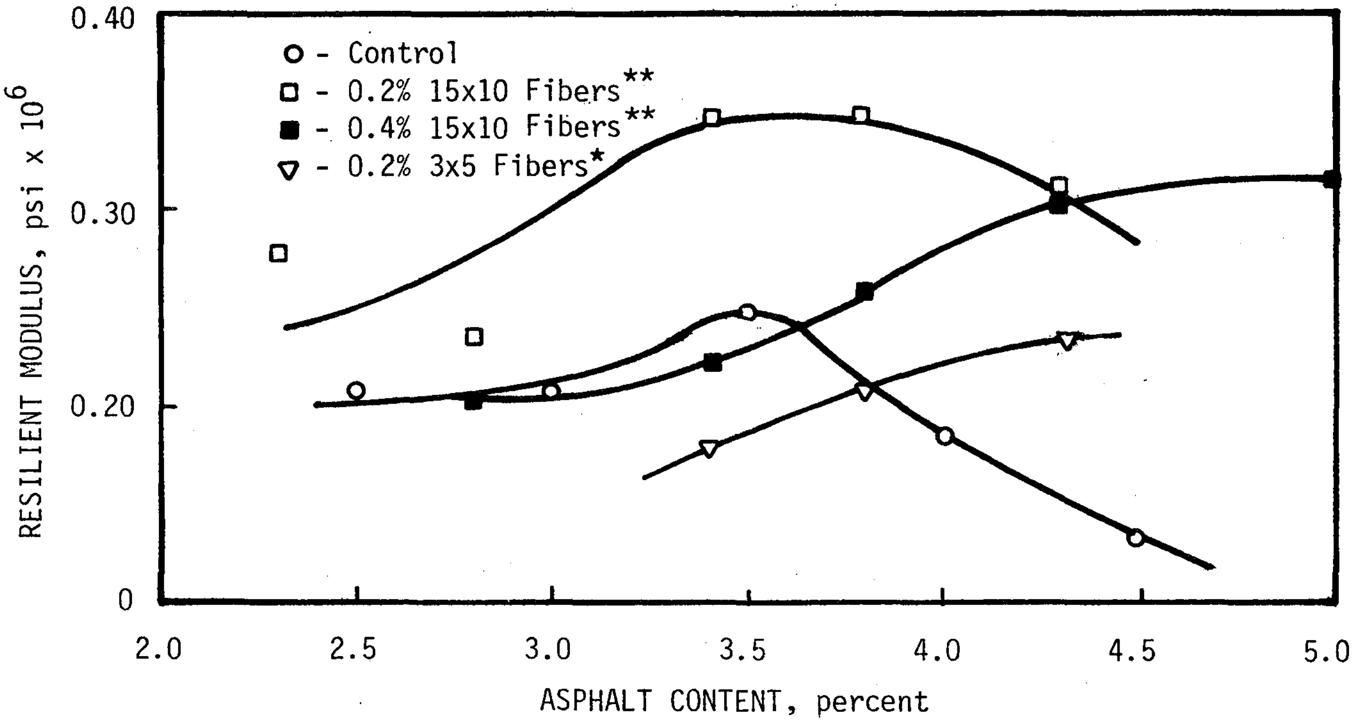


FIGURE 23. Resilient Modulus as a function of Asphalt Content of Gyratory Compacted Specimens.
*Unwashed
**Washed

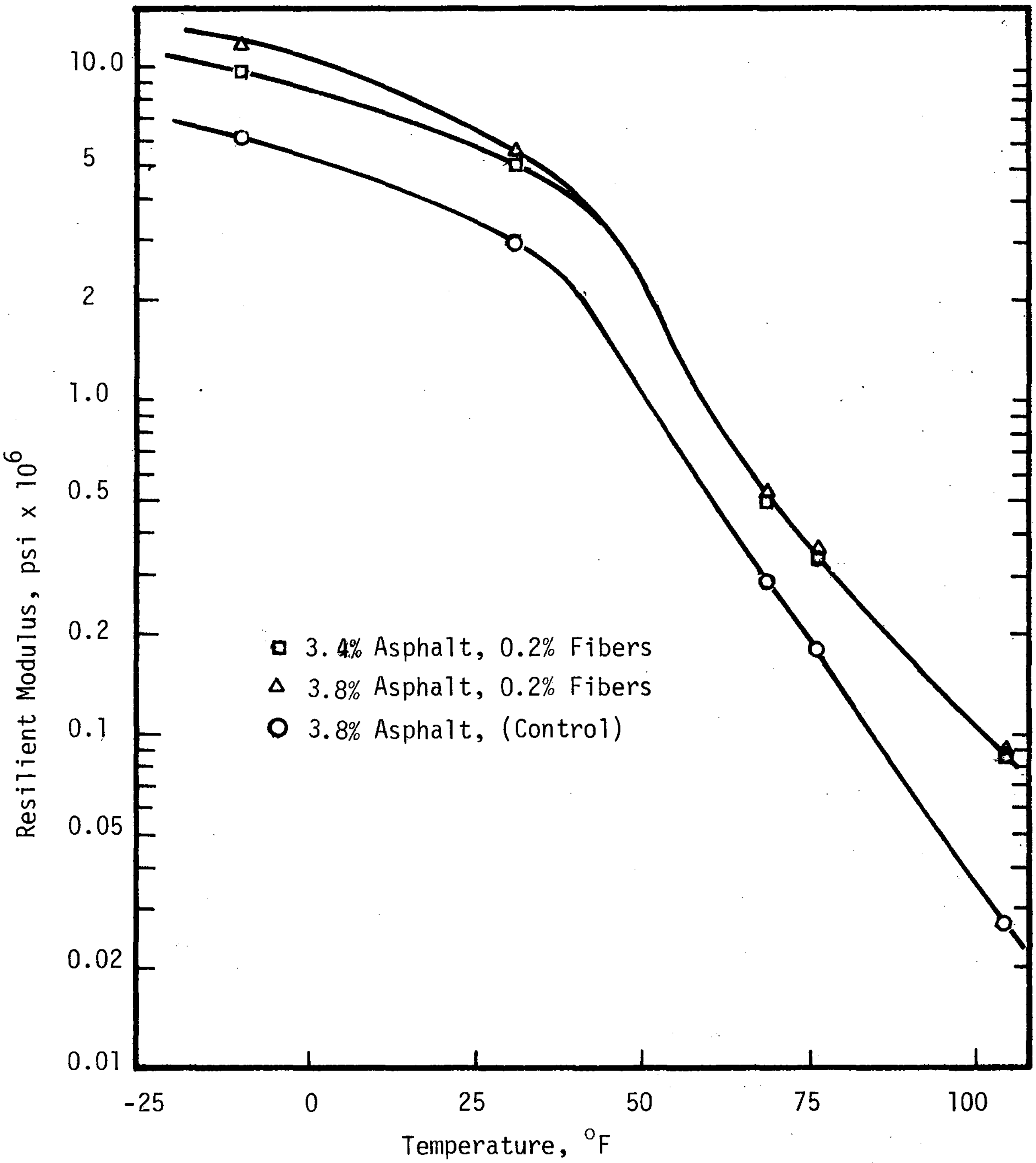


Figure 24. Resilient Modulus as a Function of Temperature for Specimens With and Without Washed 15 x 10 Fibers.

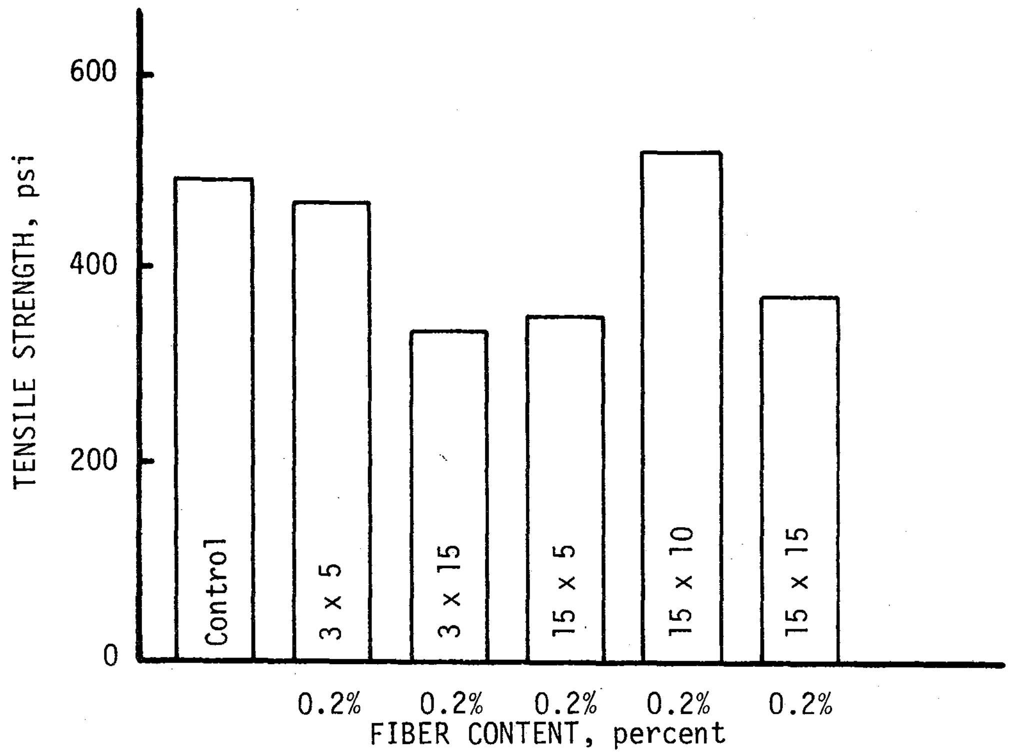


Figure 25. Tensile Strength of Specimens Tested at 2 in/min and 32°F.

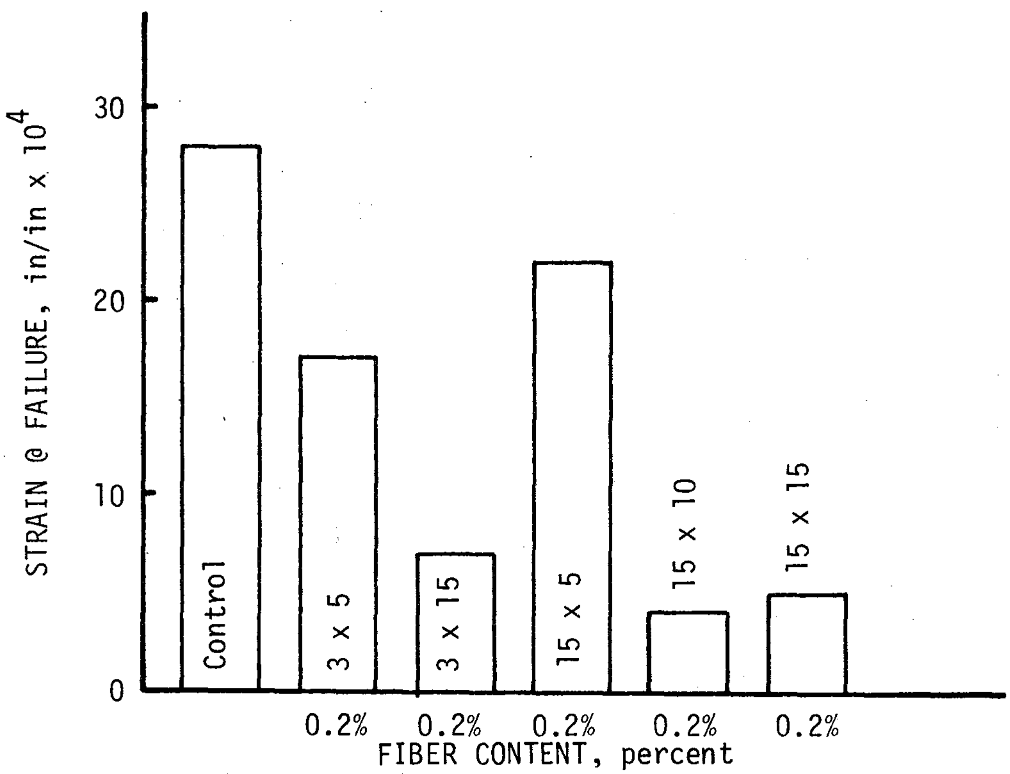


Figure 26. Tensile Strain at Failure of Specimens Tested at 2 in/min and 32°F.

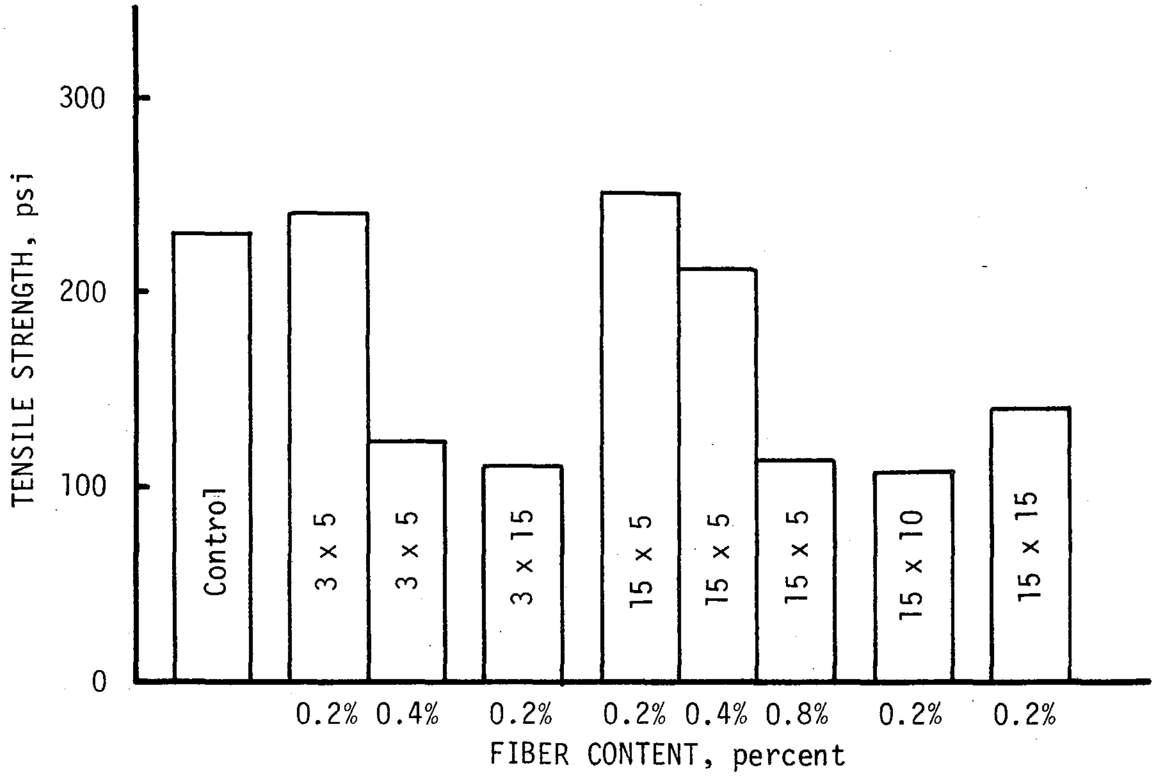


Figure 27. Tensile Strength of Specimens Tested at 0.02 in/min and 32°F.

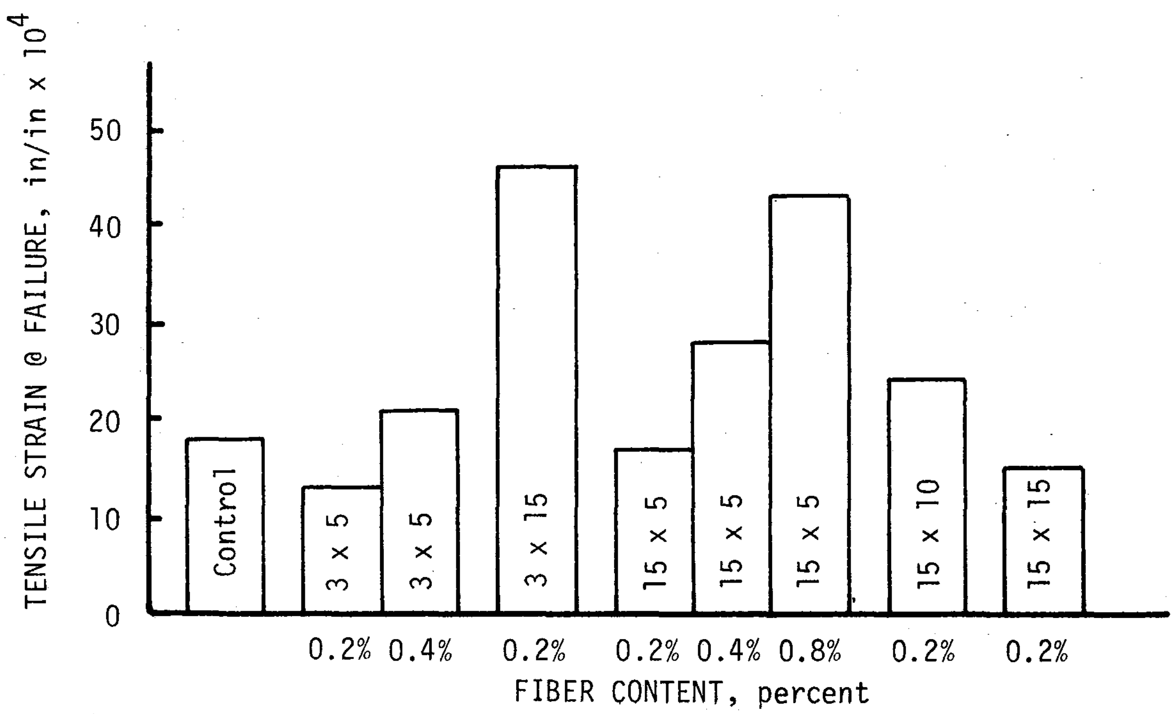


Figure 28. Tensile Strain at Failure of Specimens Tested at 0.02 in/min and 32°F.

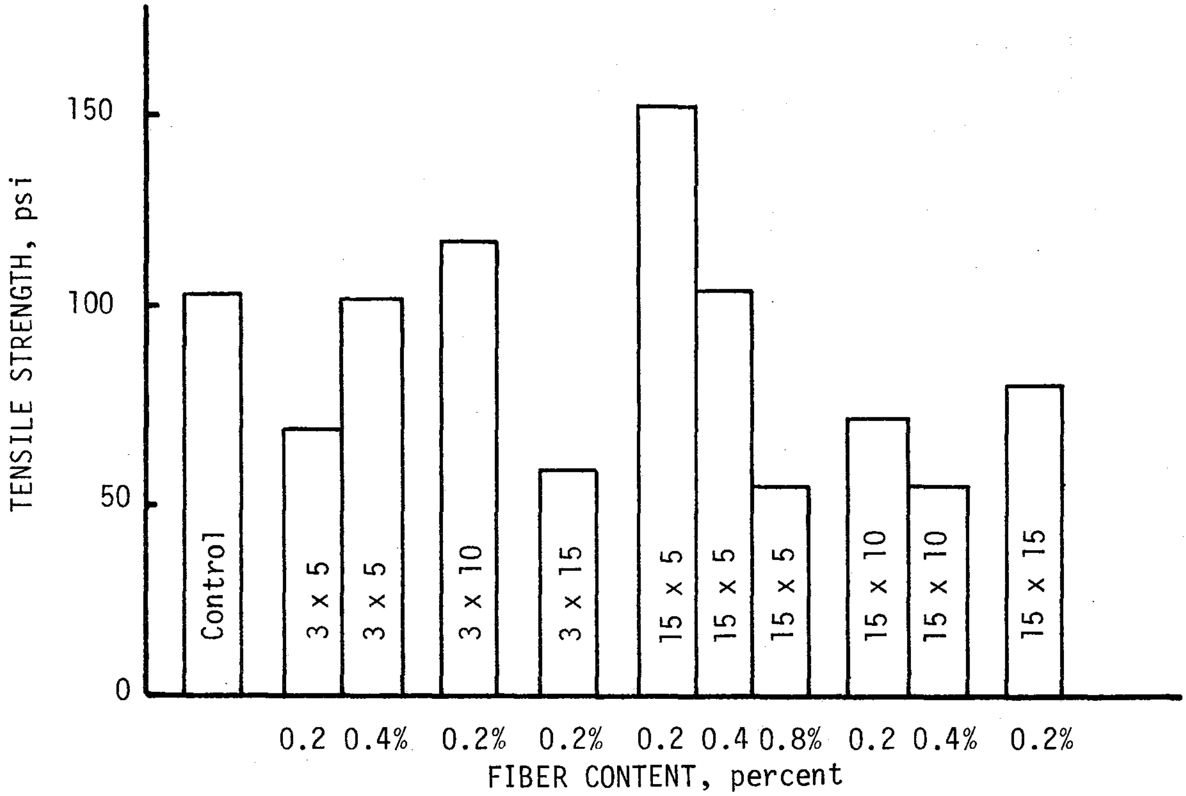


Figure 29. Tensile Strength of Specimens Tested at 0.002 in/min and 32°F.

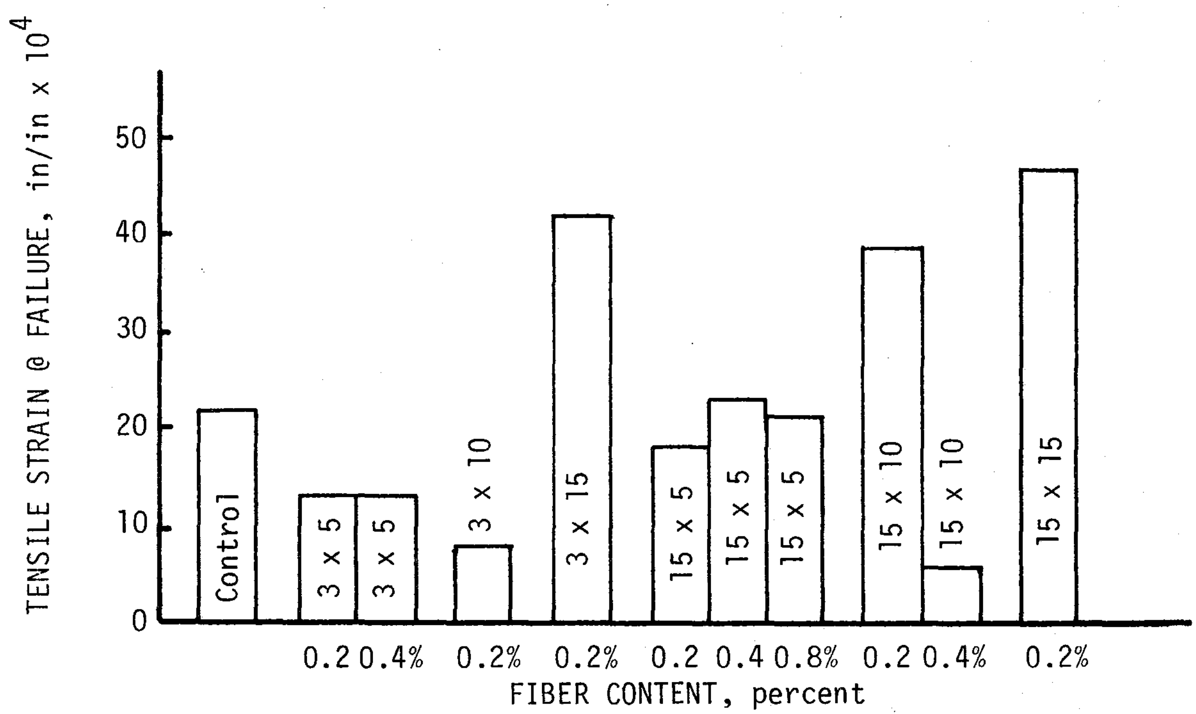


Figure 30. Tensile Strain at Failure of Specimens Tested at 0.002 in/min and 32°F.

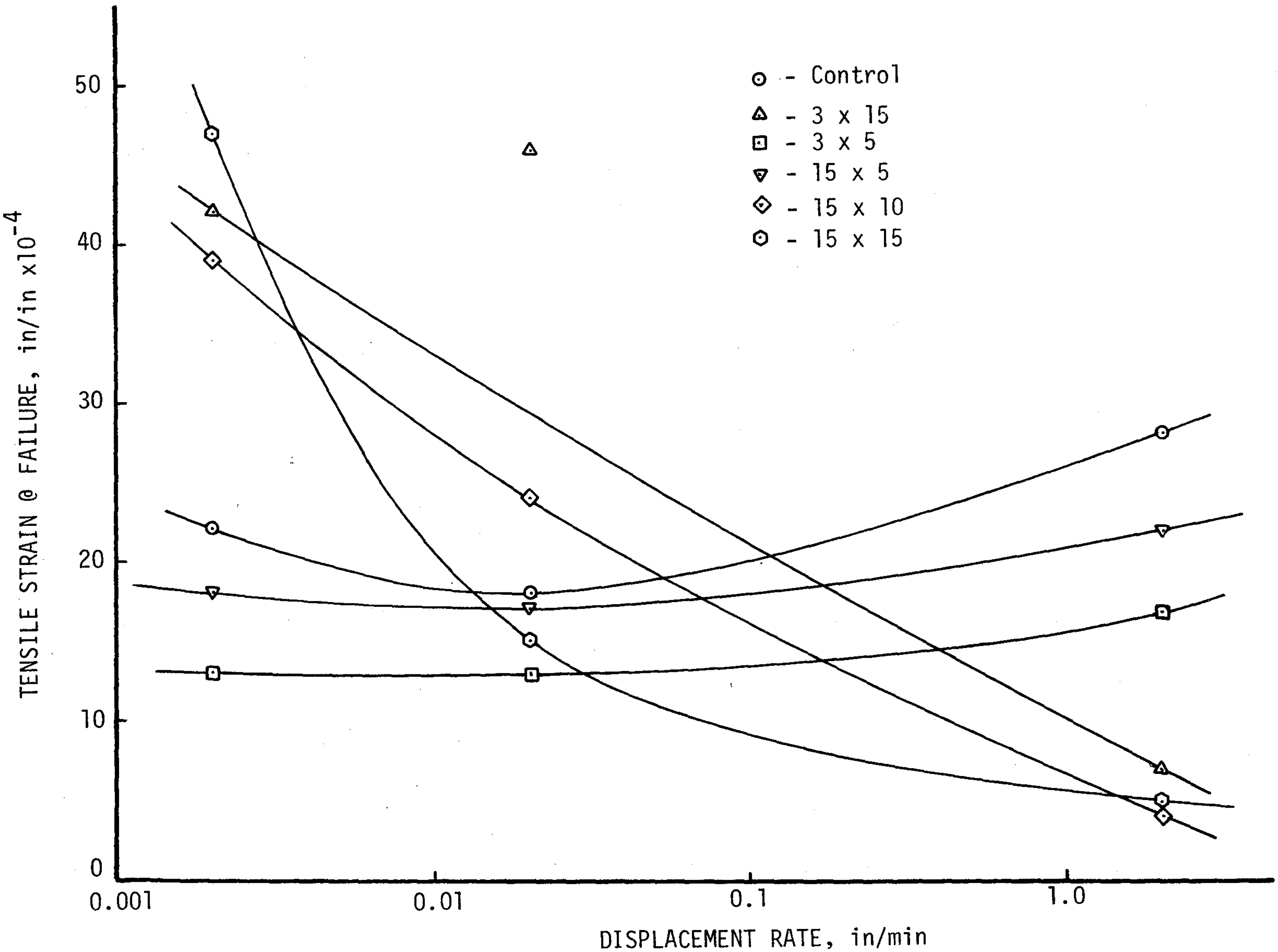


FIGURE 31. Tensile Strain at Failure of Specimens Containing 0.2 Percent Fibers as a Function of Displacement Rate

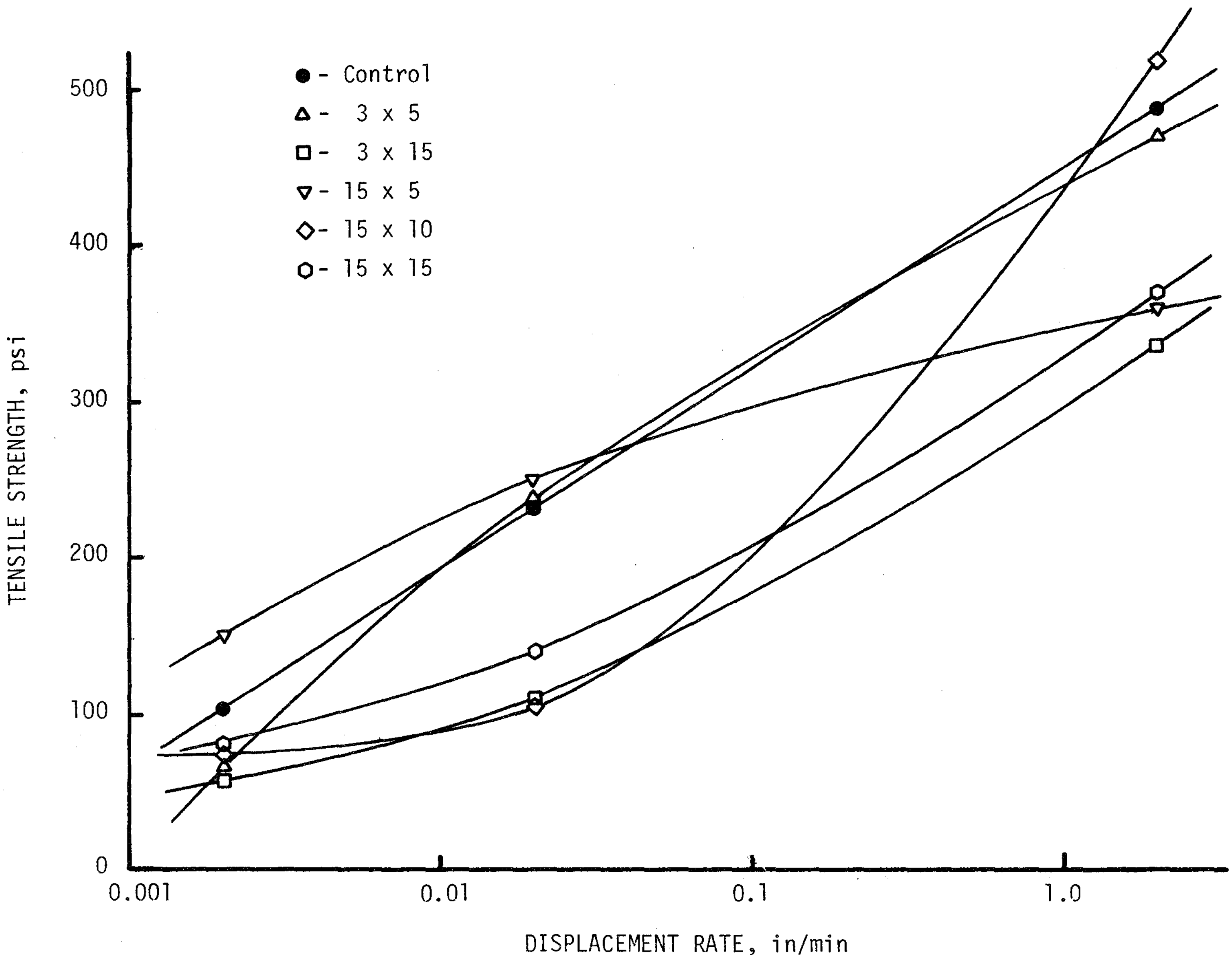


Figure 32. Tensile Strength of Specimens Containing 0.2 Percent Fibers as a Function of Displacement Rate.

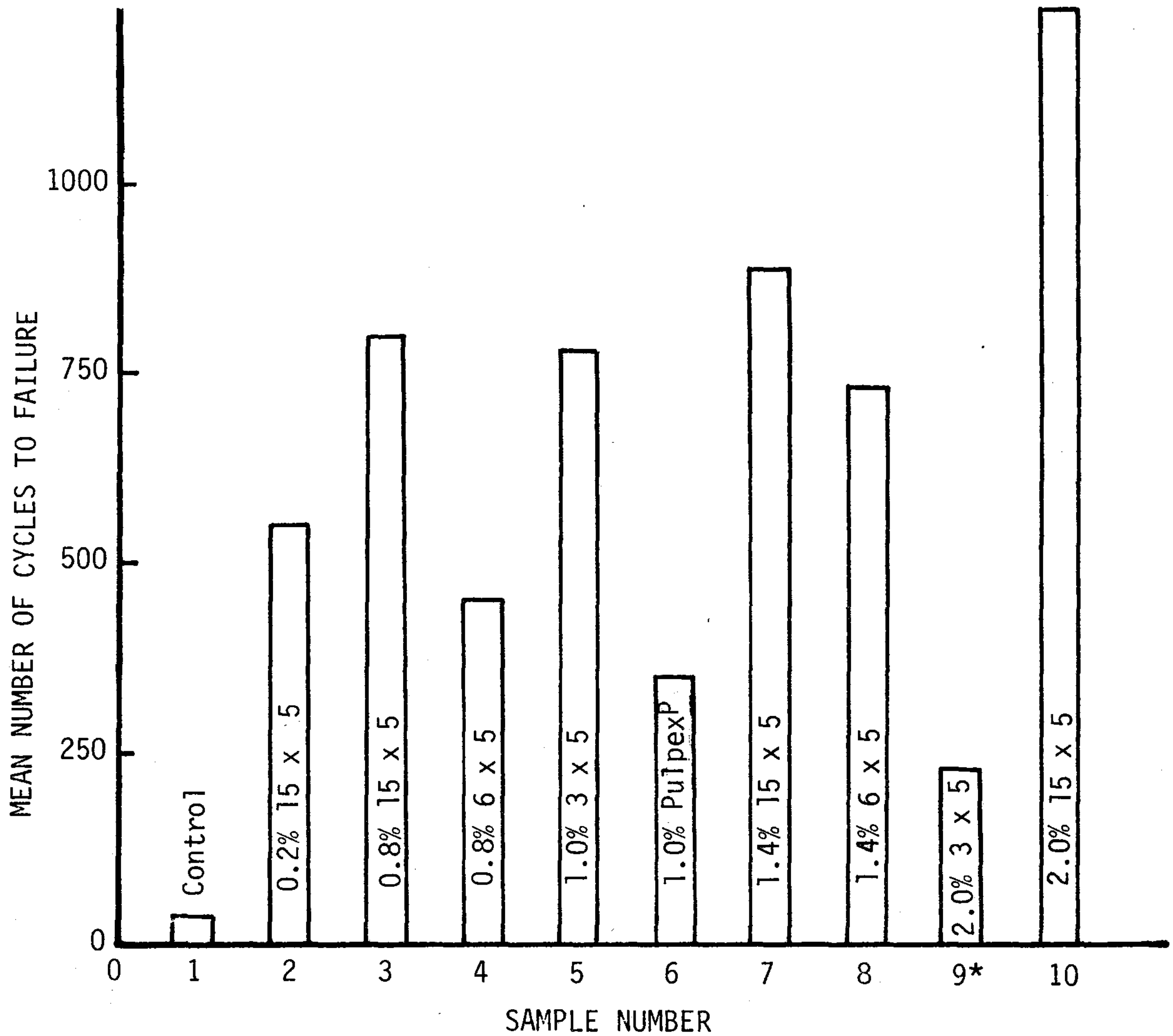


FIGURE 33. Mean Number of Cycles to Failure for Various Types of Overlay Specimens Tested at 77°F.

* Samples 9B, 9D, and 9E were shorter than all others which directly affected the number of cycles to failure. (See Table D1, Appendix D)

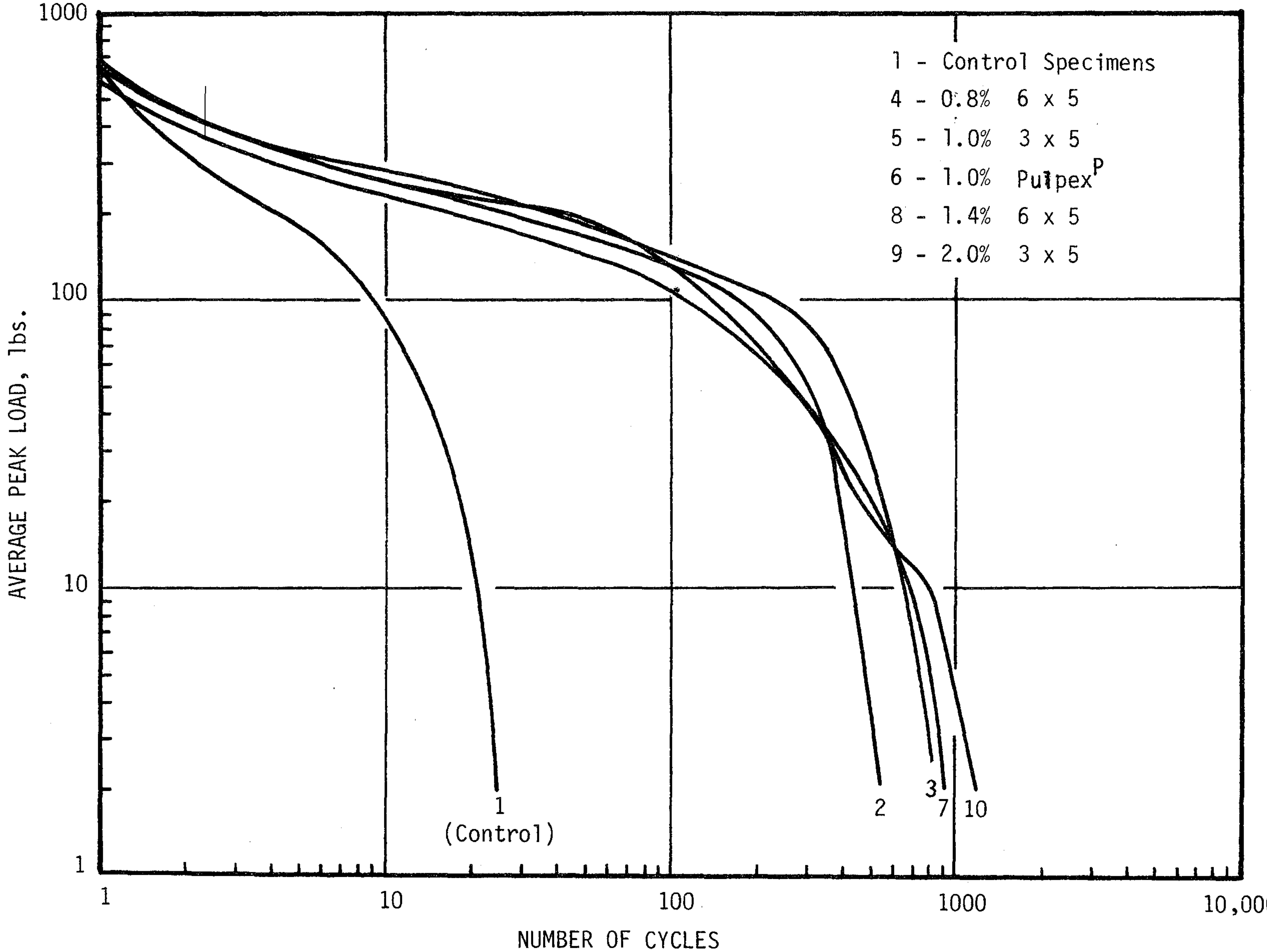


FIGURE 34. Average Peak Load Supported by Samples 1, 2, 3, 7 and 10 during the Overlay Test at 77°F.

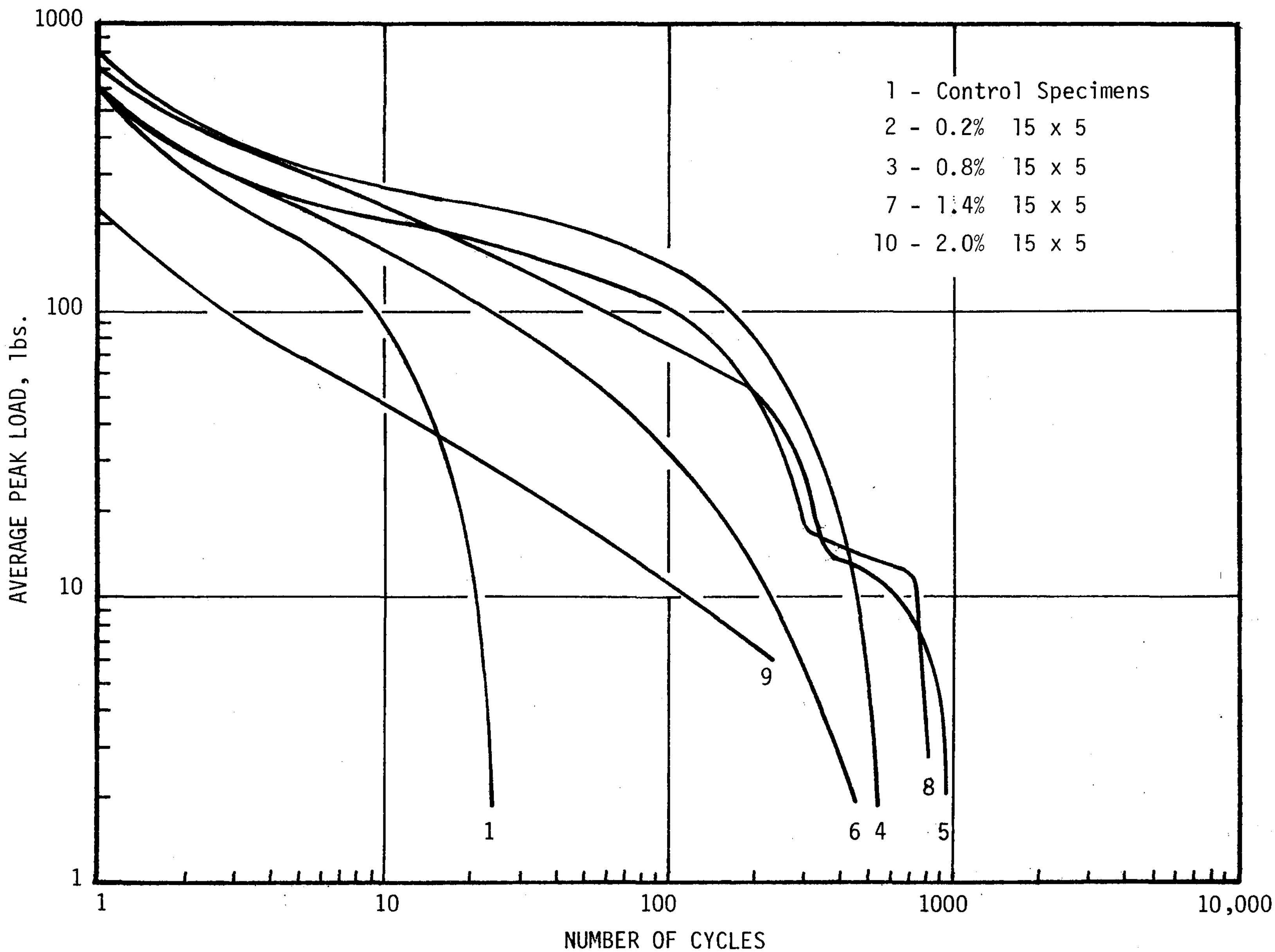
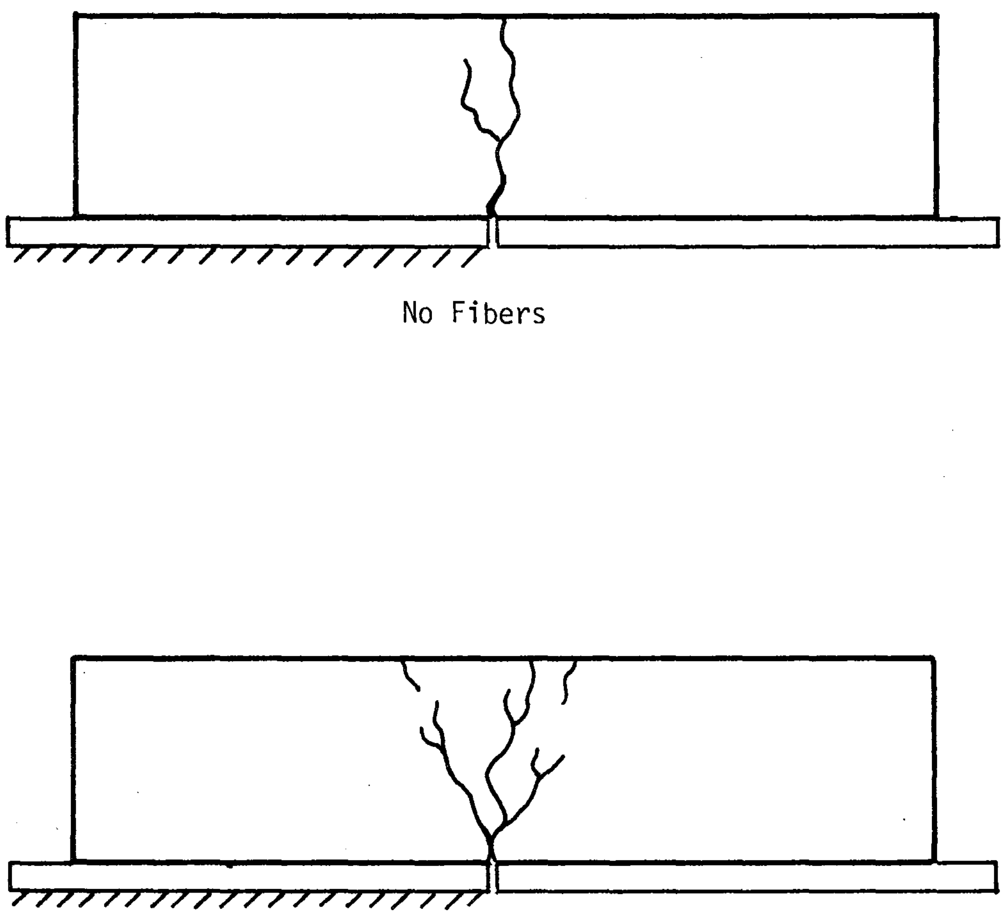


FIGURE 35. Average Peak Load Supported by Samples 1, 4, 5, 6, 8 and 9 during the Overlay Test at 77°F.



No Fibers

With Fibers

Figure 36. Typical Cracking Patterns of Overlay Test Specimens With and Without Fibers.

APPENDIX A

Materials Properties

Table A1. Asphalt Cement Properties

Asphalt Code	LS
Production Method	Vacuum Distribution
Viscosity, 77°F (25°C) poise	5.8×10^5
Viscosity, 140°F (60°C) poise	1580
Viscosity, 275°F (135°C) poise	3.8
Penetration, 77°F (25°C), dmm	118
Penetration, 60°F (16°C), dmm (100 gm @ 5 sec)	---
Penetration, 39.2°F (4°C), dmm (100 gm @ 5 sec	4
Penetration, 39.2°F (4°C), dmm (200 gm @ 60 sec)	26
Soft. Point, R & B, °F (°C)	107 (42)
Specific Gravity, 77°F (25°C)	1.02
Ductility, 77°F (25°C, cm)	150+
Solub., (CH Cl:CCL_2), %	99.99
Spot Test	Pos.
Flash Point, °F (°C)	615 (324)
Fire Point, °F (°C)	697 (370)
Thin Film Oven Test	
Pen. of Residue, 77°F (25°C), dmm	68
Duct. of Residue, 77°F (25°C), cm	150+
Vis. of Residue, 140°F (60°C), p	3050
Loss of Heating	Neg.
Hardening Index (due to Actinic light)	1.9
Vanadium Content, ppm	3.4

Table A2. Physical Properties of Aggregates.

Physical Property	Designation	Aggregate Grading	Test Results: Gravel	Test Results: Limestone
Bulk Specific Gravity			2.621	2.663
Bulk Specific Gravity (SSD)	ASTM C 127	Course* Material	2.640	2.678
Apparent Specific Gravity	AASHTO T 85		2.672	2.700
Absorption			0.72	0.7
Bulk Specific Gravity			2.551	2.537
Bulk Specific Gravity (SSD)	ASTM C 218	Fine** Material	2.597	2.597
Apparent Specific Gravity	AASHTO T 84		2.675	2.702
Absorption, percent			1.8	2.2
Bulk Specific Gravity	ASTM C 127 & C 128	Project Design Gradation	2.580	2.589
Apparent Specific Gravity	AASHTO T 84		2.671	2.701
Absorption, percent	& T 85		1.3	1.56
Abrasion Resistance, percent loss	ASTM C 131 AASHTO T 96	Grading C	19	23
Compacted Unit Weight, pcf	ASTM C 29 AASHTO T 19	Project Design Gradation	129	122
Surface Capacity, percent by wt. dry aggregate	Centifage Kerosene Equivalent	Fine Material**	3.0	4.1
Surface Capacity, percent oil retained by wt. agg.	Oil Equivalent	-3/8 inch to + No. 4	1.8	2.3
Estimated Optimum Asphalt Content, percent by wt. dry aggregate	C.K.E. and Oil Equivalent	Project Design Gradation	4.7	5.5

*Material retained on No. 4 sieve from Project Design Gradation.

**Material passing No. 4 sieve from Project Design Gradation.

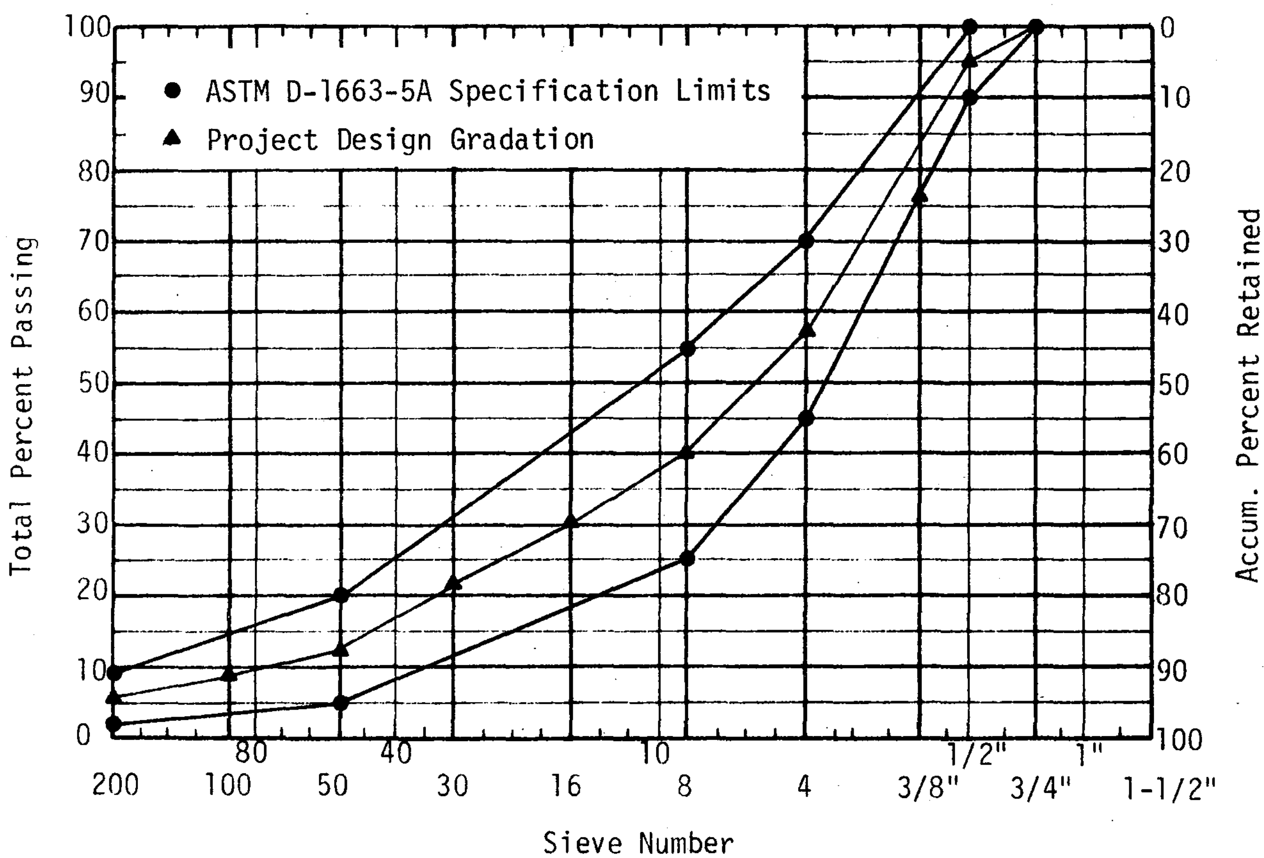


Figure A1. ASTM D-1663 - Aggregate Gradation 5A Specification and Project Gradation Design.

CONTROL MIXTURE PROPERTIES (11)

Mixing of Asphalt with Aggregate

The various aggregate size fractions were recombined to meet specifications. The mixing and compacting temperatures for the asphalt-aggregate mixtures were determined to be 305 ± 5°F (152°C) and 283 ± 5°F (140°C), respectively, by using the test procedure described in ASTM D-1559. (The procedure requires mixing at the temperature that produces an asphalt viscosity of 170 ± 20 centistokes and compacting at the temperature that produces an asphalt viscosity of 280 ± 30 centistokes kinematic.) Prior to mixing with asphalt cement, the aggregates were heated a minimum of four hours in 305 ± 5°F oven. The asphalt cement was heated in the same oven a minimum of 3/4 hour and a maximum of 2 hours. The appropriate quantity of asphalt cement was added to the heated aggregate then the mixture was blended in a mechanical mixer while heat was applied using a Bunsen burner. When blending was completed (all aggregate particles coated with asphalt cement) the mixture was carefully divided into three aliquots of predetermined weight and placed in an oven of appropriate compaction temperature. The mixing and batching operation was completed in approximately four minutes. A data summary of the asphalt aggregate mixtures is presented in Table A3.

Table A3. Properties of Control Mixtures (No Fibers) at Optimum Asphalt Content (11).

Property	Rounded Gravel
Design Asphalt Content, percent by wt. aggregate	3.8
Marshall Specimens	
Unit Weight, pcf	152
Air Void Content, percent	2.1
VMA, percent	9.1
VMA Filled with Asphalt, percent	80
Marshall Stability, lbs	1270
Marshall Flow, 0.1 inch	7
Hveem Specimens	
Unit Weight, pcf	151
Air Void Content, percent	2.9
VMA, percent	9.7
VMA Filled with Asphalt, percent	76
Hveem Stability, percent	25
Resilient Modulus, psi	570,000
Elastic Modulus, @ Failure*, psi	39,000

*From Splitting Tensile Test.

Table A4. Gradation of Aggregate Used in Overlay Test Specimens.

Sieve Size	% Passing	Tolerance
3/4 inch	100	100
3/8 inch	96	89-100
4	59	52-60
8	48	44-52
16	41	37-45
30	28	24-32
50	11	7-18
100	5	1-9
200	2.8	0.8-4.8

Table A5. Description of Overlay Test Specimens Supplied by Hercules, Inc.

Mold No.	% Asphalt (AC-20)	Fiber (% and type)	Compaction Temperature, °F
1	5.8	control	270
2	6.0	0.2%, 15 x 5	265
3	6.7	0.8%, 15 x 5	275
4	6.8	0.8%, 6 x 5	275
5	7.0	1.0%, 3 x 5	260
6	7.0	1.0%, Pulpex[P]	255
7	7.5	1.4%, 15 x 5	270
8	7.5	1.4%, 6 x 5	270
9	8.4	2.0%, 3 x 5	260
10	8.4	2.0%, 15 x 5	255

APPENDIX B

Marshall, Hveem and Resilient Modulus Test Data

Table B1 . Properties of Marshall Compacted Specimens at Various Asphalt Contents.

Type of Specimen	Asphalt Content, Percent	Sample No.	Bulk Specific Gravity	Air Voids, Percent	Marshall Stability, Lbs.	Marshall Flow, 0.01-inch
Control, No Fibers	2.5	25 A	2.37	7.0	1133	5
		25 B	2.39	6.2	950	5
		25 C	2.38	6.6	1208	5
		Ave	2.38	6.6	1100	5
	3.0	30 A	2.40	5.3	1372	6
		30 B	2.40	5.1	1188	5
		30 C	2.40	5.2	1264	6
		Ave	2.40	5.2	1280	6
	3.5	35 A	2.42	4.1	1250	6
		35 B	2.42	4.0	1190	6
		25 C	2.42	3.8	1374	7
		Ave	2.42	4.0	1270	6
	4.0	40 A	2.43	2.8	1456	7
		40 B	2.45	2.1	1342	8
		40 C	2.44	2.3	1275	8
		Ave	2.44	2.4	1360	8
	4.5	45 A	2.44	1.9	1030	10
		45 B	2.44	1.5	999	10
		45 C	2.43	2.2	948	11
		Ave	2.44	1.9	990	10
0.2% 15 x 10 Fibers (Washed)	2.5	21 x	2.33	6.8	998	5
		21 y	2.33	6.8	832	5
		21 z	2.33	6.8	823	5
		Ave	2.33	6.8	880	5
	2.8	22 x	2.34	6.4	894	4
		22 y	2.34	6.4	980	4
		22 z	2.35	6.0	1113	4
		Ave	2.34	6.3	1000	4

(Continued)

Table B1. Continued.

Type of Specimen	Asphalt Content, Percent	Sample No.	Bulk Specific Gravity	Air Voids, Percent	Marshall Stability, Lbs.	Marshall Flow, 0.01-inch
0.2% 15 x 10 Fibers (Washed)	3.4	23 x	2.38	4.4	1079	6
		23 y	2.38	4.4	1254	6
		23 z	2.39	4.0	1308	6
		Ave	2.38	4.3	1210	6
	3.8	24 x	2.38	2.5	927	6
		24 y	2.41	--	1221	6
		24 z	2.37	2.9	883	6
		Ave	2.39	2.7	1010	6
	4.3	25 x	2.37	3.3	801	7
		25 y	2.40	2.0	1112	7
		25 z	2.41	1.6	1101	7
		Ave	2.39	2.3	1000	7
0.4% 15 x 10 Fibers (Washed)	2.8	41 x	2.28	7.7	710	6
		41 y	2.29	7.3	730	6
		41 z	2.29	7.3	720	6
		Ave	2.29	7.4	720	6
	3.4	42 x	2.32	5.7	967	6
		42 y	2.31	6.1	910	7
		42 z	2.32	5.7	900	7
		Ave	2.32	5.8	930	7
	3.8	43 x	2.36	2.9	1300	7
		43 y	2.36	2.9	1269	6
		43 z	2.36	2.9	1092	6
		Ave	2.36	2.9	1220	6
	4.3	44 x	2.39	1.2	1144	8
		44 y	2.38	1.7	1144	7
		44 z	2.40	0.8	1196	8
		Ave	2.39	1.2	1160	8

(Continued)

Table B1 . Continued.

Type of Specimen	Apshalt Content, Percent	Sample No.	Bulk Specific Gravity	Air Voids, Percent	Marshall Stability, Lbs.	Marshall Flow, 0.01-inch
0.4% 15 x 10 Fibers (Washed)	5.0	45 x	2.40	0.1	1040	10
		45 y	2.40	0.1	1071	10
		45 z	2.39	0.4	1050	10
		Ave	2.40	0.2	1090	10
0.2% 15 x 10 Fibers (Unwashed)	2.5	16	2.33	8.1	586	6
		17	2.33	8.0	576	6
		18	2.31	8.7	588	6
		Ave	2.32	8.3	580	6
	3.0	26	2.34	6.8	730	6
		27	2.34	7.0	701	6
		28	2.37	5.6	970	6
		Ave	2.35	6.5	800	6
	3.5	36	2.39	4.7	1020	6
		37	2.39	4.7	1121	7
		38	2.39	4.7	1091	6
		Ave	2.39	4.7	1080	6
	4.0	46	2.42	2.4	1186	7
		47	2.42	2.5	1092	7
		48	2.41	2.8	1040	7
		Ave	2.42	2.6	1110	7
	4.5	56	2.42	1.3	957	9
		57	2.43	1.1	967	9
		58	2.43	1.0	998	10
		Ave	2.43	1.1	970	9
0.4% 15 x 10 Fibers (Unwashed)	3.0	A 6	2.34	6.3	774	7
		A 7	2.35	5.6	883	7
		A 8	2.34	6.2	893	7
		Ave	2.34	6.0	850	7

(Continued)

Table B1. Continued.

Type of Specimen	Asphalt Content, Percent	Sample No.	Bulk Specific Gravity	Air Voids, Percent	Marshall Stability, Lbs.	Marshall Flow, 0.01-inch
0.4% 15 x 10 Fibers (Unwashed)	3.5	B 6	2.37	4.4	1030	7
		B 7	2.36	4.9	833	8
		B 8	2.37	4.5	1050	8
		Ave	2.37	4.6	970	8
	4.0	C 6	2.39	3.0	1101	8
		C 7	2.39	3.1	1075	8
		C 8	2.39	3.1	1111	9
		Ave	2.39	3.1	1100	8
	4.5	D 6	2.41	1.7	960	10
		D 7	2.41	1.8	1000	10
		D 8	2.42	1.5	949	10
		Ave	2.41	1.7	970	10
	5.0	E 6	2.41	1.3	796	11
		E 7	2.40	1.6	836	12
		E 8	2.40	1.6	790	11
		Ave	2.40	1.5	810	11
0.2% 3 x 5 Fibers (Unwashed)	3.4	1	2.37	4.4	840	6
		2	2.38	4.0	915	6
		3	2.37	4.4	940	6
		Ave	2.37	4.3	900	6
	3.8	4	2.39	3.2	965	7
		5	2.39	3.2	1024	6
		6	2.39	3.2	1004	7
		Ave	2.39	3.2	1000	7
	4.3	7	2.41	1.6	1123	9
		8	2.42	1.2	1113	9
		9	2.41	1.6	1019	9
		Ave	2.41	1.5	1090	9

(Continued)

Table B1 . Continued.

Type of Specimen	Asphalt Content, Percent	Sample No.	Bulk Specific Gravity	Air Voids, Percent	Marshall Stability, Lbs.	Marshall Flow, 0.01-inch
0.4% 3 x 5 Fibers (Unwashed)	3.8	10	2.35	4.5	1195	8
		11	2.33	5.3	1018	9
		12	2.34	4.9	1152	8
		Ave	2.34	4.9	1120	8

Table B2 . Properties of Gyratory Compacted Specimens at Various Asphalt Contents.

Fiber Content, Percent	Asphalt Content, Percent	Sample No.	Bulk Specific Gravity	Air Voids, Percent	VMA, Percent	Resilient Modulus, @ 77°F psi x 10^6	Hveem Stability, Percent
None, Control Specimens	2.5	1 A	2.37	7.1		0.130	34
		1 B	2.39	6.2		0.258	33
		1 C	2.37	7.4		0.234	31
		1 D	2.37	6.6		--	30
		1 E	2.40	5.8		--	34
		1 F	2.40	5.8		--	34
		Ave	2.39	6.5	9.62	0.207	33
	3.0	2 A	2.42	4.2		0.206	35
		2 B	2.41	4.8		0.202	30
		2 C	2.40	4.7		0.215	29
		2 D	2.39	5.5		--	28
		2 E	2.40	5.3		--	26
		2 F	2.40	5.2		--	29
		Ave	2.40	5.0	9.68	0.207	30
	3.5	3 A	2.45	2.3		0.251	32
		3 B	2.44	2.5		0.275	33
		3 C	2.44	2.8		0.215	30
		3 D	2.43	2.9		--	32
		3 E	2.43	2.9		--	34
		3 F	2.44	2.5		--	33
		Ave	2.44	2.7	8.62	0.247	32
	4.0	4 A	2.47	1.1		0.197	20
		4 B	2.46	1.4		0.168	25
		4 C	2.46	1.3		0.190	28
		4 D	2.46	0.8		--	28
		4 E	2.46	1.0		--	28
		4 F	2.46	1.0		--	28
		Ave	2.46	1.1	8.32	0.185	26

(Continued)

Table B2 . Continued.

Fiber Content, Percent	Asphalt Content, Percent	Sample No.	Bulk Specific Gravity	Air Voids, Percent	VMA, Percent	Resilient Modulus, @ 77°F psi x 10^6	Hveem Stability, Percent
None, Control Specimens	4.5	5 A	2.46	0.8		0.143	17
		5 B	2.46	0.6		0.126	17
		5 C	2.46	0.8		0.123	15
		5 D	2.45	1.2		--	17
		5 E	2.47	0.4		--	19
		5 F	2.44	1.6		--	15
		Ave	2.46	0.9	8.76	0.131	17
0.2% 15 x 10 Fibers (Washed)	2.3	211	2.34	7.5		0.270	38
		212	2.35	6.3		0.283	45
		213	2.34	7.4		0.276	37
		Ave	2.34	7.1	11.33	0.277	40
	2.8	221	2.35	6.5		0.232	37
		222	2.38	4.8		0.233	44
		223	2.37	5.2		0.238	40
		Ave	2.37	5.5	10.64	0.234	40
	3.4	231	2.40	3.7		0.354	40
		232	2.39	3.8		0.348	34
		233	2.40	4.2		0.333	44
		Ave	2.40	3.9	10.03	0.345	39
	3.8	241	2.41	2.1		0.324	36
		242	2.42	1.6		0.358	41
		243	2.43	1.7		0.361	40
		Ave	2.42	1.8	9.63	0.348	39
	4.3	251	2.44	0.6		0.312	31
		252	2.44	0.6		0.294	25
		253	2.43	1.5		0.323	31
		Ave	2.44	0.9	9.31	0.310	29

(Continued)

Table B2 . Continued.

Fiber Content, Percent	Asphalt Content, Percent	Sample No.	Bulk Specific Gravity	Air Voids, Percent	VMA, Percent	Resilient Modulus, @ 77°F psi x 10^6	Hveem Stability, Percent
0.4% 15 x 10 Fibers (Washed)	2.8	311	2.30	7.9		0.202	29
		312	2.32	7.4		0.204	30
		313	2.31	7.8		0.198	30
		Ave	2.31	7.7	12.89	0.202	30
	3.4	321	2.35	5.4		0.212	29
		322	2.33	5.9		0.214	28
		323	2.34	5.6		0.235	30
		Ave	2.34	5.6	12.10	0.221	29
	3.8	331	2.37	3.7		0.235	29
		332	2.38	3.4		0.262	30
		333	2.38	3.4		0.280	30
		Ave	2.38	3.5	11.12	0.259	30
	4.3	341	2.39	1.8		0.284	27
		342	2.40	1.8		0.297	28
		343	2.39	1.9		0.329	28
		Ave	2.39	1.8	11.17	0.303	28
	5.0	351	2.40	1.2		0.342	24
		352	2.42	0.5		0.296	26
		353	2.42	0.5		0.324	26
		Ave	2.41	0.7	11.02	0.320	25

(Continued)

Table B2 . Continued.

Fiber Content, Percent	Asphalt Content, Percent	Sample No.	Bulk Specific Gravity	Air Voids, Percent	VMA, Percent	Resilient Modulus, @ 77°F psi x 10^6	Hveem Stability, Percent
0.2% 3 x 5 Fibers (Unwashed)	3.4	13	2.38	3.6		0.195	32
		14	2.37	4.0		0.160	27
		15	2.37	4.0		0.175	31
		Ave	2.37	3.9	11.15	0.177	30
	3.8	16	2.39	2.8		0.184	28
		17	2.40	2.4		0.219	30
		18	2.39	2.8		0.224	28
		Ave	2.39	2.7	10.75	0.209	29
	4.3	19	2.41	1.2		0.253	25
		20	2.42	0.8		0.230	24
		21	2.41	1.2		0.220	24
		Ave	2.41	1.1	10.43	0.234	24

Table B3 . Resilient Modulus as a Function of Temperature of Laboratory Compacted Specimens With and Without 15 x 10 Specimens.

Fiber Content, Percent	Asphalt Content, Percent	Sample No.	Resilient Modulus in psi x 10^6 at				
			-13°F	33°F	68°F	77°F	104°F
None - Control Specimens	3.8	1A	6.38	2.59	0.258	0.197	0.026
		1B	6.18	2.92	0.286	0.168	0.028
		1C	5.63	3.20	0.312	0.190	0.027
		Ave	6.06	2.90	0.285	0.185	0.027
0.2 15 x 10 Fibers (Unwashed)	3.4	2A	9.61	4.57	0.491	0.354	0.086
		2B	8.55	5.33	0.503	0.348	0.087
		2C	11.30	5.24	0.518	0.333	0.091
		Ave	9.82	5.05	0.504	0.345	0.088
	3.8	3A	9.61	4.98	0.527	0.324	0.088
		3B	10.23	5.40	0.518	0.358	0.092
		3C	10.88	6.37	0.578	0.361	0.100
		Ave	10.24	5.59	0.541	0.348	0.093

APPENDIX C

Tabulated Direct Tension Test Data

Table C1. Direct Tension Data for Individual Tests

Type Fiber*	Fiber Content, Wt. percent	Deformation Rate, in/min	Tensile Strength, psi	Strain @ Failure, in/min	Secant Modulus, psi
3 x 5	0.2	2	470	0.0017	276,000
		0.02	240	0.0013	185,000
		0.002	52	0.0006	87,000
			48	0.0005	96,000
			70	0.0010	70,000
			70	0.0028	25,000
			90	0.0021	43,000
			95	0.0016	59,000
			55	0.0008	69,000
	0.4	0.002	102	0.0013	78,000
		0.02	95	0.0016	61,000
			137	0.0025	49,000
			134	0.0021	64,000
3 x 10	0.2	0.002	117	0.0008	146,000
3 x 15	0.2	2	307	0.0010	316,000
			290	-	-
			440	0.0004	1,280,000
			300	-	-
		0.02	92	-	-
			144	0.0041	35,000
			95	0.0051	19,000
		0.002	56	0.0088	6,000
			81	0.0010	82,000
			58	0.0056	10,000
			35	0.0016	22,100
15 x 5	0.2	2	540	0.0036	150,000
			263	0.0013	207,000
			275	0.0016	173,000

(Continued)

Table C1. (Continued).

Type Fiber*	Fiber Content, Wt. percent	Deformation Rate, in/min	Tensile Strength, psi	Strain @ Failure, in/min	Secant Modulus, psi
15 x 5	0.2	0.02	208	0.0016	124,000
			222	0.0023	93,000
			278	0.0014	198,000
			290	0.0014	207,000
		0.002	85	0.0023	38,000
			119	0.0021	58,000
			190	0.0012	158,000
			215	0.0016	134,000
	0.4	0.02	190	0.0037	51,000
			225	0.0021	106,000
			225	0.0026	87,000
		0.002	104	0.0023	46,000
	0.8	0.02	108	0.0039	28,000
			120	0.0046	26,000
			115	0.0044	26,000
		0.002	38	0.0011	33,000
			47	0.0014	34,000
			42	0.0009	48,000
			67	0.0033	20,000
			73	0.0040	18,000
15 x 10	0.2	2	392	0.0007	533,000
			256	0.0002	1,287,000
		0.02	111	0.0023	49,000
			109	0.0028	40,000
			115	0.0022	53,000
			92	-	-
		0.002	89	0.0034	27,000
			87	0.0025	34,000
			75	0.0076	10,000
			37	0.0021	17,000
	0.4	0.002	45	0.0007	65,000
			37	0.0004	97,000
			72	0.0005	153,000
			60	0.0006	107,000

(Continued)

Table C1. (Continued).

Type Fiber*	Fiber Content, Wt. percent	Deformation Rate, in/min	Tensile Strength, psi	Strain @ Failure, in/min	Secant Modulus, psi
15 x 15	0.2	2	361	0.0004	821,000
			372	0.0007	563,000
			376	0.0003	1,296,000
		0.02	106	-	-
			182	0.0007	280,000
			109	0.0004	312,000
			152	0.0007	216,000
			155	0.0035	44,000
			137	0.0022	61,000
		0.002	66	0.0024	26,000
			99	0.0041	24,000
			61	0.0048	13,000
			88	0.0051	17,000
			88	0.0070	12,000
Control	None	2	462	0.0029	161,000
			395	0.0024	165,000
			610	0.0031	197,000
		0.02	223	0.0018	127,000
			196	0.0019	102,000
			275	0.0016	171,000
		0.002	97	0.0025	38,000
			100	0.0029	35,000
			112	0.0011	102,000

*Numbers indicate size of fibers, for example, 3 x 5 means 3 denier and 5 mm length.

APPENDIX D

Data from Overlay Test Data

Table D1. Properties of Overlay Test Beams Furnished by Hercules and Number of Cycles at Failure at 77°F.

Test Temp. °F	Type Fiber	Fiber Content, percent	Asphalt Content, percent	Sample Number	Sample Height, inches	Sample Width, inches	Bulk Specific, Gravity	Air Voids, percent	No. Cycles @ Failure @ 77°F
77	Control	None	5.8	1A	2.25	3.25	2.29	6.9	35
				1E	2.25	3.13	2.28	7.3	25
	15 x 5	0.2	6.0	2C	3.20	3.05	2.30	6.0	700
				2D	3.16	3.10	2.32	5.5	450
				2E	3.08	3.16	2.31	5.6	500
	15 x 5	0.8	6.7	3C	3.19	3.06	2.25	7.5	750
				3D	3.15	3.15	2.25	7.4	850
				3E	3.06	3.21	2.24	7.7	800
	6 x 5	0.8	6.8	4A	3.11	3.10	2.23	8.2	425
				4B	3.16	2.96	2.22	8.6	475
				4D	3.18	3.17	2.22	8.6	-
	3 x 5	1.0	7.0	5B	3.12	3.06	2.17	9.8	700
				5C	3.20	3.17	2.17	9.8	850
				5D	3.18	3.07	2.17	9.5	800
	Pulpex[P]	1.0	7.0	6B	3.23	3.25	2.04	14.8	400
				6C	3.23	2.99	2.05	14.4	300
				6D	3.18	3.08	2.06	14.0	350
	15 x 5	1.4	7.5	7A	3.23	3.20	2.13	9.8	900
				7C	3.07	3.08	2.14	9.4	775
				7E	3.17	3.13	2.14	9.5	1000
	6 x 5	1.4	7.5	8A	3.06	3.14	2.07	12.5	700
				8B	3.17	3.18	2.07	12.2	800
				8E	3.13	3.10	2.09	11.6	700

(Continued)

Table D1. Continued.

Test Temp. °F	Type Fiber	Fiber Content, percent	Asphalt Content, percent	Sample Number	Sample Height, inches	Sample Width, inches	Bulk Specific, Gravity	Air Voids, percent	No. Cycles @ Failure @ 77°F
77	3 x 5	2.0	8.4	9B	1.64	-	2.02	12.1	200
				9D	1.65	-	2.01	12.8	200
				9E	1.66	-	2.00	13.0	300
	15 x 5	2.0	8.4	10C	3.20	3.45	2.07	10.0	1000
				10D	3.10	3.09	2.07	9.9	1600
				10E	3.18	2.98	2.07	10.0	1100
32	Control	None	5.8	1CA	~1.5	~3	-	-	1
				1CB	~1.5	~3	-	-	1
				1CF	~1.5	~3	-	-	1
	3 x 5	1.0	7.0	5A	~3	~3	-	-	3
				5E	~3	~3	-	-	5
	15 x 5	1.4	7.5	7B	~3	~3	-	-	4
				7D	~3	~3	-	-	3
	15 x 5	2.0	8.4	10F	~3	~3	-	-	14

*These specimens were contaminated and had to be trimmed to the smaller height in order to salvage them for testing.

Table D2. Average Crack Height of Specimens During the Overlay Tests at 77°F.

Sample Number Set	AVERAGE CRACK HEIGHT AT THE GIVEN CYCLE, inches												
	1	5	50	100	200	300	400	500	600	700	800	900	1000
1	.75	1.25	1.813[1]	2.281[2]	2.467[3]								
2	.60	.82	1.471	1.779	2.248	2.518	2.950	2.975	3.000				
3	.75	.77	1.167	1.583	1.854	2.208	2.573	2.625	2.938	2.938	3.000		
4	.50	.72	1.281	1.688	2.156	2.675	3.000	3.000					
5	.52	.93	1.417	1.667	2.292	2.496	2.663	2.725	2.800	2.933	2.933		
6	.86	1.21	1.917	2.333	2.554	2.979	3.021						
7	.48	.58	.917	1.104	1.396	1.725	2.00	2.438	2.792	3.042	3.042	3.042	
8	.38	.60	1.022	1.242	1.958	2.292	2.604	2.916	2.936	2.936	2.936		
9	.40	.76	1.205	1.346	1.541	1.541							
10	.41	.63	.896	.958	1.383	1.713	1.721	1.903	2.029	2.188	2.333	2.667	2.783

[1]Crack Height After 10th cycle.

[2]Crack Height After 25th cycle.

[3]Crack Height After 35th cycle.

Table D3. Data for Individual Overlay Test Specimens.

Sample No.	Temp. °F	Percent Fiber and Type	Cycle No.	Actual Displacement, inches	Peak Load, lbs.	Mean Crack Height, inches
1A	77	None Control	1	0.051	675	0.75
			5	0.063	161	1.19
			10	0.063	92	1.56
			25	0.070	-	2.06
			35	0.070	-	2.45
1E	77	None Control	1	0.053	593	0.75
			5	0.062	195	1.31
			10	0.070	87	2.06
			25	0.070	0	2.25
			35	0.070	0	2.25
2C	77	0.2 15 x 5	1	-	-	0.50
			5	-	377	1.00
			50	-	147	1.72
			100	-	144	2.15
			200	-	71	2.30
			300	-	24	2.80
			400	-	18	2.87
			500	-	12	2.95
			600	-	0	3.00
2D	77	0.2 15 x 15	2	-	485	0.44
			5	-	300	0.44
			50	-	218	1.31
			100	-	150	1.62
			200	-	113	2.12
			300	-	68	2.18
			400	-	0	3.00
2E	77	0.2 15 x 15	1		695	0.88
			5	0.064	234	1.00
			50	0.068	135	1.37
			100	0.068	93	1.56
			200	0.067	90	2.31
			300	0.068	66	2.56
			400	0.070	29	3.00
			450	0.070	3	3.00

(Continued)

Table D3. Continued.

Sample No.	Temp. °F	Percent Fiber and Type	Cycle No.	Actual Displacement, inches	Peak Load, lbs.	Mean Crack Height, inches
			1	0.058	692	0.62
			5	0.056	351	0.62
			50	0.061	210	1.25
			100	0.065	126	1.56
			200	0.068	119	1.81
3C	77	0.8	300	0.069	90	2.50
		15 x 15	400	0.069	60	2.71
			500	0.069	45	3.00
			600	0.070	9	3.00
			700	0.070	9	3.00
			800	0.070	2	3.00
			1	0.050	609	0.68
			5	0.052	315	0.75
			50	0.057	182	1.00
			100	0.056	150	1.31
3D	77	0.8	200	0.058	128	1.50
		15 x 15	300	0.058	105	1.68
			400	0.058	71	2.00
			500	0.059	27	2.25
			600	0.059	18	2.87
			700	0.063	8	3.00
			800	0.063	5	3.00
			1	0.058	660	0.94
			5	0.058	333	0.94
			50	0.058	174	1.18
			100	0.058	123	1.87
			200	0.061	71	2.25
3E	77	0.8	300	0.059	56	2.38
		15 x 15	400	0.065	30	3.00
			500	0.067	8	3.00
			600	0.067	6	3.00
			700	0.066	6	3.00
			800	0.067	2	3.00
			1	0.050	684	0.50
			5	0.052	159	0.75
			100	0.065	126	1.44
4A	77	0.8	200	0.066	45	2.31
		6 x 5	300	0.069	24	2.66
			400	0.069	-	3.00
			425	0.069	12	3.00

(Continued)

Table D3. Continued.

Sample No.	Temp. °F	Percent Fiber and Type	Cycle No.	Actual Displacement, inches	Peak Load, lbs.	Mean Crack Height, inches
4B	77	0.8 6 x 5	1	0.048	852	0.50
			5	0.053	383	0.69
			100	0.061	168	1.50
			200	0.064	114	2.00
			300	0.066	30	2.69
			400	0.067	15	3.00
			475	0.069	8	3.00
4D	77	0.8 6 x 5	1	0.049	825	0.50
			5	0.054	393	0.63
			100	0.064	129	1.75
			200	0.065	81	2.13
			300	0.065	21	2.58
			400	0.067	15	2.94
			500	0.068	12	3.00
5B	77	1.0 3 x 5	1	0.030	690	0.50
			5	0.035	285	0.90
			100	0.068	93	1.56
			200	0.068	36	2.81
			300	0.068	15	2.94
			400	0.069	12	2.94
			500	0.069	12	2.94
			600	0.069	9	2.94
			700	0.069	8	2.94
5C	77	1.0 3 x 5	1	0.036	737	0.38
			5	0.041	348	0.75
			100	0.065	129	1.56
			200	0.068	83	1.88
			300	0.068	38	2.13
			400	0.068	15	2.36
			500	0.069	12	2.55
			600	0.069	12	2.55
			700	0.069	12	2.55
			800	0.069	12	2.55
			850	0.069	9	2.55

(Continued)

Table D3. Continued.

Sample No.	Temp. °F	Percent Fiber and Type	Cycle No.	Actual Displacement, inches	Peak Load, lbs.	Mean Crack Height, inches
7C	77	1.4 15 x 5	1	0.051	690	0.50
			5	0.052	362	0.50
			20	0.055	-	0.60
			50	0.062	237	0.75
			100	0.063	186	0.81
			200	0.064	53	0.81
			300	0.065	33	1.19
			400	0.065	27	1.75
			500	0.066	18	2.19
			600	0.066	15	2.50
			700	0.066	12	3.00
			775	0.066	8	3.00
7E	77	1.4 15 x 5	1	0.050	642	0.44
			5	0.050	282	0.69
			50	0.063	188	1.13
			100	0.065	147	1.38
			200	0.066	104	1.69
			300	0.066	30	1.81
			400	0.067	27	2.06
			500	0.067	15	2.38
			600	0.068	15	2.81
			700	0.068	12	3.00
			800	0.068	9	3.00
8A	77	1.4 6 x 5	1	0.054	593	0.25
			2	0.056	270	0.50
			50	0.065	-	0.91
			100	0.065	120	1.23
			200	0.069	26	1.75
			300	0.069	18	1.88
			400	0.070	15	2.75
			500	0.070	15	3.06
			600	0.070	14	3.06
			700	0.070	12	3.06
8B	77	1.4 6 x 5	1	0.053	501	0.31
			5	0.057	225	0.63
			50	0.064	119	1.09
			200	0.065	36	1.75
			300	0.065	33	2.19
			400	0.066	15	2.25
			500	0.066	12	2.81
			600	0.066	12	2.81
			700	0.067	12	2.81
			800	0.069	12	2.81

(Continued)

Table D3. Continued.

Sample No.	Temp. °F	Percent Fiber and Type	Cycle No.	Actual Displacement, inches	Peak Load, lbs.	Mean Crack Height, inches
5D	77	1.0 3 x 5	1	0.055	690	0.69
			5	0.057	308	1.13
			100	0.063	-	1.56
			200	0.063	41	1.94
			300	0.063	29	2.19
			400	0.065	12	2.50
			500	0.065	12	2.69
			600	0.065	11	2.76
			700	0.065	8	3.06
			800	0.065	8	3.06
6B	77	1.0 Pulpex[P]	1	0.052	588	0.50
			5	0.059	237	0.88
			100	0.067	47	1.63
			200	0.069	18	1.94
			300	0.069	11	3.00
			450	0.070	6	3.00
6C	77	1.0 Pulpex[P]	1	0.052	576	0.81
			5	0.056	225	1.25
			100	0.069	27	3.06
			200	0.069	8	3.06
			300	0.069	5	3.06
6D	77	1.0 Pulpex[P]	1	0.053	570	0.78
			5	0.058	207	1.50
			100	0.065	20	2.31
			200	0.067	6	2.69
			300	0.068	6	2.88
			350	0.069	5	3.00
7A	77	1.4 15 x 5	1	0.051	639	0.50
			5	0.057	329	0.56
			50	0.063	155	0.88
			200	0.068	80	1.69
			300	0.068	45	2.19
			400	0.068	23	2.19
			500	0.070	15	2.75
			600	0.070	12	3.06
			700	0.070	8	3.06
			800	0.070	5	3.06
			900	0.070	5	3.06

(Continued)

Table D3. Continued.

Sample No.	Temp. °F	Percent Fiber and Type	Cycle No.	Actual Displacement, inches	Peak Load, lbs.	Mean Crack Height, inches
			1	0.052	593	0.56
			5	0.058	252	0.69
			50	0.066	123	1.00
			100	0.067	105	1.00
			200	0.067	17	1.25
8E	77	1.4	300	0.068	15	2.38
		6 x 5	400	0.069	15	2.81
			500	0.069	14	2.81
			600	0.069	14	2.88
			700	0.069	12	2.88
			1	0.053	387	0.50
			5	0.065	93	0.81
9B	77	2.0	100	0.067	12	1.32
		3 x 5	200	0.069	8	1.64
			1	0.061	219	0.38
9D	77	2.0	5	0.065	72	0.60
		3 x 5	100	0.067	11	1.33
			200	0.068	8	1.33
			1	0.061	225	0.31
9E	77	2.0	5	0.068	45	0.88
		3 x 5	100	0.069	9	1.46
			200	0.069	6	1.66
			1	0.050	507	0.50
			5	0.055	285	0.63
			50	0.065	114	1.00
			100	0.065	86	1.06
			200	0.065	66	1.40
			300	0.065	51	1.69
10C	77	2.0	400	0.065	36	1.69
		15 x 5	500	0.066	21	2.01
			600	0.066	11	2.25
			700	0.066	8	2.38
			800	0.066	8	2.75
			900	0.066	5	3.06
			1000	0.066	-	3.06

(Continued)

Table D3. Continued.

Sample No.	Temp. °F	Percent Fiber and Type	Cycle No.	Actual Displacement, inches	Peak Load, lbs.	Mean Crack Height, inches
			1	0.056	605	0.31
			5	0.057	279	0.50
			50	0.065	147	0.56
			100	0.065	143	0.69
			200	0.069	54	1.38
10D	77	2.0	400	0.070	23	1.76
		15 x 5	500	0.070	18	1.76
			600	0.070	18	1.76
			800	0.070	15	1.94
			1000	0.070	8	2.69
			1500	0.070	5	-
			1	0.039	582	0.41
			5	0.058	267	0.75
			50	0.063	165	1.13
			100	0.066	120	1.13
			200	0.066	51	1.44
			300	0.066	33	1.69
10E	77	2.0	400	0.067	17	1.81
		15 x 5	500	0.067	15	1.94
			600	0.067	12	2.08
			700	0.067	11	2.25
			800	0.067	8	2.31
			900	0.068	6	2.31
			1000	0.068	3	3.00
			1	0.066	1148	1.50
			5	-	-	-
			20	-	-	-
1CA	32	None	50	-	-	-
		Control	100	-	-	-
			200	-	-	-
			300	-	-	-
			1	0.067	1380	1.50
			5	-	-	-
			20	-	-	-
1CB	32	None	50	-	-	-
		Control	100	-	-	-
			200	-	-	-
			300	-	-	-

(Continued)

Table D3. Continued.

Sample No.	Temp. °F	Percent Fiber and Type	Cycle No.	Actual Displacement, inches	Peak Load, lbs.	Mean Crack Height, inches
1CF	32	None Control	1	0.064	84	1.50
			5	-	-	-
			20	-	-	-
			50	-	-	-
			100	-	-	-
			200	-	-	-
			300	-	-	-
5A	32	1.0 3 x 5	2	0.032	1053	3.00
			3	0.046	-	3.00
			5	0.046	390	3.00
			20	0.056	165	3.00
			50	0.058	129	3.00
			100	0.060	90	3.00
			200	0.065	60	3.00
			300	-	-	-
5E	32	1.0 3 x 5	1	0.031	1839	2.08
			5	0.035	1560	3.00
			20	0.039	465	3.00
			50	0.045	270	3.00
			100	0.051	180	3.00
			200	0.062	120	3.00
			300	0.064	90	3.00
7B	32	1.4 15 x 5	2	0.033	1530	2.63
			4	0.034	1080	3.00
			20	0.045	390	3.00
			50	0.050	240	3.00
			100	0.060	159	3.00
			200	0.062	75	3.00
			300	0.063	57	3.00
7D	32	1.4 15 x 5	1	0.033	1785	1.88
			3	0.033	1302	3.00
			20	0.046	372	3.00
			50	0.050	246	3.00
			100	0.054	150	3.00
			200	0.059	84	3.00
			300	0.060	54	3.00

(Continued)

Table D3. Continued.

Sample No.	Temp. °F	Percent Fiber and Type	Cycle No.	Actual Displacement, inches	Peak Load, lbs.	Mean Crack Height, inches
			1	0.032	-	1.83
			14	0.047	-	3.00
			20	0.047	-	3.00
10F	32	2.0	50	0.051	-	3.00
		15 x 5	100	0.056	-	3.00
			200	0.059	-	3.00
			300	0.061	-	3.00

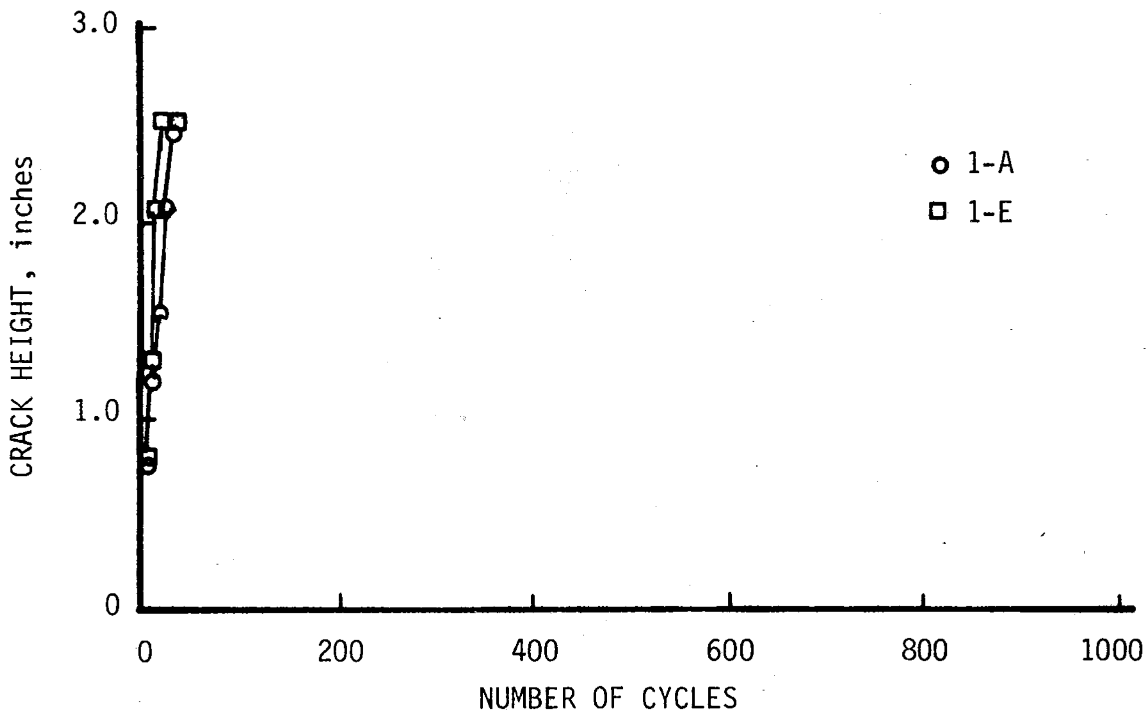


FIGURE D1. Crack Height versus Number of Cycles for Control Specimens.

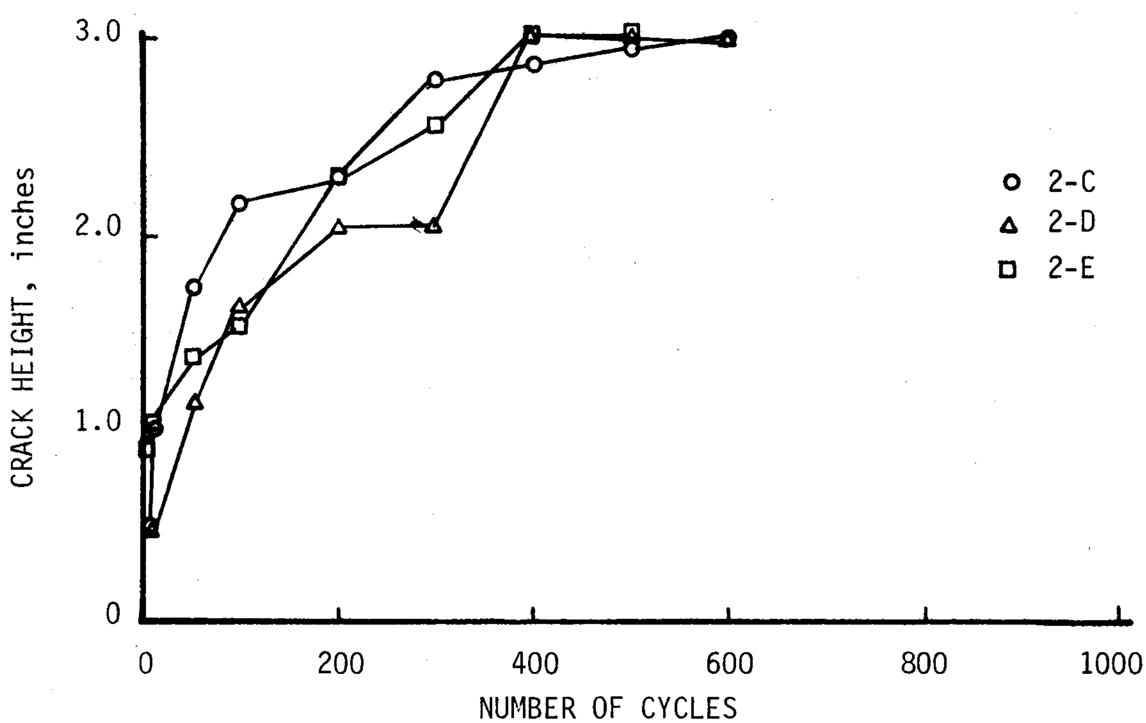


FIGURE D2. Crack Height versus Number of Cycles for Specimens containing 0.2% of 15x5 Fibers.

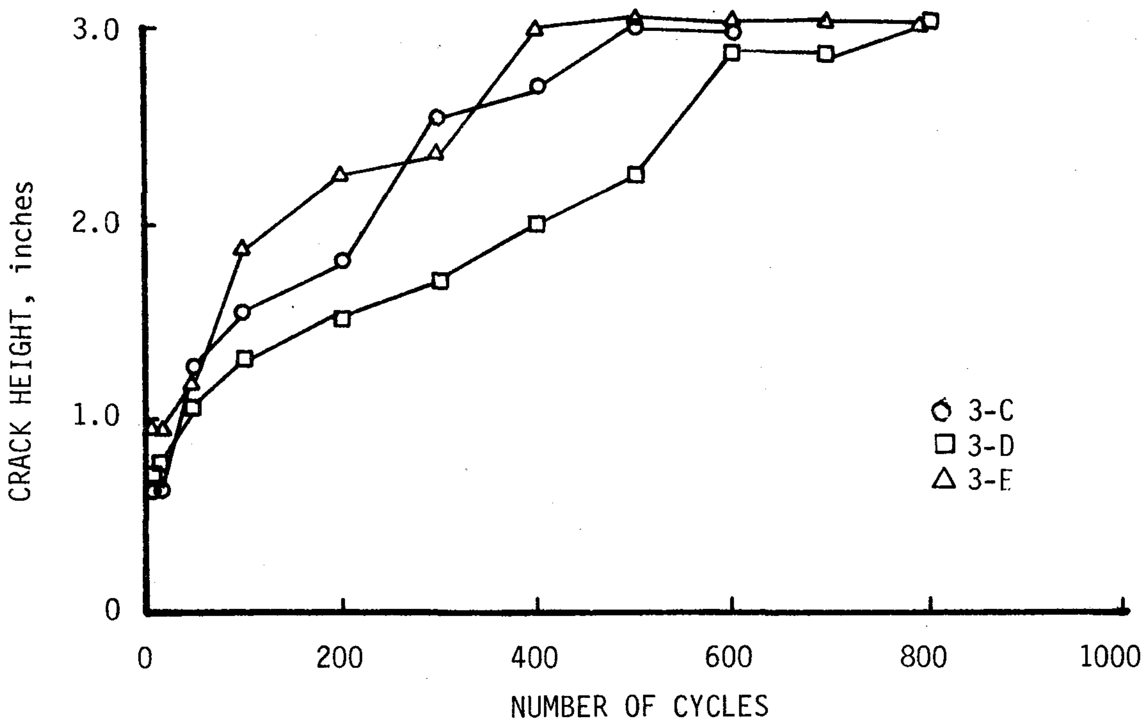


FIGURE D3. Crack Height versus Number of Cycles for Specimens Containing 0.8% of 15x5 Fibers.

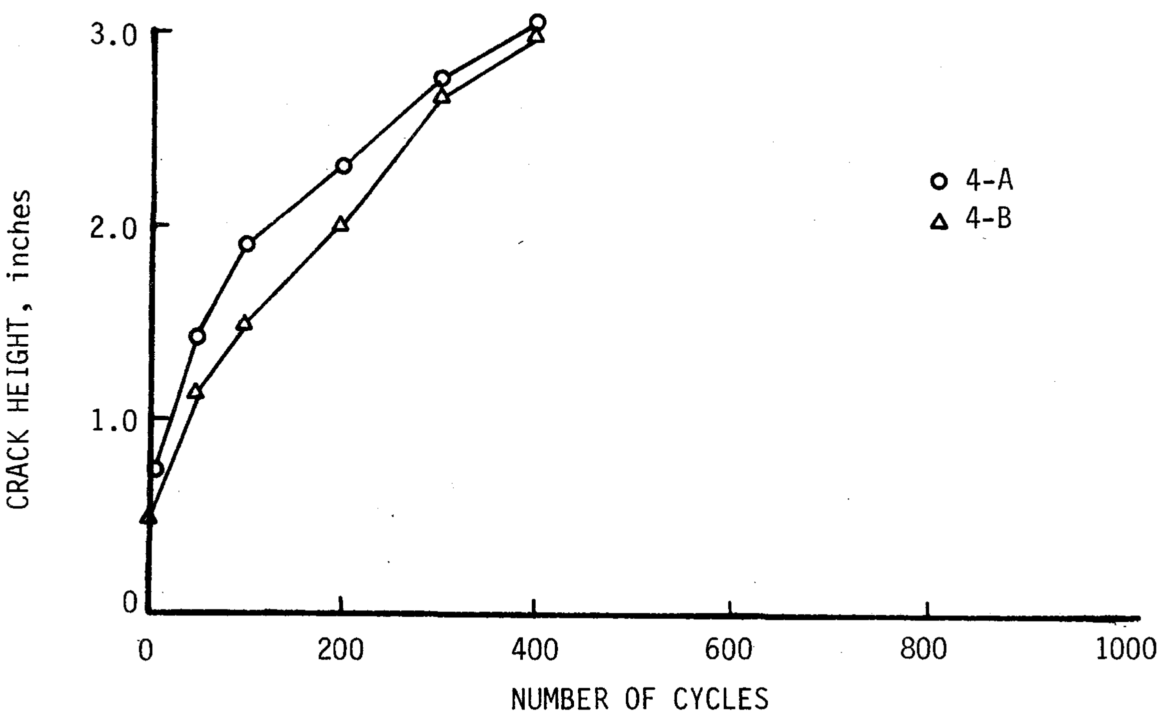


FIGURE D4. Crack Height versus Number of Cycles for Specimens Containing 0.8% of 6x5 Fibers.

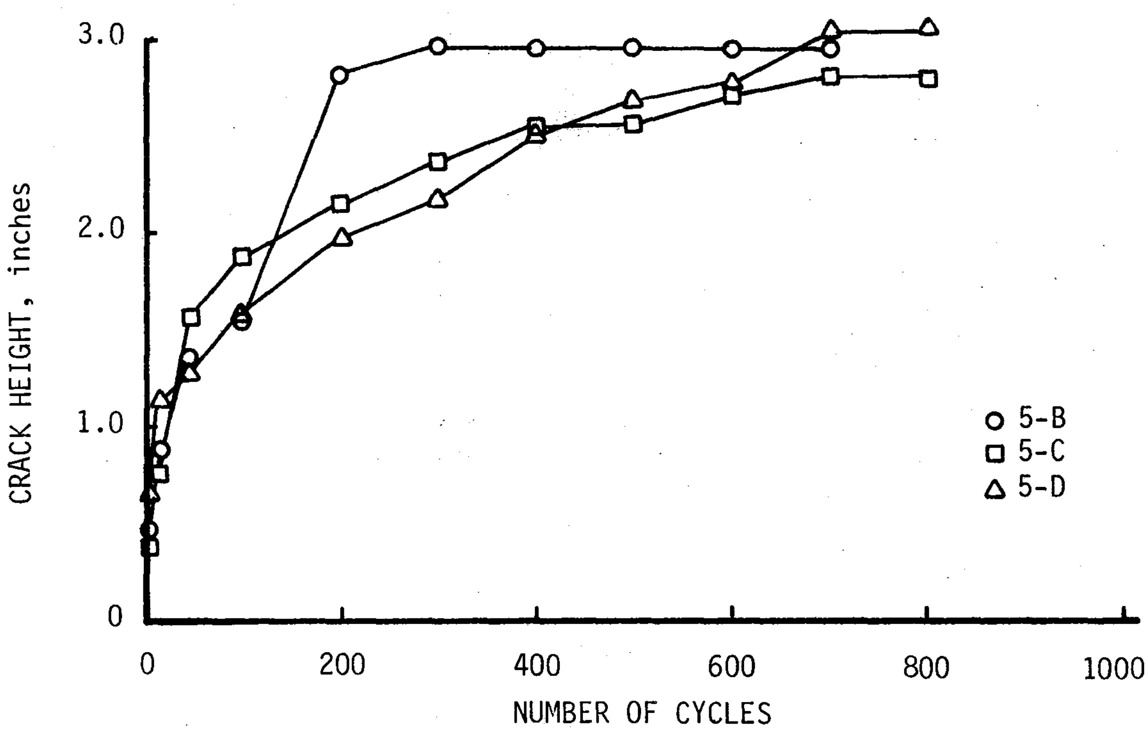


FIGURE D5. Crack Height versus Number of Cycles for Specimens Containing 1.0% of 3x5 Fibers.

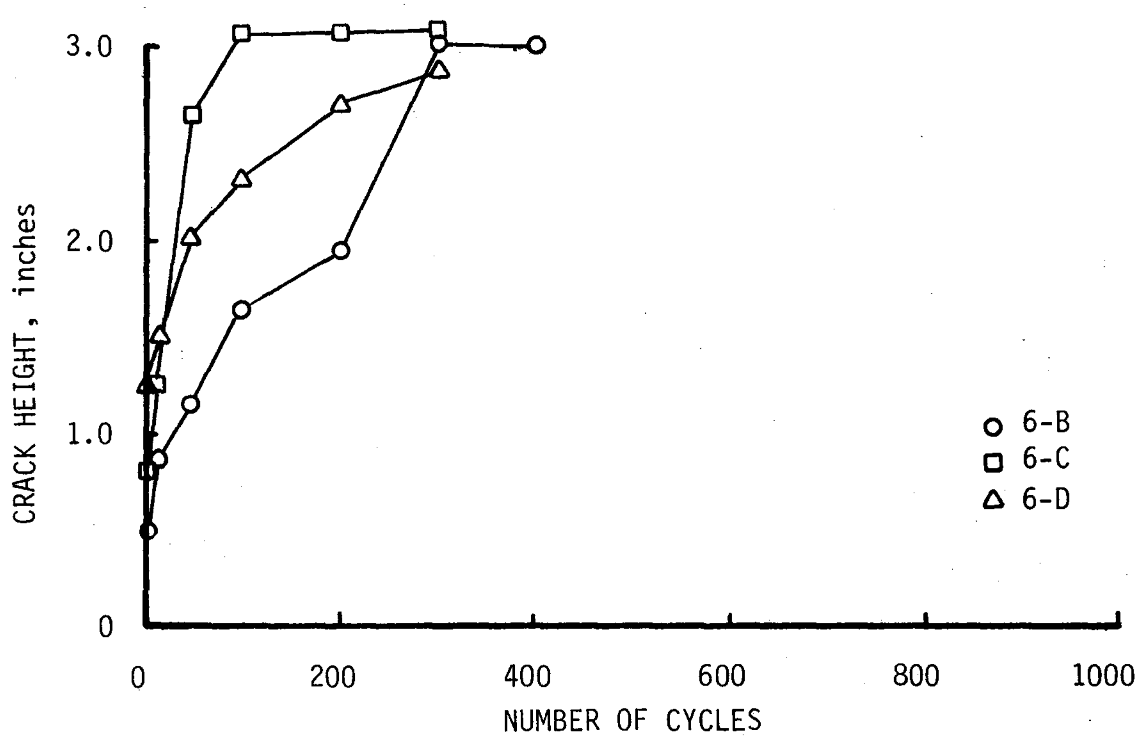


FIGURE D6. Crack Height versus Number of Cycles for Specimens Containing 1.0% of Pulpex[P] Fibers.

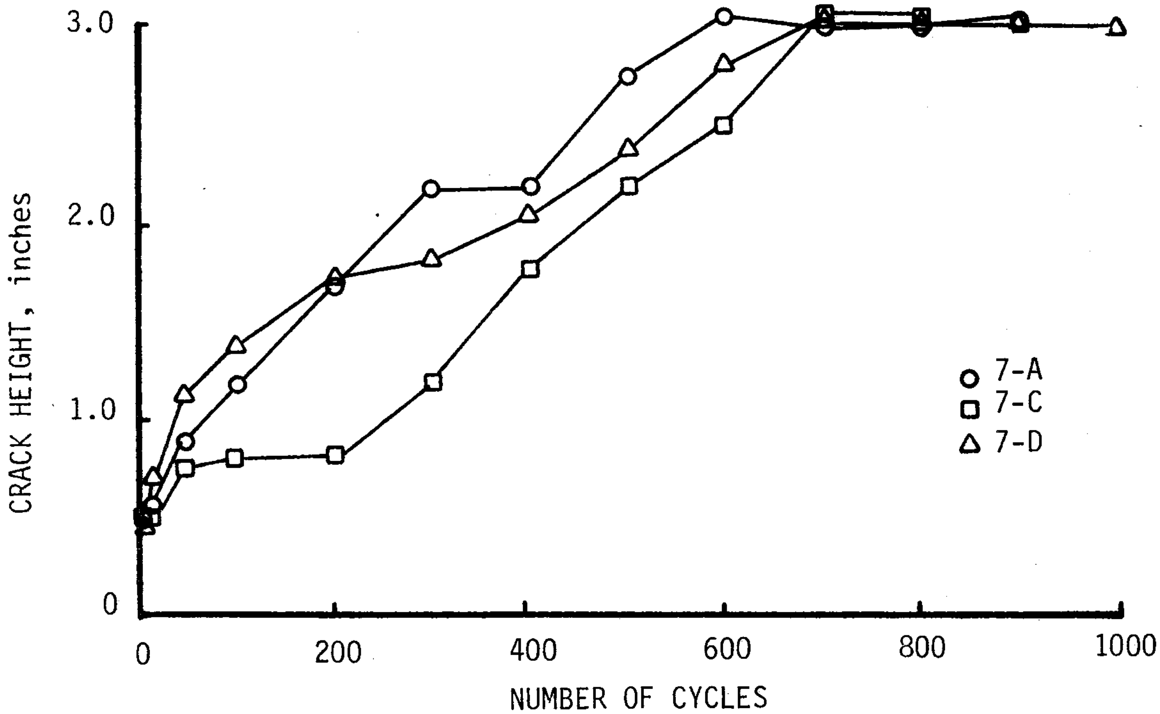


FIGURE D7. Crack Height versus Number of Cycles for Specimens Containing 1.4% of 15x5 Fibers.

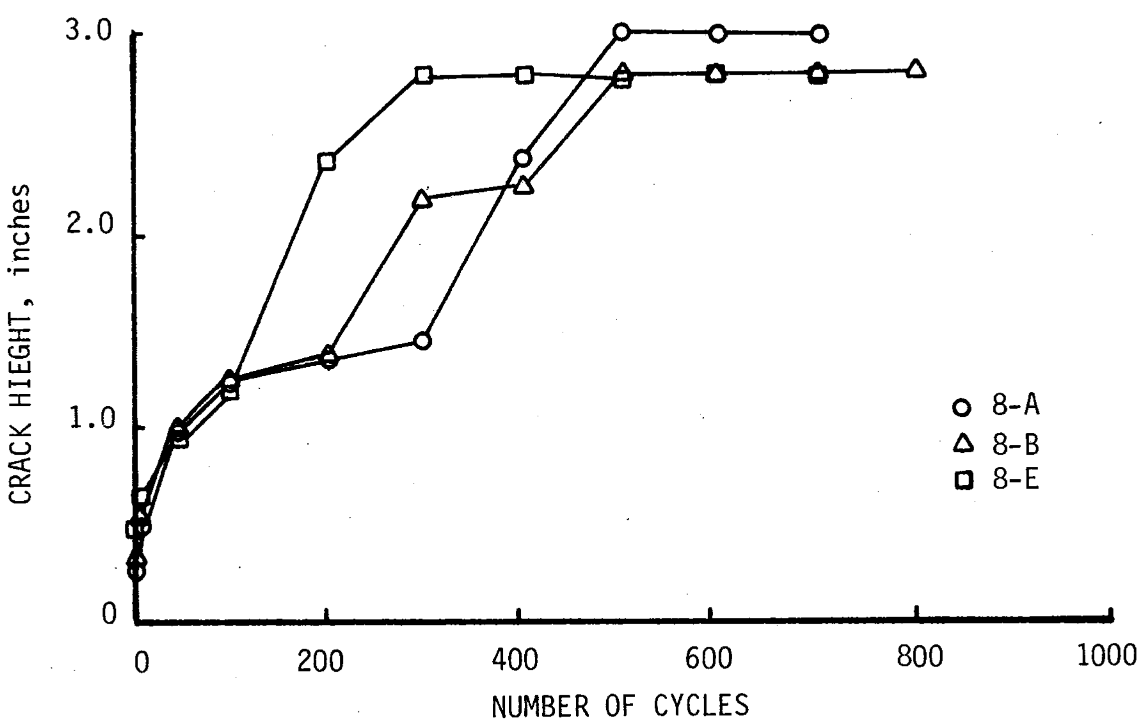


FIGURE D8. Crack Height versus Number of Cycles for Specimens Containing 1.4% of 6x5 Fibers.

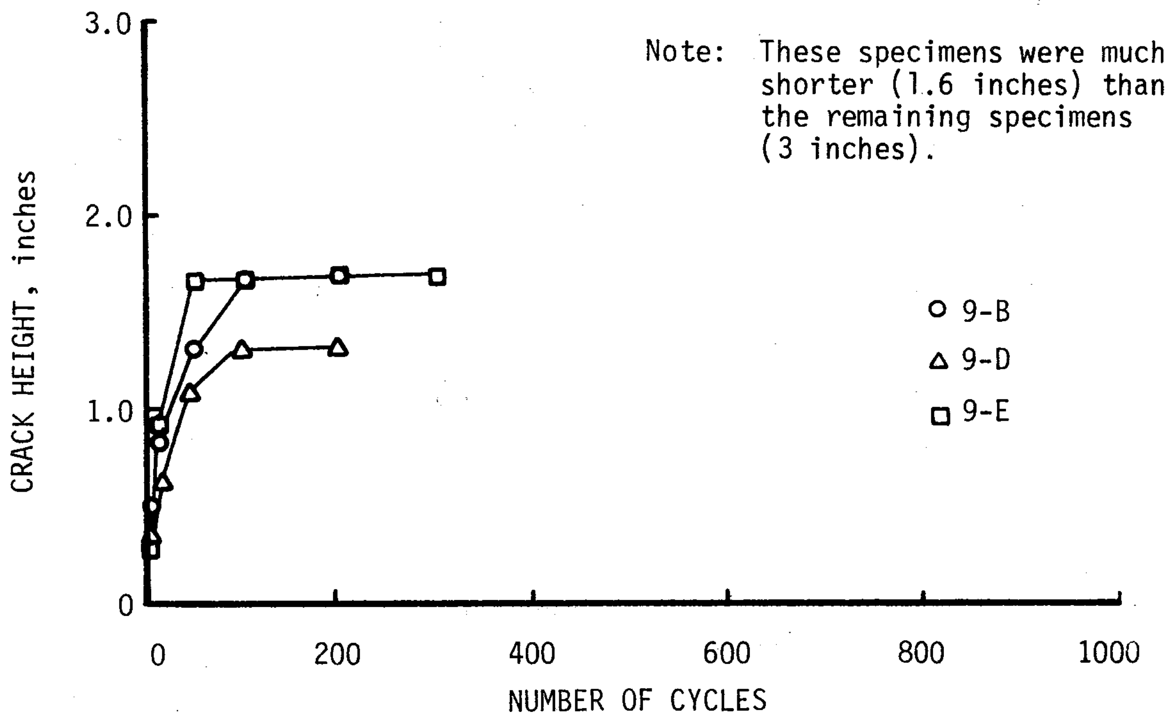


FIGURE D9. Crack Height versus Number of Cycles for Specimens Containing 2.0% of 3x5 Fibers.

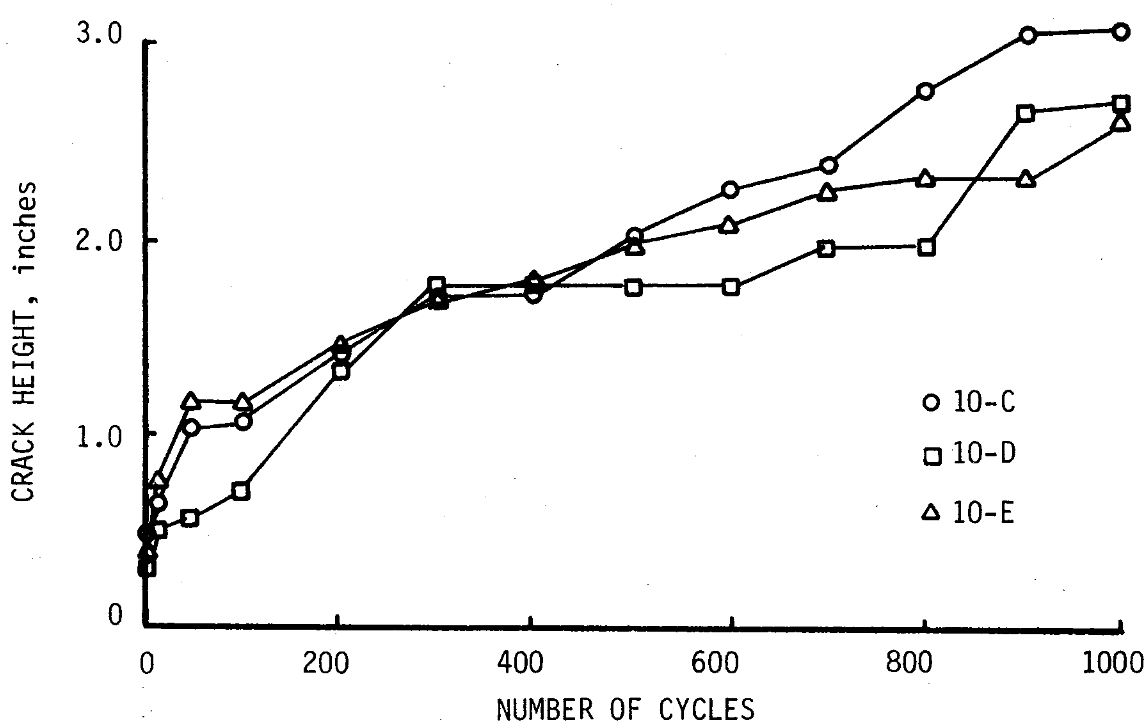


FIGURE D10. Crack Height versus Number of Cycles for Specimens Containing 2.0% of 15x5 Fibers.

APPENDIX E

Description of Experimental Program

Table E1. Marshall, Hveem and Resilient Modulus Test Program

Asphalt Content	Mixture Composition						
	Control	15 x 10 Fiber Concentration, % by wt. of mixture				3 x 5 Fiber Concentration, wt. %	
		0.2 (Washed)	0.4 (Washed)	0.2 (Unwashed)	0.4 (Unwashed)	0.2 (Unwashed)	0.4 (Unwashed)
Opt --	M, H, M_{R1}	M, H, M_{R1}	M, H, M_{R1}	M	M	-	-
Opt -	M, H, M_{R1}	M, H, M_{R4}	M, H, M_{R1}	M	M	M, H, M_{R1}	M
Optimum	M, H, M_{R4}	M, H, M_{R4}	M, H, M_{R1}	M	M	M, H, M_{R1}	-
Opt +	M, H, M_{R1}	M, H, M_{R1}	M, H, M_{R1}	M	M	M, H, M_{R1}	-
Opt ++	M, H, M_{R1}	M, H, M_{R1}	M, H, M_{R1}	M	M	-	-

M = Marshall compaction and testing

H = Gyratory compaction and Hveem testing

M_{R1} = Resilient Modulus of gyratory compacted specimens at 1 temperature (77°F)

M_{R4} = Resilient Modulus of gyratory compacted specimens at 4 temperatures (-13, 32, 68, 77, 104°F)

Table E2. Direct Tension Test Program @ 32°F (0°C)

FIBER CONTENT, wt. percent \ DEFORMATION RATE, in/min	2	0.02	0.002
0	X	X	X
0.2	A, C, D, E, F	A, C, D, E, F	A, B, C, D, E, F
0.4	-	A, D	A, D, E
0.8	-	D	D

A - 3 x 5 fibers

B - 3 x 10 fibers

C - 3 x 15 fibers

D - 15 x 5 fibers

E - 15 x 10 fibers

F - 15 x 15 fibers

X - No fibers (Control Specimens)