

MECHANICAL PROPERTIES OF FIBER-REINFORCED
ASPHALT CONCRETE

Report RF 3835-1

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INTRODUCTION

Asphalt concrete which is a widely used pavement construction, rehabilitation and maintenance material has relatively low strength and strain properties at failure. Improved stress-strain characteristics will extend the useful life and hence life cycle cost of pavements constructed with asphalt concrete.

Over the years, many techniques have been investigated to improve the strength properties of asphalt concrete. One method with demonstrated merit involves reinforcement of the mixture with fibers and fabrics (1-6). Potential pavement performance improvements include:

1. Reduced cracking due to repeated traffic loads (fatigue cracking)
2. Reduced cracking due to thermal loading (thermal cracking)
3. Reduced cracking due to reflection of cracks from cracked layers below the asphalt concrete layer (reflection cracking)
4. Reduced cracking due to volume changes occurring in the base, subbase and/or subgrade
5. Reduce wheel path depressions and corrugations (rutting and stability failures)

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. Increased stability

5. Shear strength

6. Shear strain at failure

It should be recognized that these properties are highly dependent upon the temperature and rate of loading or deformation used to define the mechanical property.

Literature

Bucking, Elliott and Reyneveld have prepared an extensive review of the literature associated with reinforced asphalt concrete paving mixtures (2). To date most of the reinforcement used has been continuous rather than particulate. Particulate fibers used to date include asbestos (6-12), cotton (2) and fiberglass (2). Continuous reinforcement in the form of welded wire, synthetic yarns and fabrics has been used in the United States for over 30 years.

Bushing and Antrim (1) 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. Bushing and Antrim (1) 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 Bushings unconfined compression tests while Figure 2 shows results from his rupture test (1).

Puzinauskas (6) has indicated 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 (6). In addition, asbestos fibers have a proven effectiveness to improve the low temperature cracking properties of asphalt concrete mixtures.

Based on the above literature review, it is apparent that certain types of fibers can be successfully used as a reinforcement in asphalt concrete mixtures. These fibers and asphalt concrete must have compatible mechanical, chemical and thermal properties. Asbestos is a natural fiber with suitable properties; however, EPA considers asbestos fibers a health hazard and these fibers are no longer used. Synthetic fibers because their properties can be tailor made, offer promise as an asphalt concrete reinforcement.

Research Study

Because of the potential benefits cited above, the E. I. DuPont de Nemours and Company sponsored a research program at Texas A&M University with the following objectives:

1. Establishment of the relative reinforcing effect of a single fiber chopped into lengths of 1/4, 1/2 and 3/4 inches.
2. Determination of the comparative stress-strain behavior of asphalt concrete mixtures containing chopped fibers.
3. Definition of the low temperature properties of fiber reinforced asphalt concrete for prediction of low temperature cracking.

A two-phase research program was formulated by the research sponsor and research agency. The Phase A test program is shown in Table 1. Direct tension tests were used to determine the effect of fiber length, fiber

content and asphalt content on the tensile stress-strain properties of asphalt concrete.

The Phase B research program was formulated by the research sponsor and research agency based on results from Phase A and the overall project objectives. The purpose of this second phase was to determine the effect of test temperature, test deformation rate and asphalt content on an asphalt concrete containing a single fiber size and content. Direct-tension, Resilient Modulus and both Marshall and Hveem stability tests were performed (Table 2 and Figure 6).

MATERIALS AND MIXTURES

The asphalt cement and aggregates used in this study are utilized as laboratory standard materials in the Texas Transportation Institute Materials Testing Laboratory. The fibers utilized in the study were supplied by the E. I. DuPont de Nemours and Company. Properties of the fibers were not supplied by the manufacturer nor were they determined by Texas A&M University. Basic properties of the asphalt cement, aggregates and mixture design information are given below.

Asphalt Cement

The asphalt cement utilized in the study was supplied by the American Petrofina Company from its Mt. Pleasant refinery. The physical-chemical characteristics of the vacuum distilled asphalt are shown in Table 3. The asphalt cement meets all the requirements of an AC-10 asphalt cement as specified by ASTM and AASHTO.

Aggregates

Two aggregates were utilized for this study. Both aggregates are utilized as laboratory standard aggregates and were selected for their widely varied shape and surface characteristics as well as their surface chemistry. The washed, subrounded, siliceous gravel was obtained from the Gifford-Hill plant near the Brazos River in Brazos County, Texas. The second aggregate was obtained from White's Mines quarry near Brownwood, Texas. This material is a very hard crushed limestone. Properties of the two aggregates are shown in Table 4.

Both aggregates were separated into fractions sized from 3/4 inch to minus No. 200 mesh and recombined to meet the ASTM D-3515 5A grading specification. Figure 7 shows the gradation utilized in this research study.

Mixture Design

For comparison purposes a standard asphalt concrete mixture was prepared and tested. Mixtures prepared from the laboratory standard asphalt cement and aggregate were selected for this purpose. Determination of the optimum asphalt cement content for these mixtures was performed according to established procedures. These procedures have been reviewed and test data from these tests are summarized in Appendix B. The resulting properties will be utilized for comparison purposes later in the report.

Asphalt concrete mixtures containing fibers were designed with various fiber concentrations expressed as a percent by dry weight of aggregate (0.25, 0.50 and 0.75). Asphalt cement contents were varied

as follows for Phase A; optimum, optimum plus 20 percent of optimum and optimum plus 40 percent of optimum. Phase B mixtures were prepared at optimum, optimum plus 5 percent of optimum and optimum plus 20 percent of optimum. Asphalt cement contents for the mixtures used in this study are given below and are expressed as a percent by dry weight of aggregate.

| | <u>Gravel</u> | <u>Limestone</u> |
|-------------------------|---------------|------------------|
| Optimum asphalt content | 3.8 | 4.5 |
| Optimum plus 5 percent | 4.0 | 4.7 |
| Optimum plus 20 percent | 4.6 | 5.4 |
| Optimum plus 40 percent | 5.3 | 6.3 |

Additional properties describing the laboratory standard mixtures can be obtained from References 13 and 14.

TEST PROCEDURES

Direct tension, resilient modulus, Hveem stability and Marshall stability tests were performed on mixtures prepared in this study. A brief description of the test procedures for each of these tests follows.

Direct Tension

Results from tensile tests can be used to define a materials stress-strain behavior to failure, predict thermal cracking as well as provide information for crack prediction models based on fracture mechanics theory. Uniaxial tensile tests were conducted on laboratory molded samples (Figure 8).

All samples were prepared with the laboratory standard asphalt cement

and aggregate and with various types and concentrations of fiber. The aggregate was introduced into the mixing bowl followed by the fiber and asphalt cement. The aggregate and fiber were premixed for 30 seconds prior to introduction of the asphalt cement. Mixing was performed at 300°F and the samples were molded at 250°F in a 2 x 3 x 15 inch beam mold using a modified Soil-Test Model CN-425 Kneading Compactor with a 3 x 4 inch tamping foot applying 35 tamps on the 1.75 inch layer. A leveling load of 12,000 pounds for 5 seconds was applied to the sample. Samples were cut into 1.5 x 1.5 x 5 inch prisms for testing with an Instron controlled rate of deformation machine.

Aluminum end caps were epoxied to the sample ends and dual LVDT's attached to the sides of the samples to record displacement. The load was measured with the Instron load cell. A continuous load deformation trace was obtained during the direct tension tests. Plots of stress and strain to failure were prepared for each sample tested.

Resilient Modulus

The resilient modulus is an approximation of the elastic modulus of a material measured under dynamic loads. The equation for calculating the resilient modulus is given below.

$$M_R(t, T) = \frac{\sigma}{\epsilon_R}$$

where

M_R = Resilient Modulus, psi

t = Time of loading, seconds

T = Temperature, °F

σ = Applied stress, psi

ϵ_R = Resilient or recovered strain, in/in

Thus, resilient modulus must be reported with the time of loading and temperature used for the test.

A Mark III Resilient Modulus Device developed by Schmidt was utilized in this study (15) (Figures 9 and 10). The load duration was 0.1 second. Twenty load pulses per minute were utilized. Test temperatures were 104, 77, 32, 0 and -10°F.

Hveem Stability

The Hveem stability value of asphalt concrete is a measure of the materials ability to resist plastic flow. Mixtures with adequate Hveem stability will not shove, corrugate or rut. 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.

Mixing of these samples was performed at 300°F and compacted at 250°F with the Marshall hammer (ASTM D-1559) (50 blows per face). Testing was performed according to ASTM D-1560. It should be noted that the standard method for preparation of Hveem stability samples is either kneading or gyratory compaction rather than the impact compaction used in this study.

Marshall Stability

The Marshall stability and flow values of an asphalt concrete material are measures of the materials ability to resist plastic flows. Mixtures with adequate Marshall stability and flow will not shove, corrugate or rut. The test was developed in the late 1930's and early 1940's by the Mississippi highway department and the U. S. Army Corps of Engineers. The test is used by a large number of states in the United States as well as by a number of countries throughout the world.

Mixing of these samples was performed at 300°F and compacted at 250°F according to the method described in ASTM D-1559 (50 blows per face). Testing was performed according to the same test method.

TEST RESULTS - PHASE A

Direct tension tests conducted at 32°F and 0.002 inches per minute were utilized to define the effect of fiber length, fiber content, and asphalt content on the tensile stress-strain properties of asphalt concrete (Table 1). Table 5 presents a summary of the strength, strain at failure and modulus at failure for each sample tested.

Stress-Strain plots for each sample are shown in Appendix A. A review of these figures indicates that data scatter exists among the three replicate samples in some cases. When excessive data scatter was evident, a fourth sample was tested and the stress and strain at failure data plotted on the appropriate figure. The average of three tests were utilized to determine representative average test result values (Table 5).

Data scatter obtained in this study is typical of that associated with the tensile testing of asphalt concrete. A typical stress-strain plot obtained for three replicate samples is shown in Figure 11. A review of data presented in Appendix A will indicate that Figure 11 contains more data scatter than the majority of the replicate tests conducted.

The effects of fiber length, fiber content and asphalt content on the tensile stress-strain properties of asphalt concrete are shown on Figures 12-17. Specific relationships are given below.

Fiber Length

Figures 18 and 19 illustrates the relationships between stress and

strain at failure and fiber length for a fiber concentration of 0.50 percent in asphalt concrete mixtures of various asphalt contents. At optimum asphalt contents the strength varies slightly with increase in fiber length while a slight decrease in strength is noted with increase in fiber length at the higher asphalt contents. From a statistical standpoint it is difficult to prove that fiber length has a significant effect on tensile strength. With additional testing it may be possible to illustrate a slight decrease in strength with increase in fiber length (Figures 12, 13 and 14).

Figure 19 indicates that a significant relationship does not exist between fiber length and strain at failure. A slight decrease in strain at failure is noted with increase in fiber length.

Figures 20 and 21 illustrate the effect to fiber length on stress and strain at failure for mixtures containing various concentrations of fibers. Figures 20 and 21 illustrates that fiber length does not significantly effect strength or strain at failures for mixtures containing a range of fiber concentrations.

Fiber Content

Figures 22 to 27 illustrates the relationships between stress and strain at failure and fiber length for mixtures at various asphalt contents and containing fibers of various lengths. At optimum and optimum plus 20 percent asphalt contents, the strength of fiber reinforced asphalt concrete decrease with fiber concentration (Figures 22 and 23). This relationship holds for all fiber lengths. Little strength changes occurred at high asphalt contents (Figure 24).

It should be noted that control mixtures containing no fibers have strengths equal or greater than mixtures containing fibers.

Figure 25 indicates that strain at failures decreases with increase in fiber concentration. Because of the data scatter exhibited on this figure and the data contained on (Figures 15, 16 and 17) it is reasonable to assume that fiber concentration does not effect the strain at failure.

Asphalt Content

Figures 28 to 35 illustrate the relationship between stress and strain at failure and asphalt content for mixture containing different fibers and fiber concentrations. Figures 28 to 30 indicate that an optimum asphalt content exists for various concentrations of fibers. For fiber concentrations of 0.25 percent, the optimum asphalt contents for tensile strength is probably between 100 and 120 percent of optimum required for mixtures without fibers. For fiber concentrations of 0.50 percent, the optimum asphalt content for tensile strength is probably between 110 and 130 percent of optimum required for mixtures without fibers. For fiber concentrations of 0.75 percent, the optimum asphalt content for tensile strength is probably in excess of 140 percent of that required for mixtures without fibers.

Figures 15-17, 31 and 35 indicate that strain at failure increases as asphalt content increases. This same trend is noted in the conventional mixtures and is not surprising.

Summary

Direct tension tests conducted at 32°F and 0.002 inches per minute deformation rate indicate the following:

1. From a statistical standpoint it is difficult to prove that fiber length has a significant effect on tensile strength and tensile strain at failure.
2. At the lower asphalt contents utilized in this study the tensile strength decreased with an increase in fiber concentration. Tensile strain at failure is little effected by the fiber concentration over the range of asphalt contents tested in this study.
3. In order to achieve maximum tensile strength in mixtures containing fibers, the asphalt content must be increased over that required for a conventional mixture containing no fibers. An optimum asphalt content exists depending upon the fiber concentration and to a lesser degree the length of fiber.
4. The addition of fibers to asphalt concrete decreased its tensile strength (Figures 12-14). Only modest increases in failure strains were noted with the addition of fibers (Figures 15-17).
5. Reinforced mixtures containing low fiber concentrations have the highest strengths and the highest strains at failure (for levels of reasonable asphalt contents).

TEST RESULTS-PHASE B

Table 2 and Figure 6 describe the test plan utilized in Phase B. Direct tension, stability and resilient modulus tests were performed on mixtures containing 1/4 inch fibers at a concentration of 0.25 percent. Mixtures were prepared at three asphalt contents.

The fiber concentration of 0.25 percent was selected based on optimal mixture properties as discussed above. The fiber length of 1/4

inch was selected based on field mixing ease and efficiency. The asphalt content range was selected for optimum properties as discussed above as well as economy. Test results are discussed below.

Direct Tension

Stress-strain properties of the mixtures were obtained over a range of temperature and rate of deformation for four different mixtures (Table 2). Individual stress-strain plots can be found in Appendix A while Table 6 presents a summary of the strength, strain at failure and modulus at failure for each sample tested.

Effect of Temperature. Figures 36 and 37 illustrate the effect of temperature on the strength and strain at failure of reinforced asphalt concrete tested at a deformation rate of 2 inches per minute. An optimum tensile strength is indicated at 32°F while tensile strain at failure decreases as the temperature increases. These observed trends are not unusual. It is interesting to note that the control mixtures have a lower strength than the fiber reinforced mixtures when tested at this rapid rate of deformation. Likewise the strain at a failure for the control mixture is nearly identical to that of the fiber reinforced mixtures.

Effect of Deformation Rate. Figures 38 to 40 illustrate the effect of deformation rate on the strength and strain at failure of reinforced asphalt concrete tested at 32°F. As expected a substantial increase in strength and reduction in strain at failure is noted as the rate of deformation is increased. The benefits of fibers in asphalt concrete mixtures are most readily apparent at high rates of loading and at

temperatures near 32°F. It is interesting to note that differences in strength and strain at failure created by the addition of fibers is smaller in magnitude than these same differences associated with changes in test temperature and rate of deformation.

Resilient Modulus

Tables 7 and 8 and Figures 41 and 42 illustrate the effect of asphalt content and test temperature on the resilient modulus of asphalt concrete. Figure 41 indicates that little increase in resilient modulus can be obtained by reinforcing asphalt concrete with fibers except at higher temperatures. Figure 42 suggests that fiber reinforced mixtures have an optimum asphalt content for maximum resilient modulus.

Conventional mixtures behave in a similar manner.

Hveem Stability

Figure 43 indicates that a substantial improvement in Hveem stability can be achieved with the use of fiber in mixtures containing subrounded aggregates. Figure 44 indicates that little or no improvement in Hveem stability results with the use of fibers in mixtures containing crushed aggregates.

Marshall Stability and Flow

Figures 45 and 46 indicates that Marshall stability and flow values can be improved with the addition of fibers to mixtures containing subrounded aggregates. Figure 47 indicates that stability can be reduced with the addition of fibers to mixtures containing crushed aggregates. Stability values are, however, above acceptable levels at

the lower asphalt contents tested.

Figure 48 suggests that flow values may increase slightly for some mixtures containing fibers. The flow values are, however, within suitable limits.

Summary

Tests conducted during the Phase B laboratory program indicate the following:

1. Tests conducted at rapid rates of deformation indicate that fiber reinforced mixtures have a higher strength.
2. A substantial increase in strength and reduction in strain at failure is noted as the rate of deformation is increased. The benefits of fibers in asphalt concrete mixtures are most readily apparent at high rates of loading and at temperatures near 32°F.
3. The differences in strength and strain at failure created by the addition of fibers is smaller in magnitude than these same differences associated with changes in test temperatures and rate of deformation.
4. Except at high temperatures the resilient modulus of unreinforced and fiber reinforced mixtures are nearly identical. The difference at high temperatures appears to be small.
5. The addition of fibers to mixtures containing marginal aggregates (aggregates that cause low stability mixes) will substantially increase stability.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based on the data presented in this report and the literature received, the following conclusions are warranted.

1. Fiber length does not have a significant effect on tensile stress and strain at failure.

2. At asphalt cement contents near those required for conventional mixtures (mixtures without fibers), the tensile strength will decrease with an increase in fiber concentration. Tensile strain at failure is little effected by the fiber concentration.

3. In order to achieve maximum tensile strength in mixtures containing fibers, the asphalt content must be increased over that required for conventional mixtures.

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

5. The differences in strength and strain at failure created by the addition of fibers is smaller in magnitude than these same differences associated with changes in test temperature and rate of deformation.

6. The resilient modulus is little effected by fiber reinforcement except at high temperatures.

7. The addition of fibers to low stability mixes will alter properties sufficiently to prevent shoving, corrugation and rutting types of failures.

Recommendations

The study reported above should be considered as only a first stage program that briefly investigated the influence of fiber reinforcement on the reduction of thermal cracking and stability associated pavement problems. Testing programs should be formulated and conducted to investigate the influence of fiber reinforcement on

1. Permanent deformation
2. Fatigue resistance
3. Reflection cracking
4. Water susceptibility and
5. Maintenance materials.

In addition different types of fibers should be investigated as well as the cost effectiveness of the use of fiber reinforced in asphalt concrete mixtures.

REFERENCES

1. Busching, H.W., and J.D. Antrim, "Fiber Reinforcement of Bituminous Mixtures," AAPT, Vol. 37, 1968.
2. Busching, H.W., E.H. Elliott and N.G. Reyneveld, "A State-of-the-Art Survey of Reinforced Asphalt Pairing," AAPT, Vol. 39, 1970.
3. den Hoedt, G., "Reinforcement Fabrics for Bituminous Roads," Textile Institute and Industry, November 1969.
4. Reyneveld, N.G., "The Reinforcement of Asphalt - Some Observations," Technical Bulletin, AS 15227, November 1968.
5. Zichner, Gerhard, "Design and Construction of Asphaltic Bridge Pavements in Germany," AAP, Vol. 35, 1966.
6. Puzinauskas, V.P., "Filler in Asphalt Mixtures," Research Report 69-2, The Asphalt Institute, February 1969.
7. "Asbestos Admixture in Asphalt Concrete," New York State Department of Public Works, Bureau of Physical Research, Physical Research Project, Engineering Research Series, Research Report RR60-5, (December, 1960), 22 pages plus appendix.
8. R. Hansen, et. al., "Effects of Asbestos Fibers in Asphaltic Concrete Paving Mixtures," Waterways Experiment Station, Miscellaneous Papers 4-355, Vicksburg, Mississippi, April, 1959, 5 pages plus tables and figures.
9. B.F. Kallas and H.C. Krueger, "Effects of Consistency of Asphalt Cements and Types of Mineral Filler on the Compaction of Asphalt Concrete," Proceedings of the Association of Asphalt Paving Technologists, Vol. 29, (1960) pp. 152-171.
10. J.H. Keitzman, "Effect of Short Asbestos Fibers on Basic Physical Properties of Asphalt Pavement Mixes." Highway Research Board Bulletin 270, Washinton, D.C. (1960) pp. 1-19.
11. T.L. Speer and J.H. Keitzman, "Control of Asphalt Pavement Rutting with Asbestos Fiber," Highway Research Board Bulletin 329 Washington D.C. (1962), pp. 64-82.
12. David A. Tamburro, Henry T. Blekicki, and John H. Keitzman, "The Effects of Short Chrysotile Asbestos Fiber on the Structural Properties of Asphalt Pavements," Proceedings of the Association of Asphalt Paving Technologist, Vol. 31 (1962), pp. 151-175.

13. 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.
14. Button, J.W. and Mahoney, J.P., "Statistical Summary of Resilient Modulus Measurements," Research Brief No. 2, Materials Division, Texas Transportation Institute, July 1977.
15. Schmidt, R.J., "A Practical Method for Measuring the Resilient Modulus of Asphalt-Treated Mixes," Highway Research Record No. 404, Highway Research Board, 1972.
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. Phase A Direct Tension Test Program.

| | 0 | 0.25 | | | 0.50 | | | 0.75 | | |
|------------------|----|------|-----|-----|------|-----|-----|------|-----|-----|
| | 0 | 1/4 | 1/2 | 3/4 | 1/4 | 1/2 | 1/4 | 1/4 | 1/2 | 3/4 |
| Optimum | 3* | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Optimum + 20% | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Optimum + 40% | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

90 TOTAL SAMPLES

All test conducted at 32°F and 0.002 inches per minute deformation rate on an asphalt concrete mixture containing a gravel aggregate.

* Indicates number of samples prepared and tested.

Table 2. Phase B Direct Tension Test Program.

| | 77 | | | 32 | | | 0 | | | -20 | | |
|---------------------|----------------|------|-------|----|------|-------|---|------|-------|-----|------|-------|
| | 2 | 0.02 | 0.002 | 2 | 0.02 | 0.002 | 2 | 0.02 | 0.002 | 2 | 0.02 | 0.002 |
| Optimum | 3 [*] | | | 3 | 3 | 3 | 3 | | | 3 | | |
| Optimum + 5% | 3 | | | 3 | 3 | 3 | 3 | | | 3 | | |
| Optimum + 20% | 3 | | | 3 | 3 | 3 | 3 | | | 3 | | |
| Control (no fabric) | 3 | | | 3 | 3 | 3 | 3 | | | 3 | | |

72 TOTAL SAMPLES

All tests conducted with a 1/4 inch fiber, 0.25% fiber by weight of aggregate on an asphalt concrete mixture containing a gravel aggregate.

* Indicates number of samples prepared and tested.

Table 3. Asphalt Cement Properties.

| Asphalt Code | LS* |
|---|-----------------------|
| Production Method | Vacuum Distribution |
| Viscosity, 77°F (25°C) poise | 5.8 x 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) | 68 |
| Duct. of Residue, 77°F (25°C) | 150+ |
| Vis. of Residue, 140°F (60°C) | 3050 |
| Loss of Heating | Neg. |
| Hardening Index (due to Actinic light) | 1.9 |
| Vanadium Content, ppm de-ashed Asphalt) | 3.4 |

* LS - Laboratory Standard

Table 4. Physical Properties of Aggregates.

| Physical Property | Designation | Aggregate Grading | Test Results | |
|---|-------------------------------------|---------------------------------|--------------|-----------|
| | | | Gravel | 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 | 2.580 | 2.589 |
| Apparent Specific Gravity | AASHTO T 84 | Gradation | 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 | Centifuge 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.

Table 5. Phase A Direct Tensile Test.

| Asphalt Content, Percent of Optimum | Fiber Concentration Percent By Wt. of | Fiber Length, Inch. | Stress at Failure psi | Strain at Failure | Modulus at Failure, $\text{psi} \times 10^3$ |
|-------------------------------------|---------------------------------------|---------------------|-----------------------|-------------------|--|
| 100 | 0 | 0 | 90.4 | 0.0049 | 18.5 |
| | | | 81.6 | 0.0055 | 14.8 |
| | | | 75.6 | 0.0049 | 15.4 |
| | | | 82.5 | 0.0051 | 16.2 |
| | 0.25 | 1/4 | 96.8 | 0.0076 | 13.0 |
| | | | 71.0 | 0.0080 | 8.9 |
| | | | 73.5 | 0.0049 | 15.0 |
| | | | 80.4 | 0.0068 | 12.3 |
| | | 1/2 | 72.9 | 0.0104 | 7.0 |
| | | | 79.1 | 0.0050 | 15.8 |
| | | | 88.3 | 0.0060 | 14.7 |
| | | | 80.1 | 0.0071 | 12.5 |
| | | 3/4 | 66.5 | 0.0080 | 8.3 |
| | | | 54.0 | 0.0043 | 12.6 |
| | | | 71.1 | 0.0049 | 14.5 |
| | | | 63.9 | 0.0057 | 11.8 |
| | 0.50 | 1/4 | 61.8 | 0.0083 | 7.5 |
| | | | 31.3 | 0.0027 | 11.6 |
| | | | 37.4 | 0.0045 | 8.3 |
| | | | 43.5 | 0.0052 | 9.1 |
| | | 1/2 | 50.3 | 0.0066 | 7.6 |
| | | | 62.2 | 0.0053 | 11.7 |
| | | | 46.8 | 0.0062 | 7.6 |
| | | | 53.1 | 0.0060 | 8.9 |
| | | 3/4 | 56.7 | 0.0040 | 14.2 |
| | | | 57.8 | 0.0070 | 8.3 |
| | | | 46.1 | 0.0065 | 7.1 |
| | | | 53.5 | 0.0058 | 9.9 |

(Continued)

Table 5. Continued.

| Asphalt Content, Percent of Optimum | Fiber Concentration Percent By Wt. of | Fiber Length, Inch. | Stress at Failure psi | Strain at Failure | Modulus at Failure, ³ psi, x 10 ³ |
|-------------------------------------|---------------------------------------|---------------------|-----------------------|-------------------|---|
| | 0.75 | 1/4 | 54.2 | 0.0075 | 7.5 |
| | | | 38.6 | 0.0052 | 7.4 |
| | | | 39.8 | 0.0061 | 6.5 |
| | | | 44.2 | 0.0063 | 7.1 |
| | | 1/2 | 46.2 | 0.0073 | 6.3 |
| | | | 53.4 | 0.0042 | 12.7 |
| | | | 41.2 | 0.0052 | 7.9 |
| | | | 46.9 | 0.0056 | 9.0 |
| | | 3/4 | 38.1 | 0.0052 | 7.3 |
| | | | 34.5 | 0.0042 | 8.2 |
| | | | 34.1 | 0.0075 | 4.5 |
| | | | 35.6 | 0.0056 | 6.7 |
| | 0 | 0 | 113.0 | 0.0056 | 20.2 |
| | | | 96.3 | 0.0070 | 13.8 |
| | | | 142.0 | 0.0047 | 30.2 |
| | | | 117 | 0.0058 | 21.4 |
| | 0.25 | 1/4 | 105.6 | 0.0155 | 6.8 |
| | | | 88.1 | 0.0058 | 15.2 |
| | | | 98.9 | 0.0106 | 9.3 |
| | | | 97.4 | 0.0106 | 10.4 |
| | | 1/2 | 65.9 | 0.0152 | 4.3 |
| | | | 67.7 | 0.0112 | 6.0 |
| | | | 89.2 | 0.0075 | 11.9 |
| | | | 74.3 | 0.0113 | 7.4 |
| | | 3/4 | 96.6 | 0.0042 | 23.0 |
| | | | 89.2 | 0.0070 | 12.7 |
| | | | 95.7 | 0.0066 | 14.5 |
| | | | 93.8 | 0.0059 | 16.7 |

(Continued)

Table 5. Continued.

| Asphalt Content, Percent of Optimum | Fiber Concentration Percent By Wt. of | Fiber Length, Inch. | Stress at Failure psi | Strain at Failure | Modulus at Failure, ³ psi, x 10 ³ |
|-------------------------------------|---------------------------------------|---------------------|-----------------------|-------------------|---|
| 120 | 0.50 | 1/4 | 56.7 | 0.0056 | 10.1 |
| | | | 68.6 | 0.0067 | 10.2 |
| | | | 58.0 | 0.0063 | 9.2 |
| | | | 61.1 | 0.0062 | 9.8 |
| | | 1/2 | 56.6 | 0.0084 | 6.7 |
| | | | 68.6 | 0.0077 | 8.9 |
| | | | 64.2 | 0.0073 | 8.8 |
| | | | 63.1 | 0.0078 | 8.1 |
| | | 3/4 | 41.7 | 0.0056 | 7.4 |
| | | | 51.9 | 0.0065 | 8.0 |
| | | | 67.3 | 0.0063 | 10.7 |
| | | | 53.6 | 0.0062 | 8.7 |
| | 0.75 | 1/4 | 39.1 | 0.0046 | 8.5 |
| | | | 44.9 | 0.0081 | 5.5 |
| | | | 53.9 | 0.0070 | 7.7 |
| | | | 46.0 | 0.0066 | 7.2 |
| | | 1/2 | 36.5 | 0.0062 | 5.9 |
| | | | 45.9 | 0.0091 | 5.0 |
| | | | 40.0 | 0.0066 | 6.1 |
| | | | 40.8 | 0.0073 | 5.6 |
| | | 3/4 | 27.9 | 0.0063 | 4.4 |
| | | | 55.2 | 0.0058 | 9.5 |
| | | | 39.7 | 0.0038 | 10.4 |
| | | | 40.9 | 0.0053 | 8.1 |
| | 0 | 0 | 84.5 | 0.0094 | 8.9 |
| | | | 84.1 | 0.0129 | 6.5 |
| | | | 74.7 | 0.0108 | 6.9 |
| | | | 81.1 | 0.0110 | 7.5 |

(Continued)

Table 5. Continued.

| Asphalt Content, Percent of Optimum | Fiber Concentration Percent By Wt. of | Fiber Length, Inch. | Stress at Failure psi | Strain at Failure | Modulus at Failure, ³ psi, x 10 ³ |
|-------------------------------------|---------------------------------------|---------------------|-----------------------|-------------------|---|
| 140 | 0.25 | 1/4 | 62.4 | 0.0101 | 6.2 |
| | | | 71.6 | 0.0101 | 7.1 |
| | | | 67.1 | 0.0101 | 6.6 |
| | | | 67.0 | 0.0101 | 6.6 |
| | | 1/2 | 52.3 | 0.0094 | 5.6 |
| | | | 49.3 | 0.0157 | 3.1 |
| | | | 51.8 | 0.0112 | 4.6 |
| | | | 51.1 | 0.0121 | 4.4 |
| | | 3/4 | 20.4 | 0.0083 | 2.5 |
| | | | 34.6 | 0.0077 | 4.5 |
| | | | 33.5 | 0.0060 | 5.6 |
| | | | 29.5 | 0.0073 | 4.2 |
| | 0.50 | 1/4 | 68.7 | 0.0104 | 6.6 |
| | | | 60.6 | 0.0105 | 5.8 |
| | | | 64.3 | 0.0087 | 7.4 |
| | | | 64.5 | 0.0099 | 6.6 |
| | | 1/2 | 43.5 | 0.0080 | 5.4 |
| | | | 39.1 | 0.0061 | 6.4 |
| | | | 40.7 | 0.0063 | 6.5 |
| | | | 41.1 | 0.0068 | 6.1 |
| | | 3/4 | 44.2 | 0.0077 | 5.7 |
| | | | 42.7 | 0.0070 | 6.1 |
| | | | 20.7 | 0.0058 | 3.6 |
| | | | 35.9 | 0.0068 | 5.1 |
| | | 1/4 | 48.7 | 0.0082 | 5.9 |
| | | | 49.9 | 0.0126 | 4.0 |
| | | | 62.5 | 0.0112 | 5.6 |
| | | | 53.7 | 0.0107 | 5.2 |

(Continued)

Table 5. Continued.

| Asphalt Content, Percent of Optimum | Fiber Concentration Percent By Wt. of | Fiber Length, Inch. | Stress at Failure psi | Strain at Failure | Modulus at Failure, $\times 10^3$ psi |
|-------------------------------------|---------------------------------------|---------------------|-----------------------|-------------------|---------------------------------------|
| 140 | 0.75 | 1/2 | 49.3 | 0.0098 | 5.0 |
| | | | 45.4 | 0.0075 | 6.1 |
| | | | 51.7 | 0.0065 | 9.0 |
| | | | 48.8 | 0.0079 | 6.7 |
| | | 3/4 | 53.1 | 0.0075 | 7.1 |
| | | | 36.8 | 0.0058 | 6.3 |
| | | | 57.4 | 0.0080 | 7.2 |
| | | | 49.1 | 0.0071 | 6.9 |

Results conducted at 32°F and at a deformation rate of 0.002 inches per minute.

Table 6. Phase B Direct Tension Test Results*.

| Asphalt Content, Percent | Rate of Deformation in/min | Temperature of Test, °F | Stress at Failure, psi** | Strain at Failure, in/in** | Modulus at Failure psi x 10 ^{3***} | Average Air Void Content, Percent | | |
|--------------------------|----------------------------|-------------------------|--------------------------|----------------------------|---|-----------------------------------|------|------|
| Control | 2.000 | 77 | 72 | 0.00820 | 9 | 7.31 | | |
| | | 32 | 205 | 0.00020 | 1000 | | | |
| | | 0 | 133 | 0.00020 | 670 | | | |
| | | -10 | 157 | 0.00006 | 2600 | | | |
| Control | 0.020 | 77* | 135 | 0.00350 | 38 | | 7.31 | |
| | | 32 | | | | | | |
| | | 0* | | | | | | |
| | | -10* | | | | | | |
| Control | 0.002 | 77* | 53 | 0.00550 | 10 | | | 7.31 |
| | | 32 | | | | | | |
| | | 0* | | | | | | |
| | | -10* | | | | | | |
| Optimum | 2.000 | 77 | 63 | 0.00930 | 7 | 8.72 | | |
| | | 32 | 283 | 0.00020 | 1400 | | | |
| | | 0 | 191 | 0.00020 | 960 | | | |
| | | -10 | 143 | 0.00004 | 3600 | | | |
| Optimum | 0.020 | 77* | 148 | 0.00280 | 53 | | 8.72 | |
| | | 32 | | | | | | |
| | | 0* | | | | | | |
| | | -10* | | | | | | |
| Optimum | 0.002 | 77* | 71 | 0.00560 | 13 | | | 8.72 |
| | | 32 | | | | | | |
| | | 0* | | | | | | |
| | | -10* | | | | | | |
| Optimum Plus 5% | 2.000 | 77 | 64 | 0.00630 | 10 | | | |
| | | 32 | 315 | 0.00050 | 630 | | | |
| | | 0 | 161 | 0.00030 | 540 | | | |
| | | -10 | 269 | 0.00010 | 2700 | | | |

(Continued)

Table 6. Continued.

| Asphalt Content, Percent | Rate of Deformation in/min | Temperature of Test, °F | Stress at Failure, psi ^{**} | Strain at Failure, in/in ^{**} | Modulus at Failure, psi x 10 ^{3***} | Average Air Void Content, Percent |
|--------------------------|----------------------------|-------------------------|--------------------------------------|--|--|-----------------------------------|
| Optimum Plus 5% | 0.020 | 77 [*] | 167 | 0.00530 | 32 | 8.72 |
| | | 32 [*] | | | | |
| | | 0 [*] | | | | |
| | | -10 [*] | | | | |
| Optimum Plus 5% | 0.002 | 77 [*] | 66 | 0.00550 | 13 | |
| | | 32 [*] | | | | |
| | | 0 [*] | | | | |
| | | -10 [*] | | | | |
| Optimum Plus 20% | 2.000 | 77 | 70 | 0.00770 | 9 | 6.44 |
| | | 32 | 317 | 0.00050 | 630 | |
| | | 0 | 140 | 0.00008 | 1800 | |
| | | -10 | 189 | 0.00007 | 2700 | |
| Optimum Plus 20% | 0.020 | 77 [*] | 174 | 0.00520 | 33 | |
| | | 32 [*] | | | | |
| | | 0 [*] | | | | |
| | | -10 [*] | | | | |
| Optimum Plus 20% | 0.002 | 77 [*] | 85 | 0.00550 | 15 | |
| | | 32 [*] | | | | |
| | | 0 [*] | | | | |
| | | -10 [*] | | | | |

* Not included in test program

** Average of three values

*** Average stress divided by average strain

Table 7. Properties of Mixtures With One Fourth Inch Fibers, 25 Percent Fiber Concentration and Rounded River Gravel Aggregate.

| ASPHALT CONTENT, PERCENT | SAMPLE NO. | AIR VOIDS, PERCENT | RESILIENT MODULUS PSI X 10 ⁶ | | | | | HVEEM STABILITY 140°F | MARSHALL STAB. 140°F | |
|-----------------------------|---------------|--------------------------|---|--------|-------|-------|-------|-----------------------------|-------------------------|------|
| | | | 104°F | 77°F | 32°F | 0°F | -15°F | | STAB. | FLOW |
| OPTIMUM | 1 | 4.3 | 0.0750 | 0.2135 | 2.744 | 6.512 | 6.430 | 34 | 2000 | 8 |
| | 2 | 3.9 | 0.0734 | 0.2294 | 2.355 | 6.753 | 7.463 | 34 | 2175 | 9 |
| | 3 | 3.7 | 0.0671 | 0.2095 | 2.710 | 7.605 | 6.803 | 38 | 2375 | 9 |
| | AVG. | 4.0 | 0.0718 | 0.2175 | 2.603 | 6.957 | 6.899 | 35 | 2183 | 9 |
| OPTIMUM + 5% | 1 | 4.0 | 0.0727 | 0.2415 | 3.059 | 6.528 | 7.308 | 39 | 1188 | 9 |
| | 2 | 3.9 | 0.0692 | 0.2153 | 3.194 | 6.155 | 6.964 | 39 | 2375 | 8 |
| | 3 | 3.6 | 0.0703 | 0.2342 | 3.418 | 6.554 | 6.936 | 38 | 2780 | 9 |
| | AVG. | 3.8 | 0.0707 | 0.2303 | 3.224 | 6.412 | 7.069 | 39 | 2114 | 9 |
| OPTIMUM + 20% | 1 | 2.2 | 0.0513 | 0.1517 | 3.246 | 6.689 | 7.647 | 37 | 1692 | 9 |
| | 2 | 1.7 | 0.0569 | 0.1753 | 2.914 | 6.607 | 6.992 | 35 | 2114 | 9 |
| | 3 | 1.8 | 0.0538 | 0.1696 | 2.743 | 6.205 | 6.536 | 34 | 1903 | 10 |
| | AVG. | 1.9 | 0.0540 | 0.1653 | 2.968 | 6.500 | 7.058 | 35 | 1806 | 9 |

Table 8. Properties of Mixtures With One Fourth Inch Fibers, 25 Percent Fiber Concentration and Limestone Aggregate.

| ASPHALT CONTENT, PERCENT | SAMPLE NO. | AIR VOIDS, PERCENT | RESILIENT MODULUS PSI X 10 ⁶ | | | | | HVEEM STABILITY 140°F | MARSHALL STAB. 140°F | |
|-----------------------------|---------------|--------------------------|---|--------|-------|-------|--------|-----------------------------|-------------------------|------|
| | | | 104°F | 77°F | 32°F | 0°F | -15°F | | STAB. | FLOW |
| OPTIMUM | 1 | 6.8 | 0.0478 | 0.1712 | 1.946 | 7.265 | 10.371 | 44 | 1250 | 16 |
| | 2 | 5.7 | 0.0747 | 0.3047 | 2.952 | 8.725 | 9.648 | 52 | 1740 | 15 |
| | 3 | 5.9 | 0.0620 | 0.2650 | 2.320 | 7.963 | 8.725 | 51 | 1600 | 14 |
| | AVG. | 6.1 | 0.0615 | 0.2407 | 2.406 | 7.984 | 9.581 | 49 | 1530 | 15 |
| | | | | | | | | | | |
| OPTIMUM + 5% | 1 | 5.1 | 0.0590 | 0.2248 | 3.417 | 7.678 | 8.795 | 49 | 1450 | 14 |
| | 2 | 5.6 | 0.0746 | 0.2539 | 3.390 | 9.648 | 7.963 | 48 | 1500 | 14 |
| | 3 | 5.3 | 0.0693 | 0.2294 | 2.968 | 7.353 | 7.995 | 50 | 1450 | 14 |
| | AVG. | 5.3 | 0.0676 | 0.2360 | 3.258 | 8.226 | 8.161 | 49 | 1467 | 14 |
| | | | | | | | | | | |
| OPTIMUM + 20% | 1 | 3.4 | 0.0499 | 0.2069 | 2.761 | 6.753 | 7.429 | 48 | 1160 | 14 |
| | 2 | 4.3 | 0.0458 | 0.1837 | 2.433 | 7.208 | 6.920 | 51 | 990 | 14 |
| | 3 | 2.8 | 0.0529 | 0.2482 | 2.963 | 6.807 | 7.353 | 44 | 1400 | 13 |
| | AVG. | 3.5 | 0.0495 | 0.2129 | 2.719 | 6.923 | 7.234 | 48 | 1183 | 14 |
| | | | | | | | | | | |

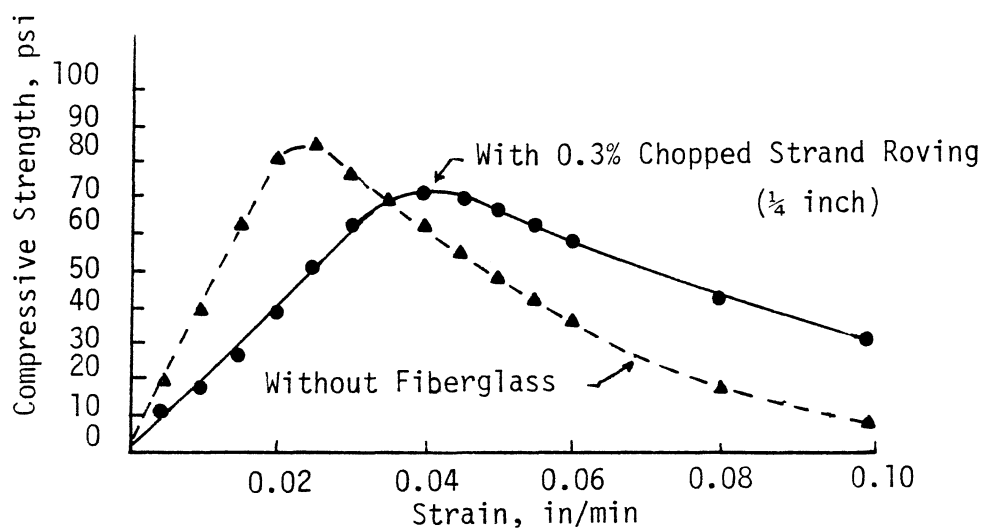


Figure 1. Stress- Strain Diagram for Sand Asphalt Cylinders, 6 Percent Asphalt at 77°F.
(After reference 1)

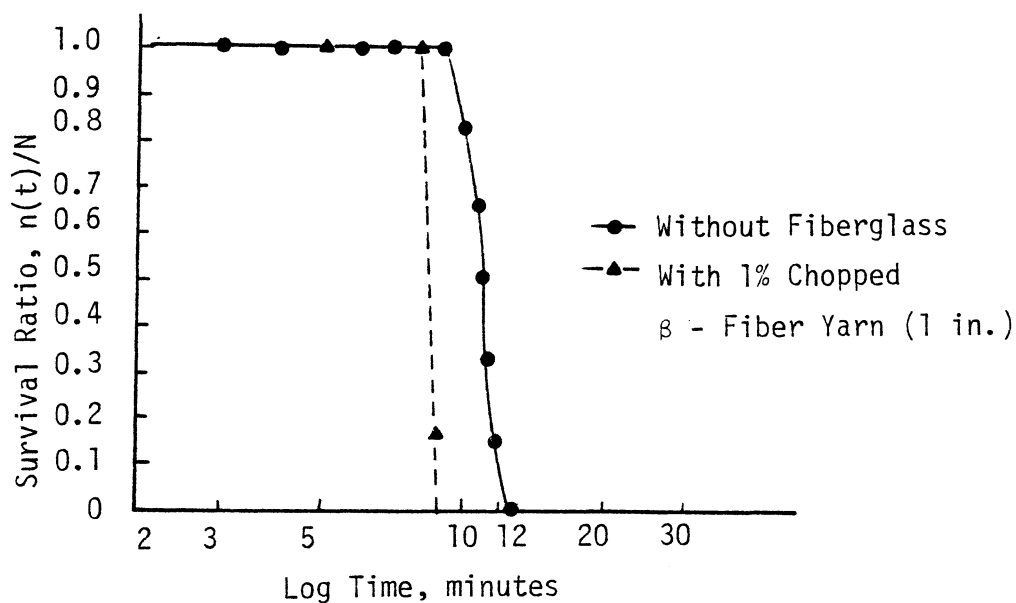


Figure 2. Survival vs. Log Time for Cylindrical Specimens, 8 Percent Asphalt at 140°F.
(After Reference 1)

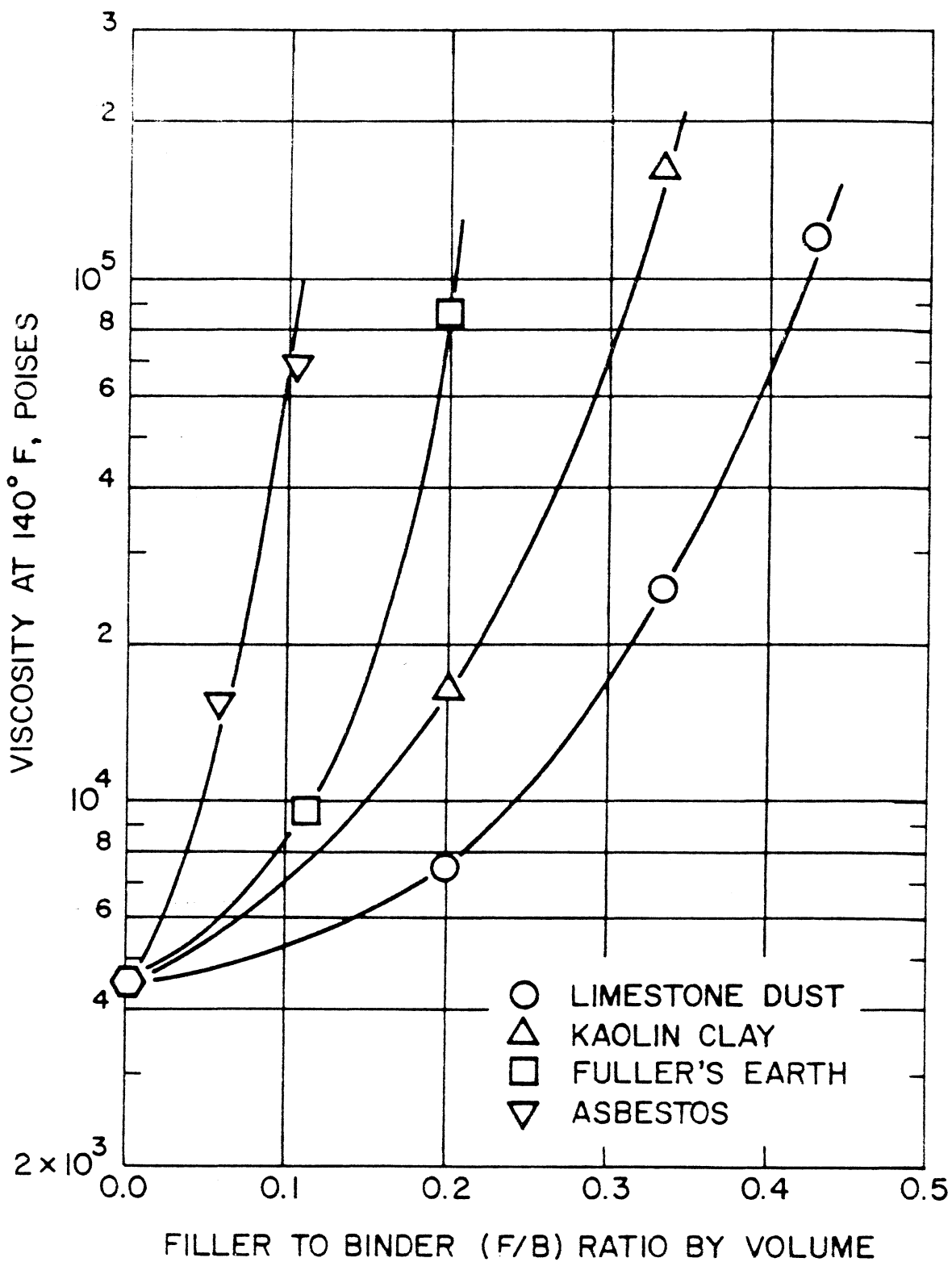


Figure 3. Effect of Filler Concentration on Viscosity at 140°F of Filler-Asphalt Mixtures.
(After Reference 6).

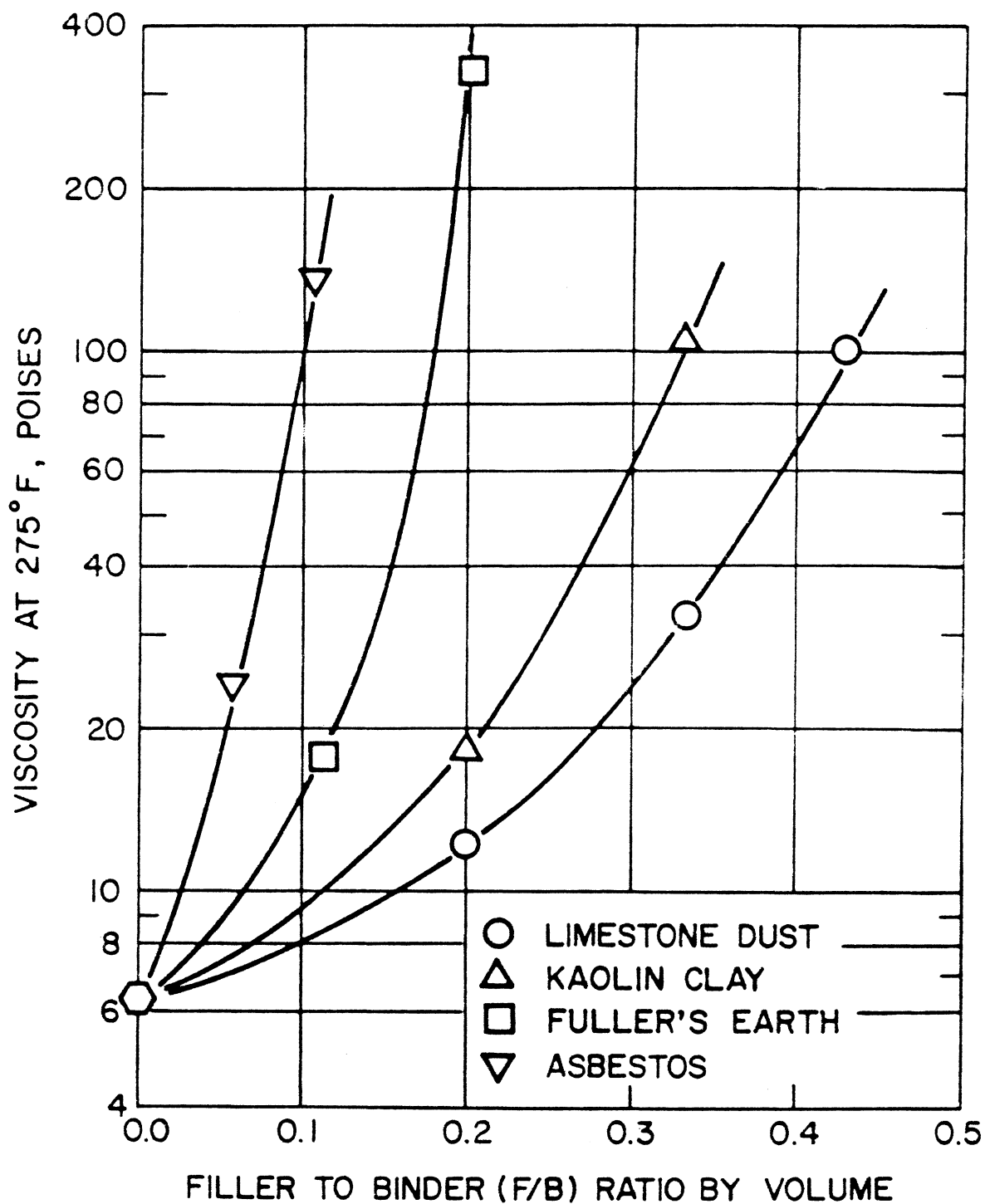


Figure 4. Effect of Filler Concentration on Viscosity at 275°F of Filler-Asphalt Mixtures.

(After Reference 6)

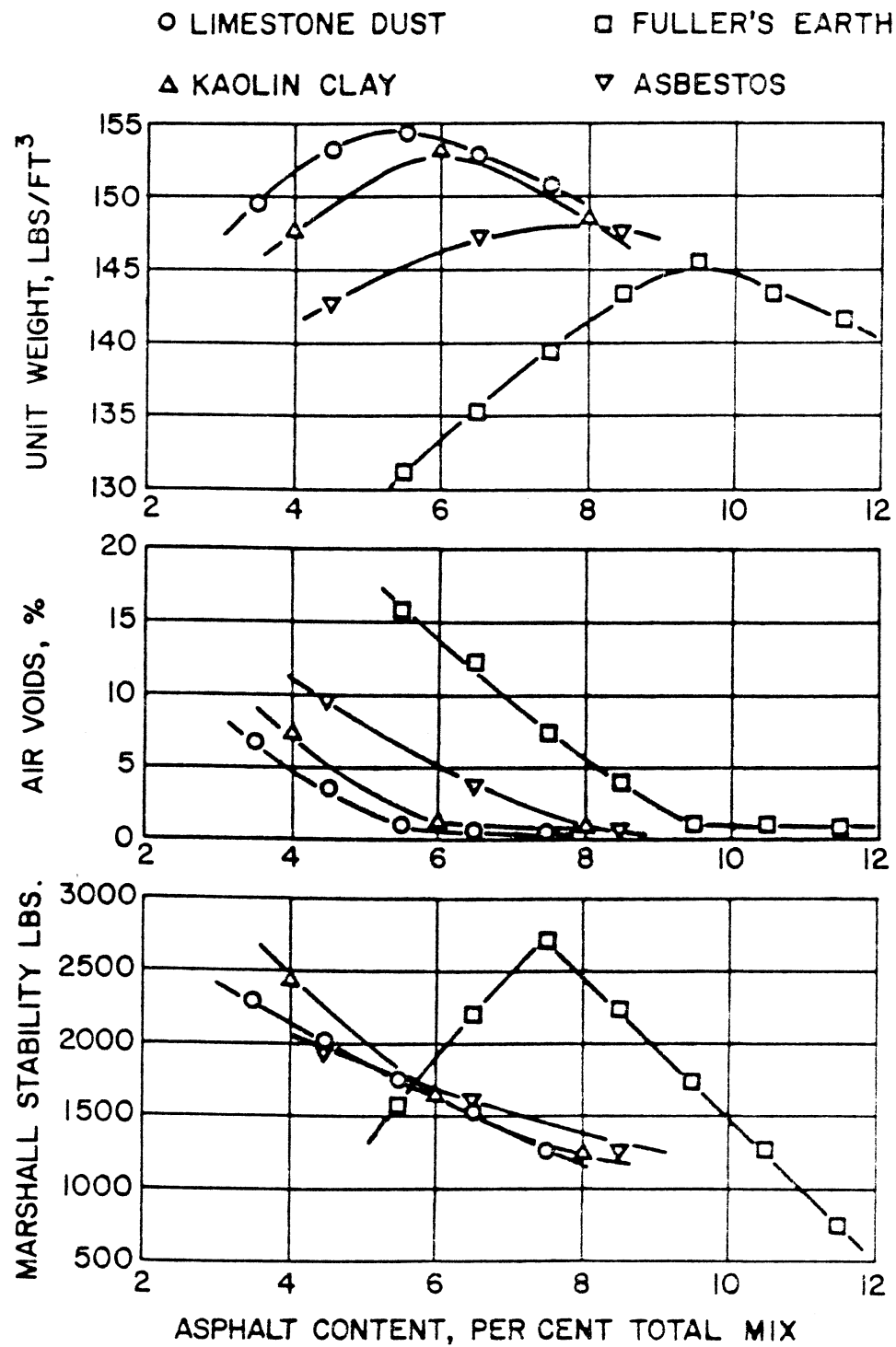


Figure 5. Effect of Various Fillers on Marshall Design Properties of Asphalt Concrete.

(After Reference 6)

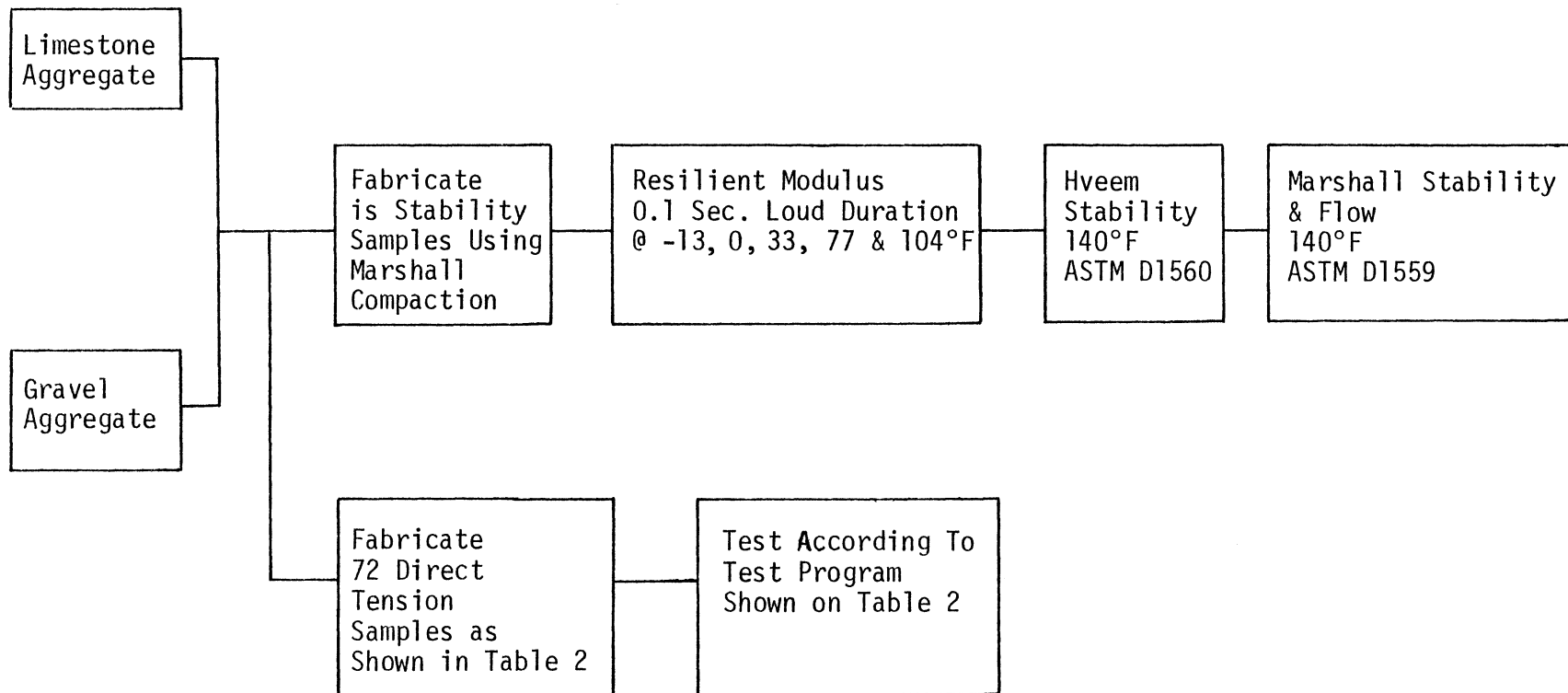


Figure 6. Test Plan for Phase B Research Program.

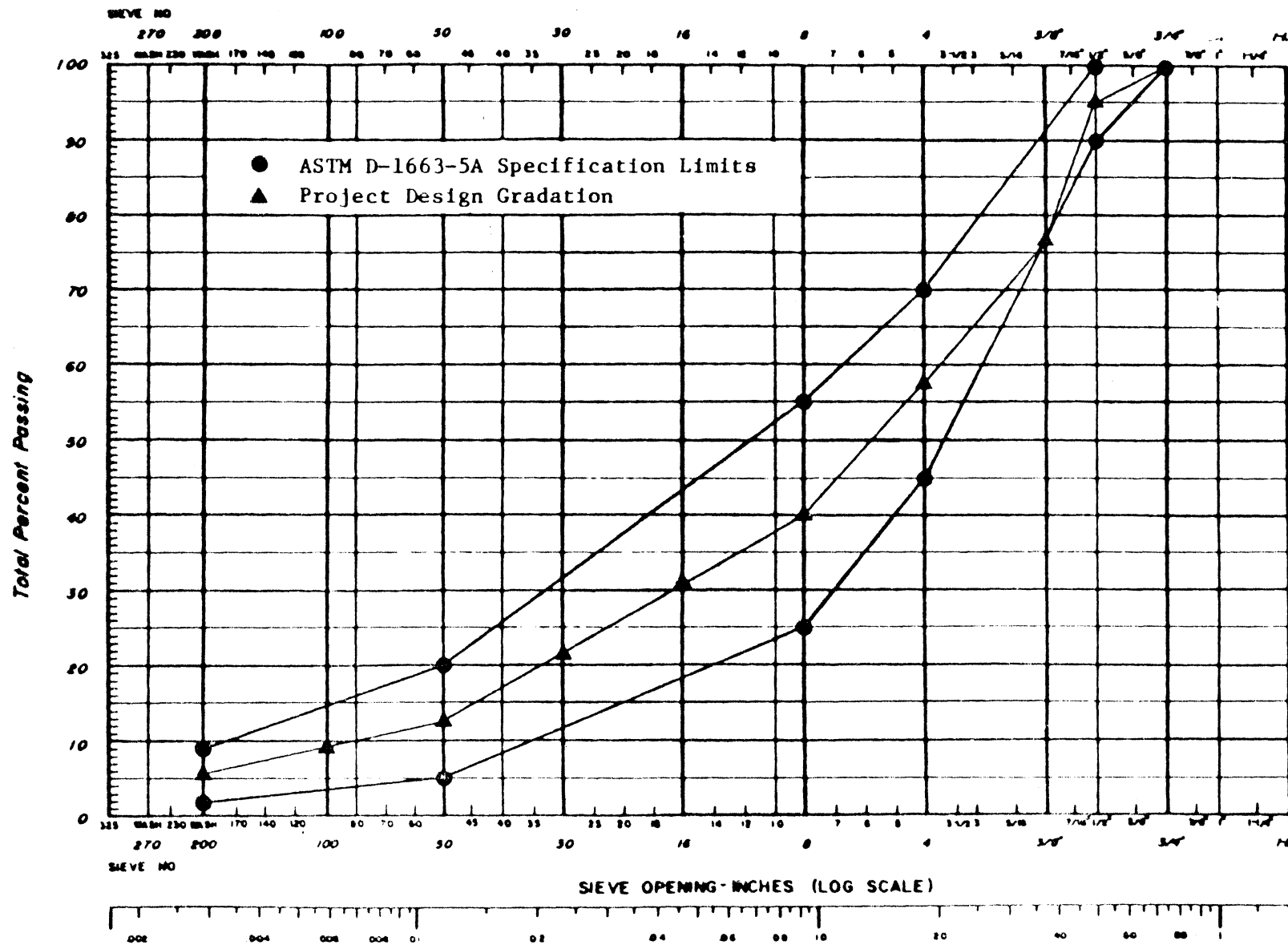


Figure 7. Gradation of Aggregate.

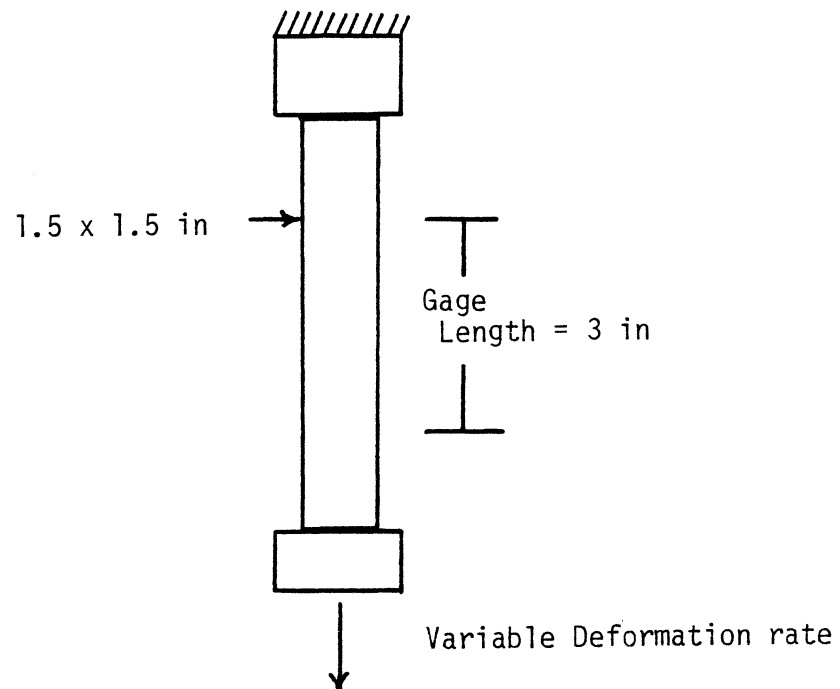


Figure 8. Direct Tension Test Apparatus.

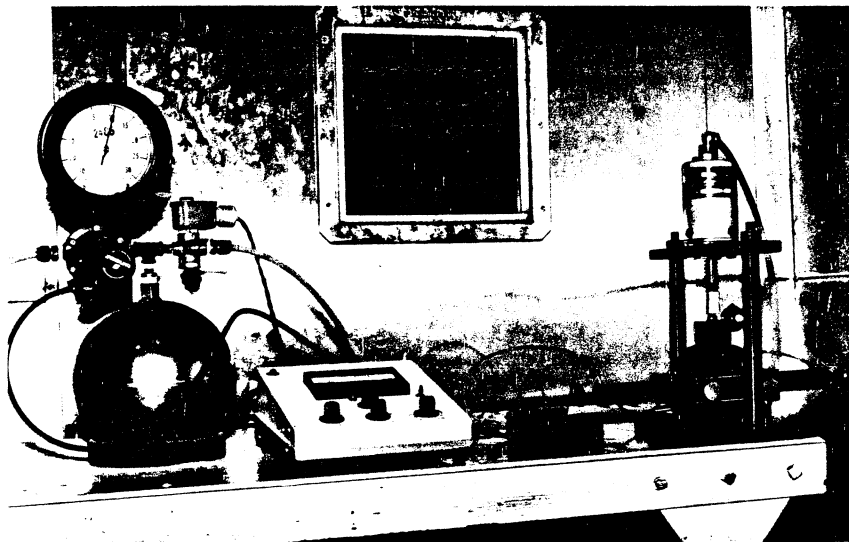


Figure 9. Overall View of Mark III Resilient Device.

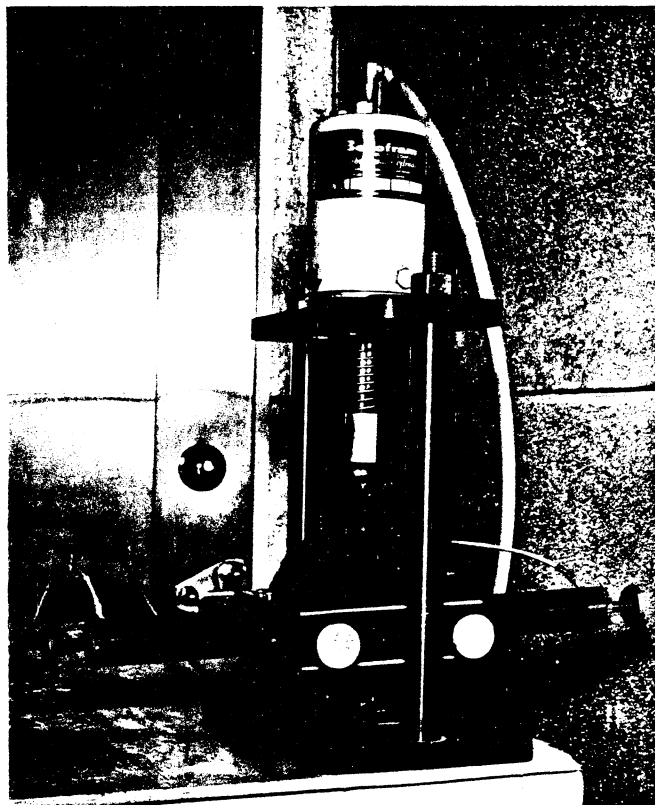


Figure 10. Close-Up View of Loading Frame and Transducers.

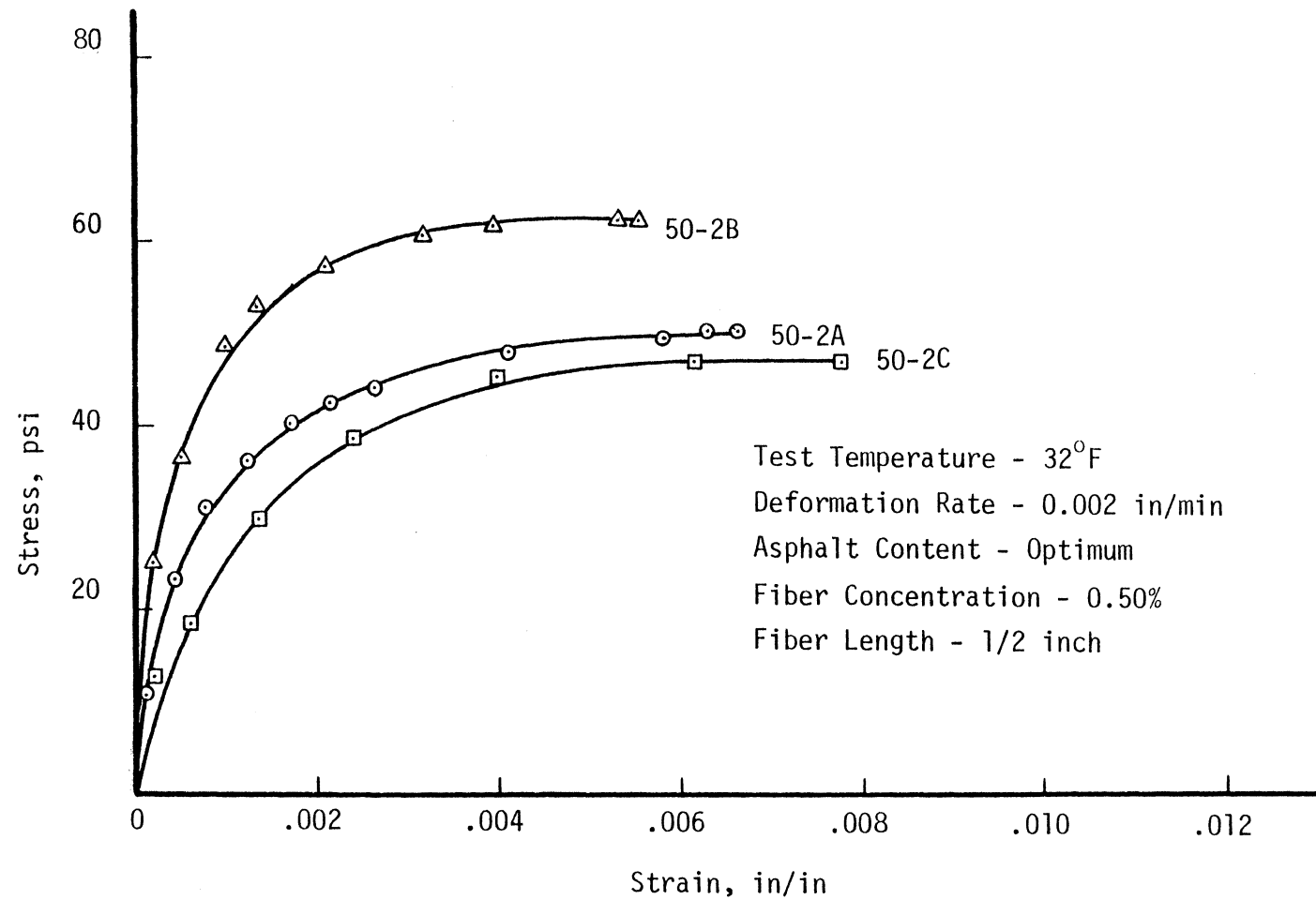


Figure 11. Typical Stress-Strain Data for Direct Tension Tests.

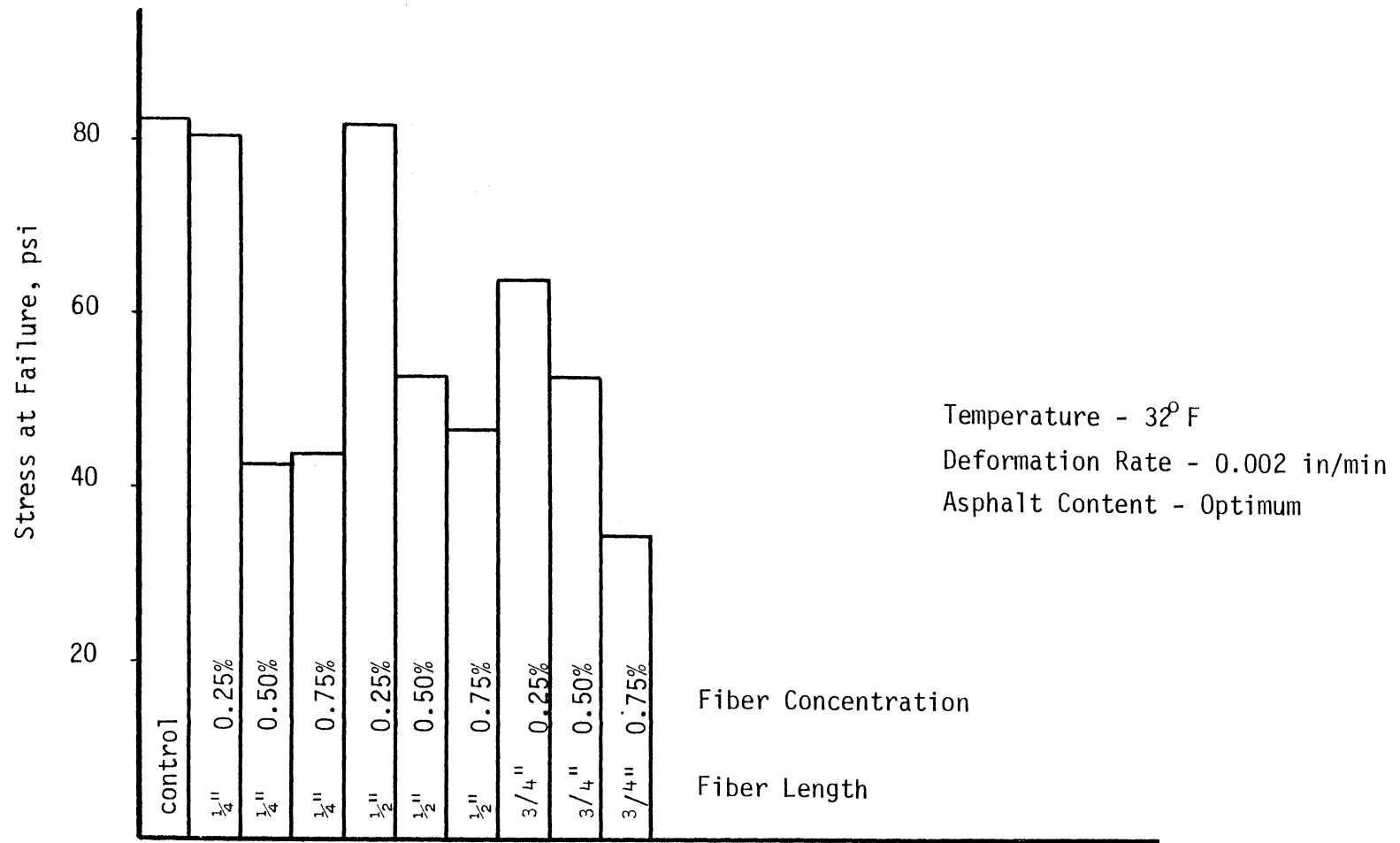


Figure 12. Effect of Fiber Length and Fiber Concentration on Direct Tensile Strength of an Asphalt Concrete at Optimum Asphalt Content.

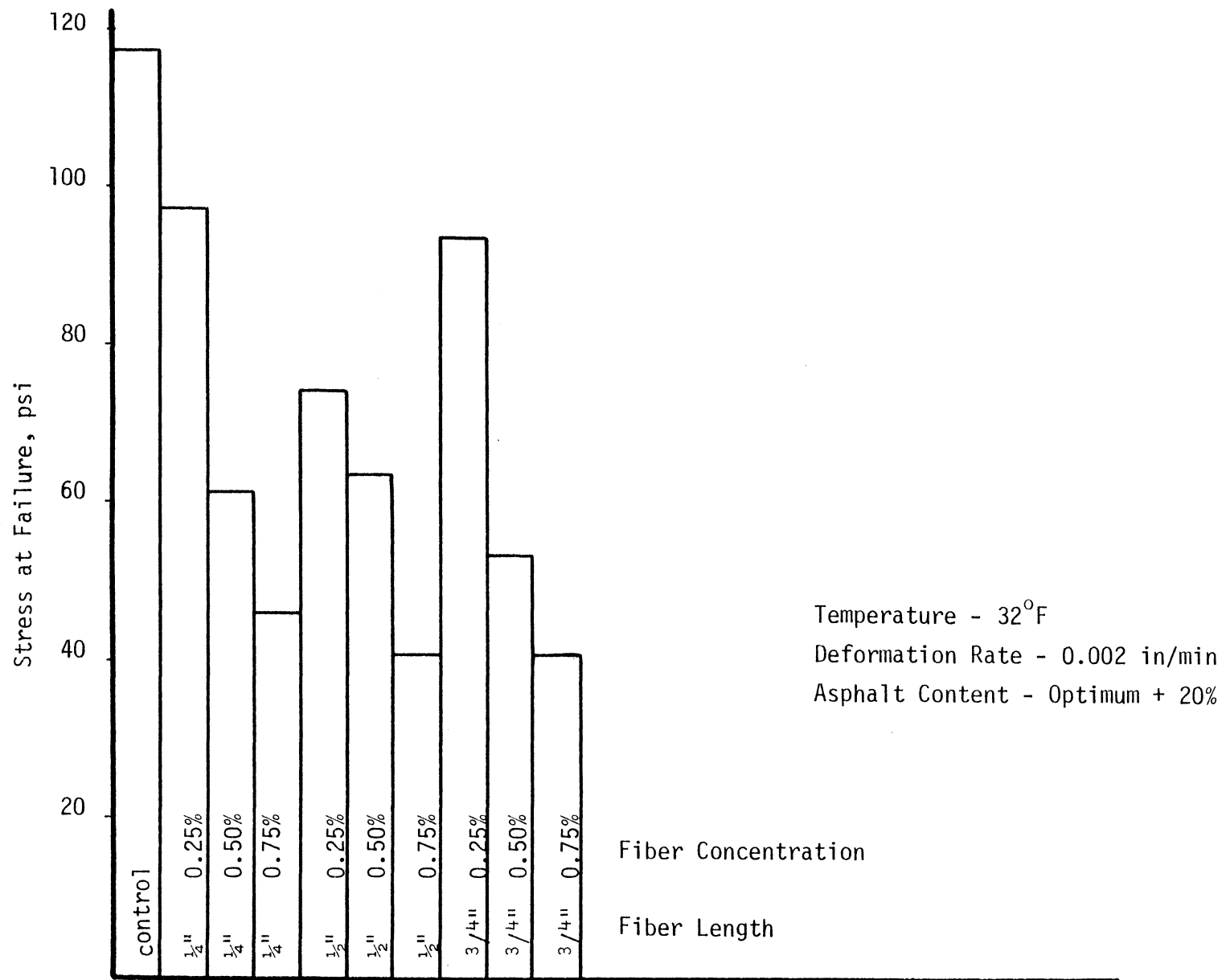


Figure 13. Effect of Fiber Length and Fiber Concentration on Direct Tensile Strength of an Asphalt Concrete at Optimum Plus 20 Percent Asphalt Content.

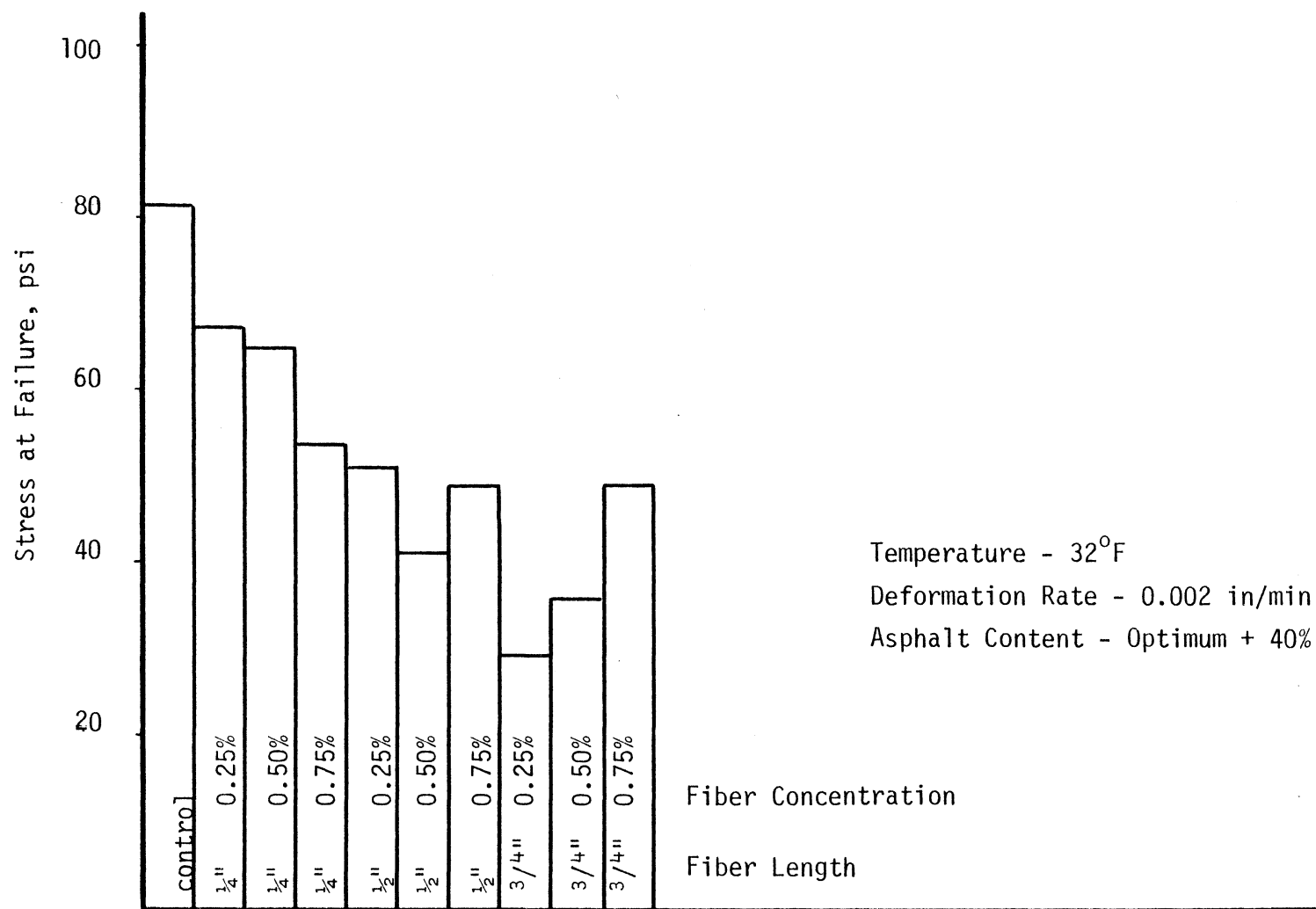


Figure 14. Effect of Fiber Length and Fiber Concentration on Direct Tensile Strength of Asphalt Concrete at Optimum Plus 40 Percent Asphalt Content.

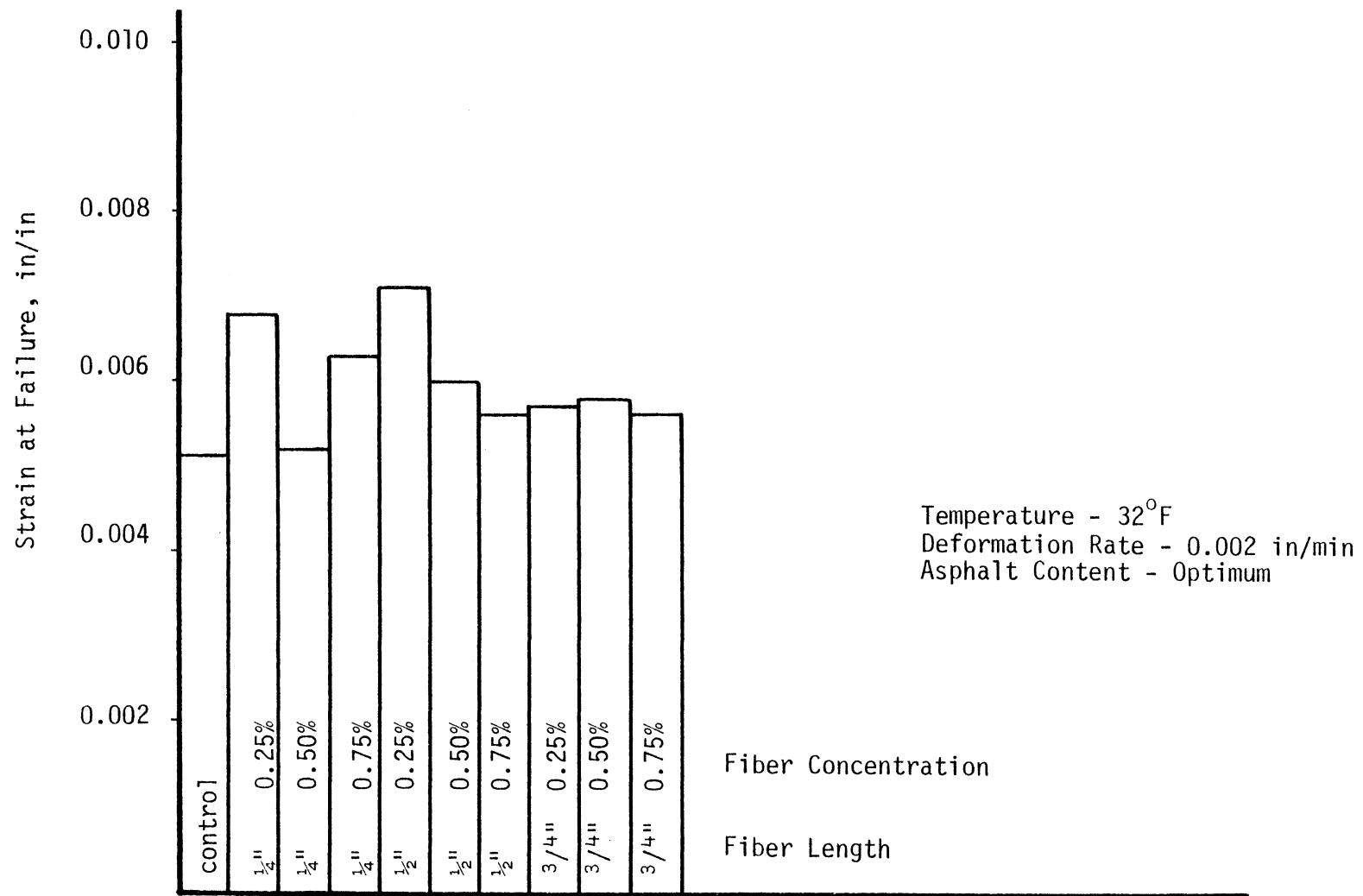


Figure 15. Effect of Fiber Length and Fiber Concentration on Direct Tensile Strain at Failure of Asphalt Concrete at Optimum Content.

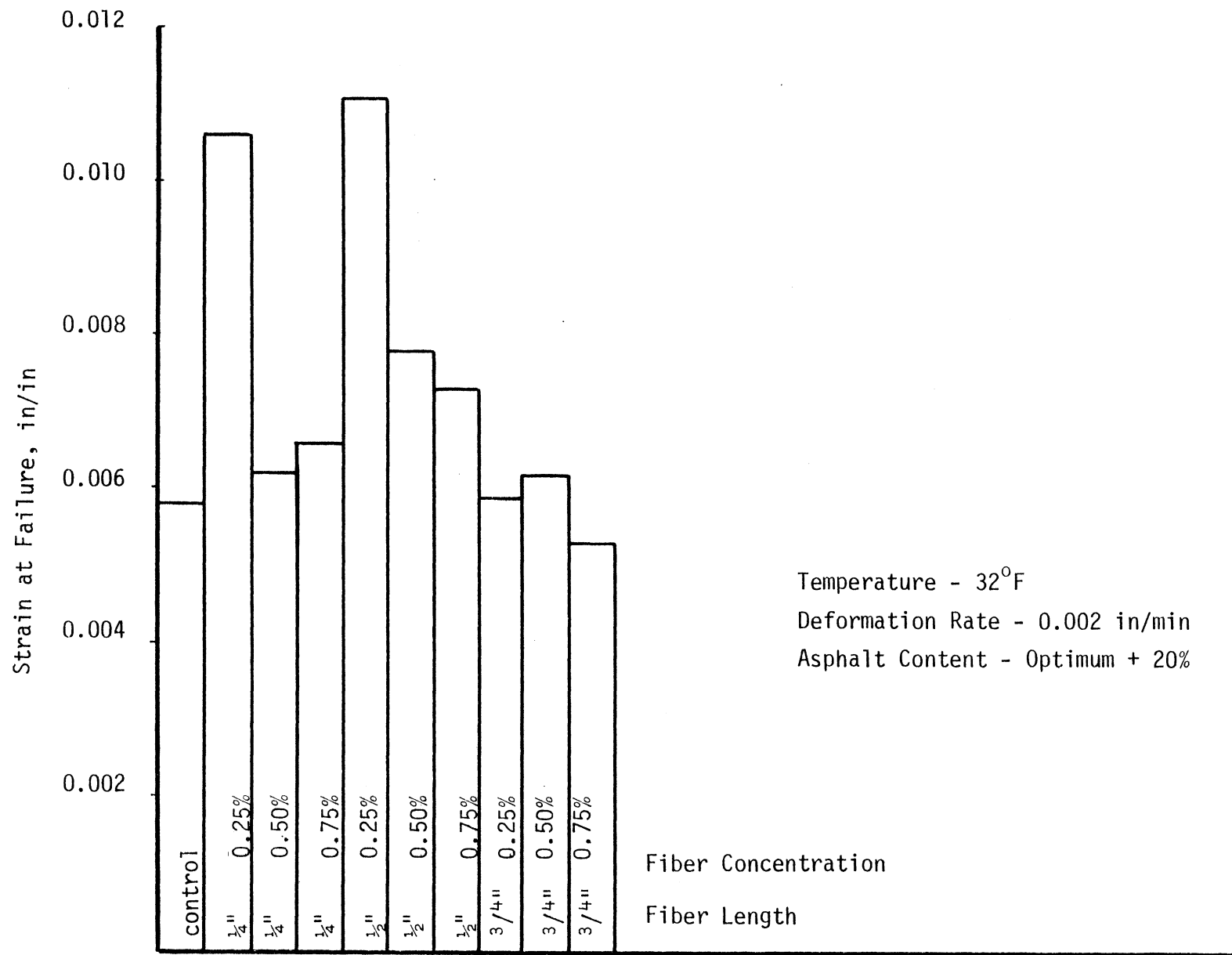


Figure 16. Effect of Fiber Length and Fiber Concentration on Direct Tensile Strain at Failure of Asphalt Concrete at Optimum Plus 20 Percent Asphalt Content.

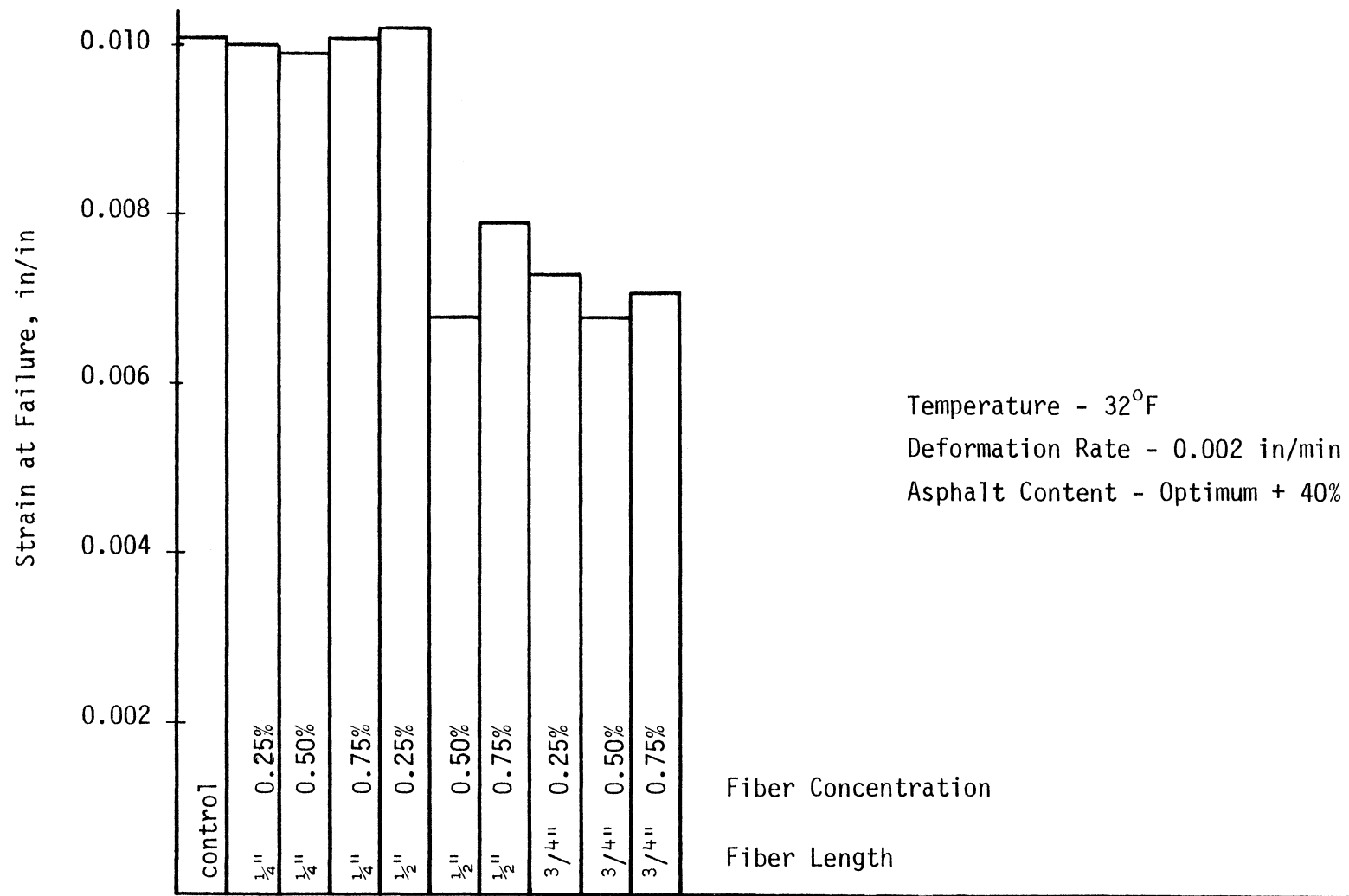


Figure 17. Effect of Fiber Length and Fiber Concentration on Direct Tensile Strain at Failure of Asphalt Concrete at Optimum + 40 Percent Asphalt Content.

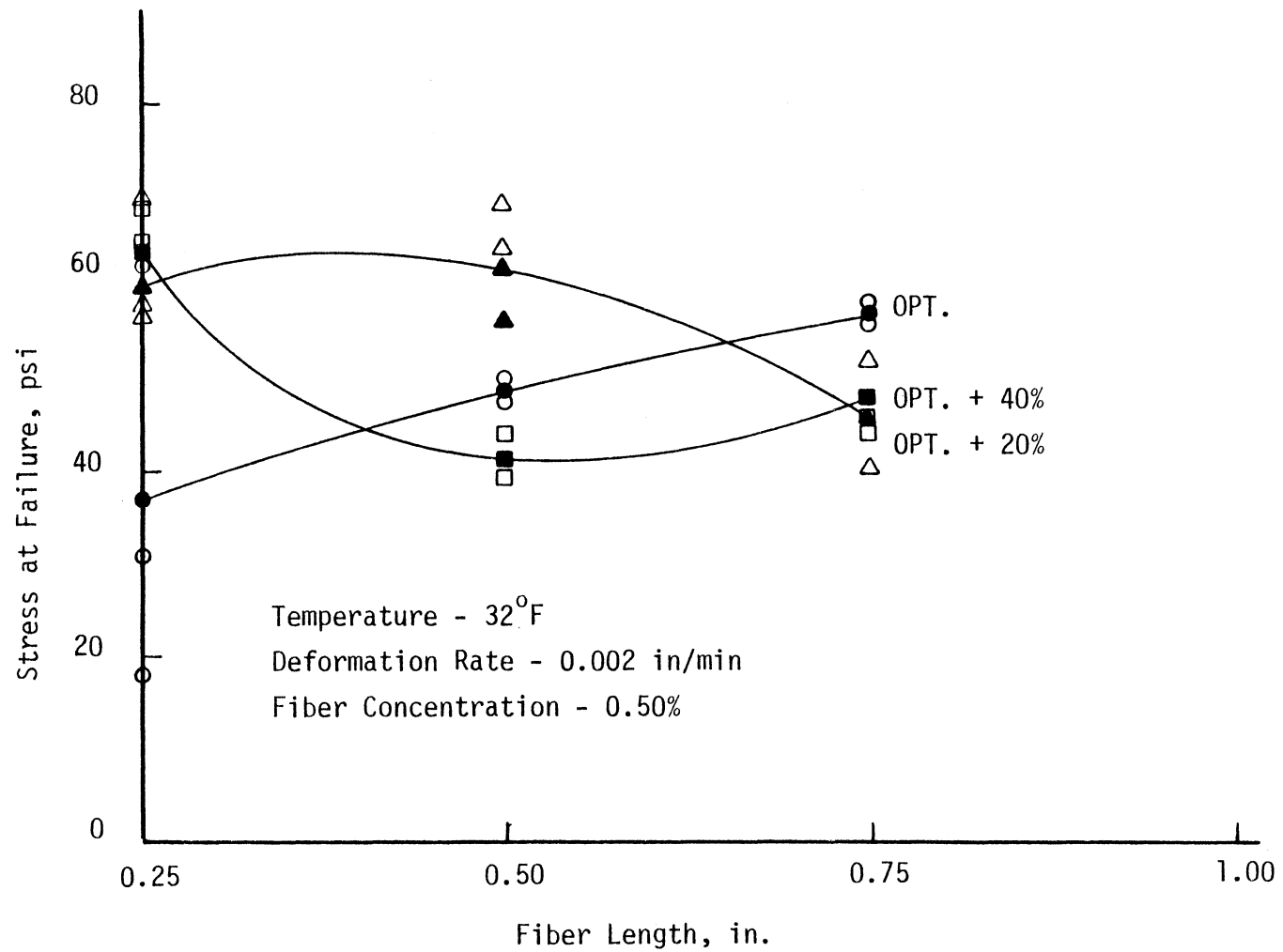


Figure 18. Relationship Between Fiber Length and Strength of Reinforced Asphalt Concrete at Various Asphalt Contents.

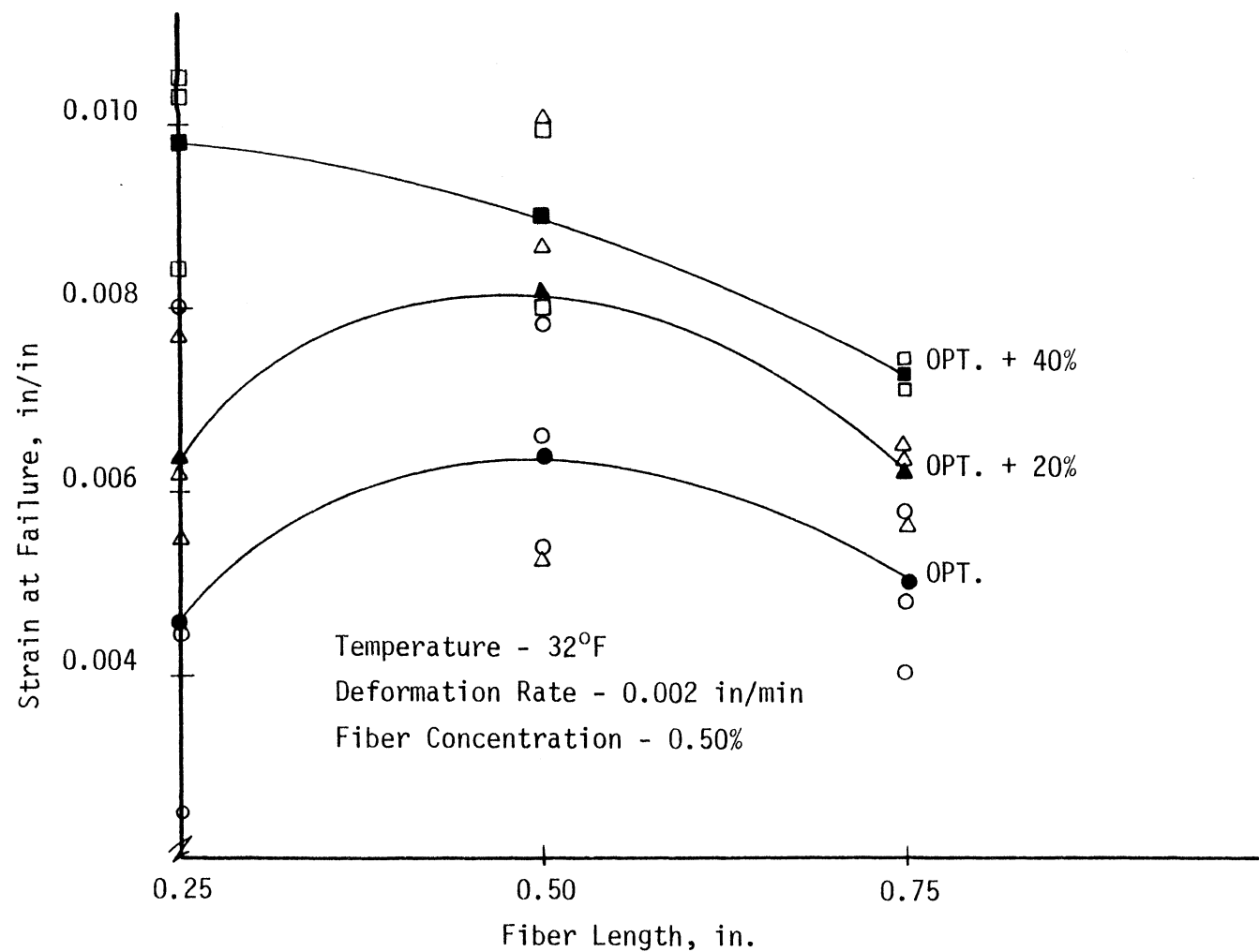


Figure 19. Relationship Between Fiber Length and Strain at Failure of Reinforced Asphalt Concrete at Various Asphalt Contents.

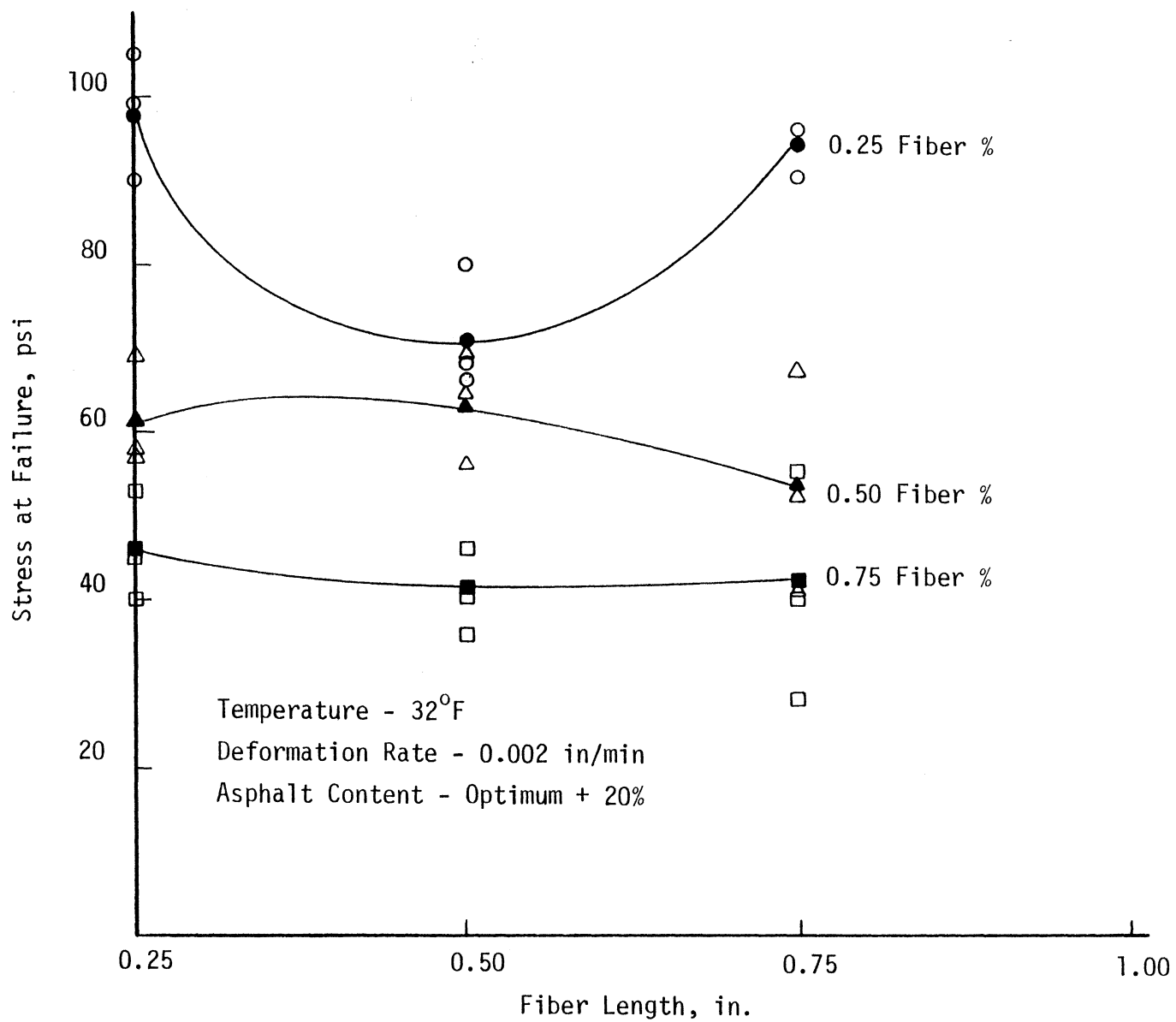


Figure 20. Relationship Between Fiber Length and Strength of Reinforced Asphalt Concrete at Various Fiber Concentrations.

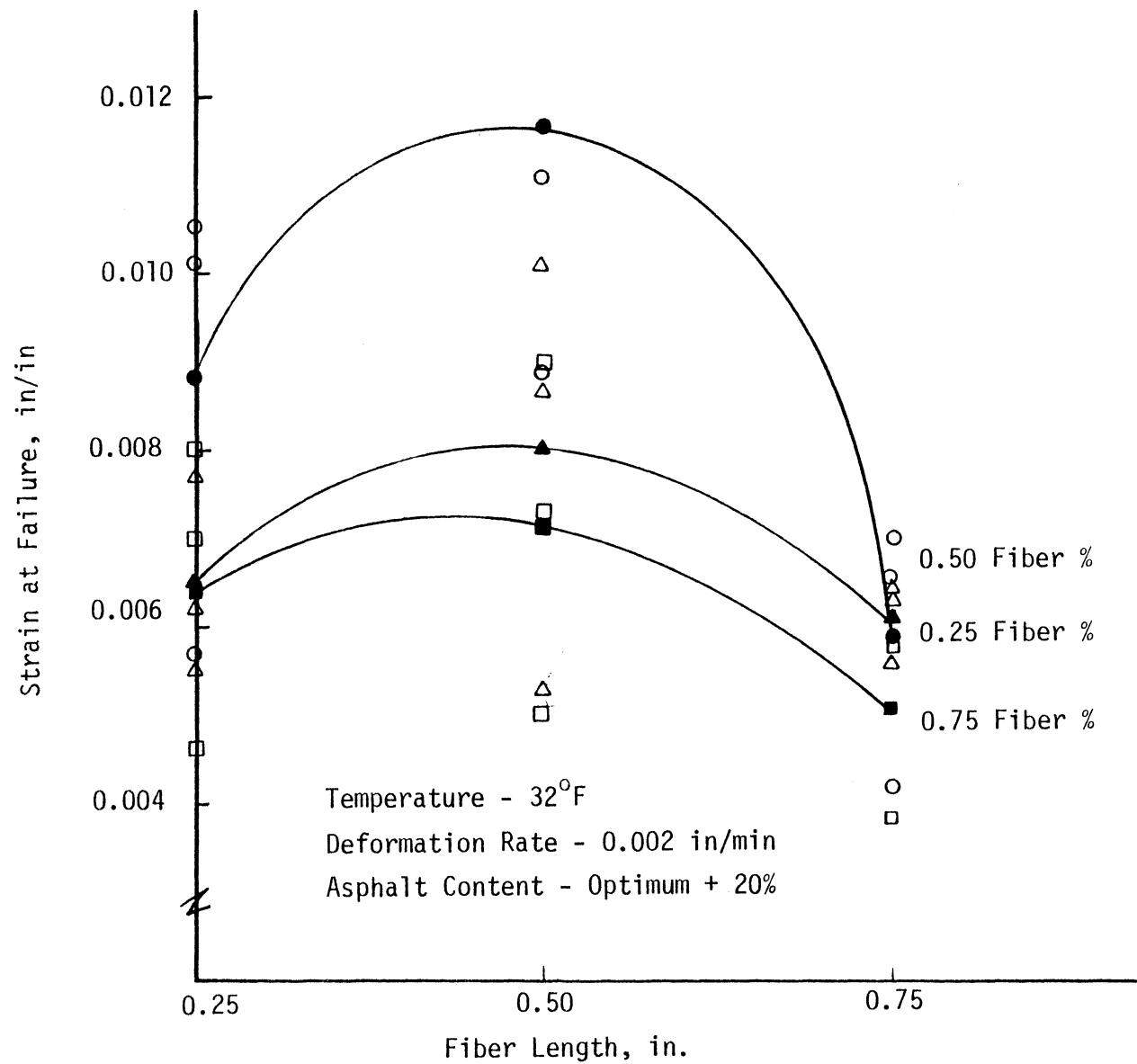


Figure 21. Relationship Between Fiber Length and Strain at Failure of Reinforced Asphalt Concrete at Various Fiber Concentrations.

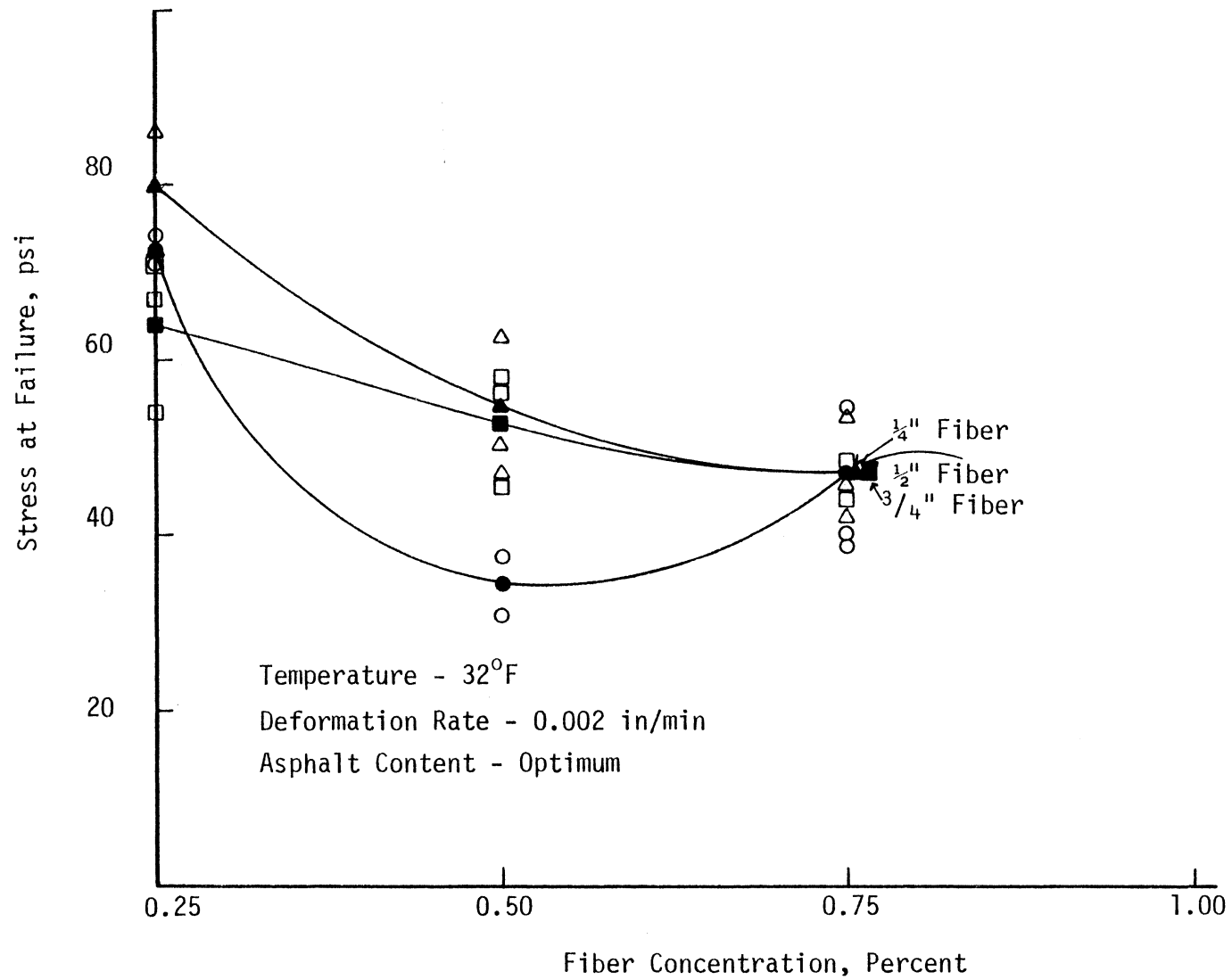


Figure 22. Relationship Between Fiber Concentration and Strength of Reinforced Asphalt Concrete at Optimum Asphalt Content.

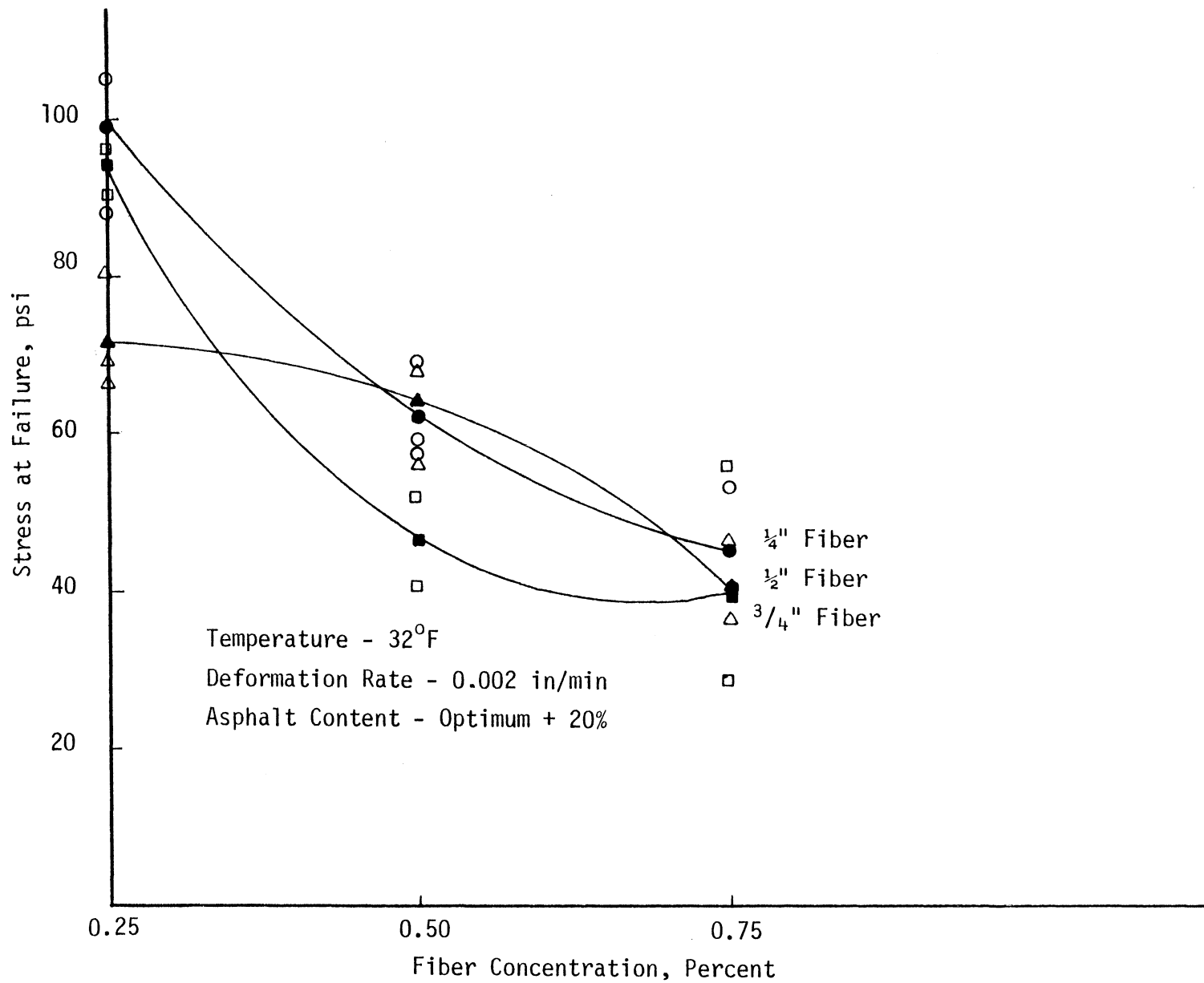


Figure 23. Relationship Between Fiber Concentration and Strength of Reinforced Asphalt Concrete at Optimum Plus 20 Percent Asphalt Content.

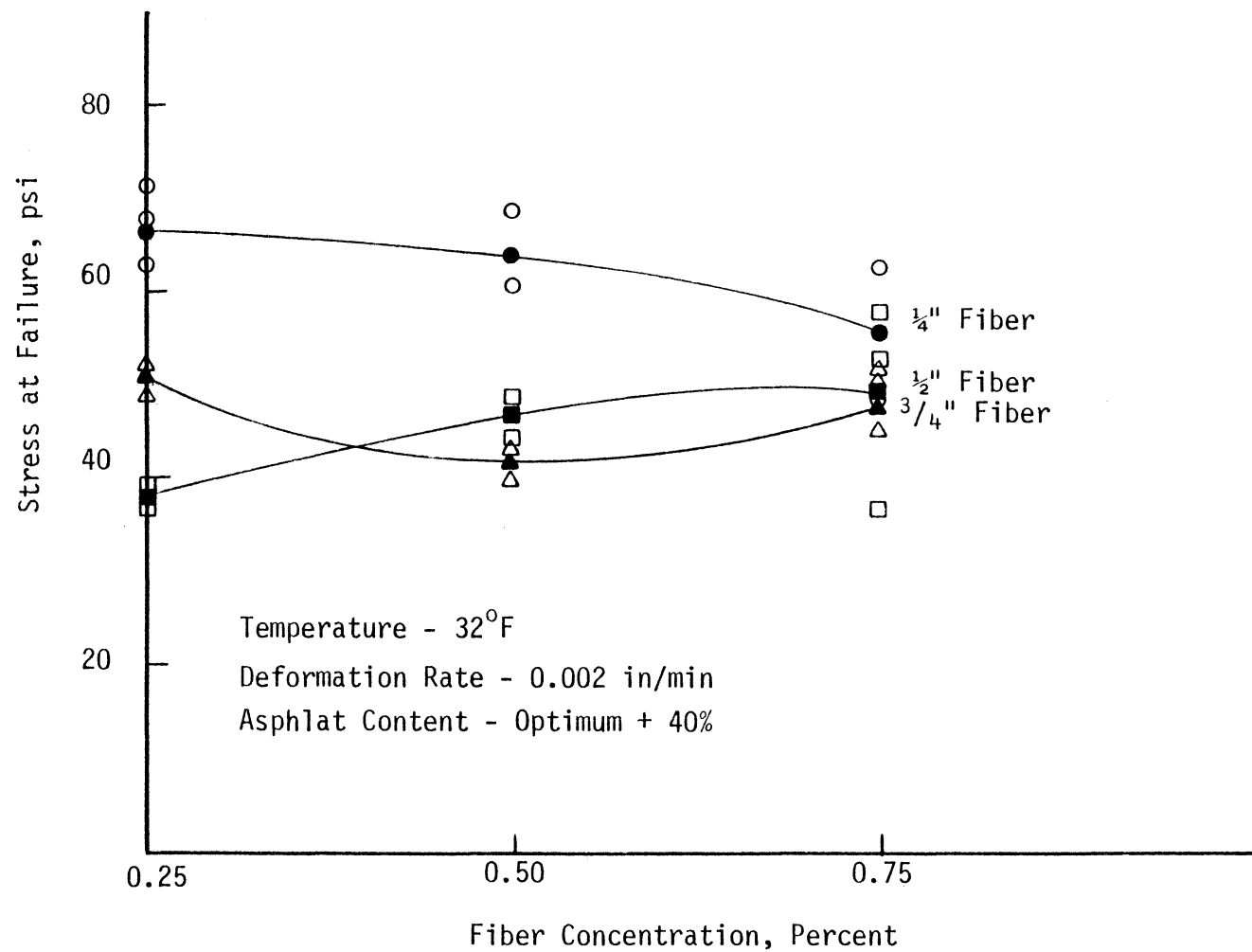


Figure 24. Relationship Between Fiber Concentration and Strength of Reinforced Asphalt Concrete at Optimum Plus 40 Percent Asphalt Content.

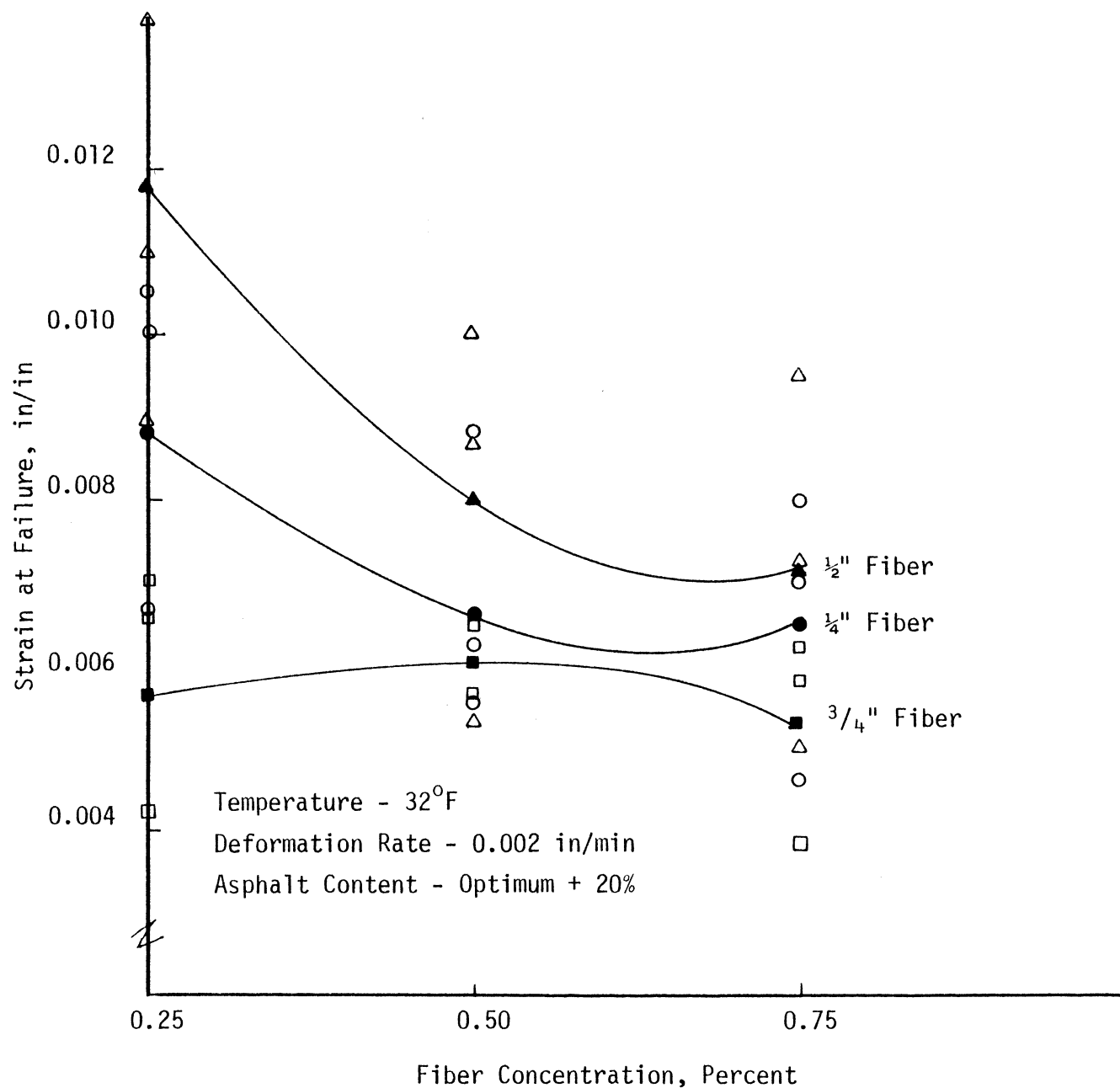


Figure 25. Relationship Between Fiber Concentration and Strain at Failure of Reinforced Asphalt Concrete at Optimum Plus 20 Percent Asphalt Content.

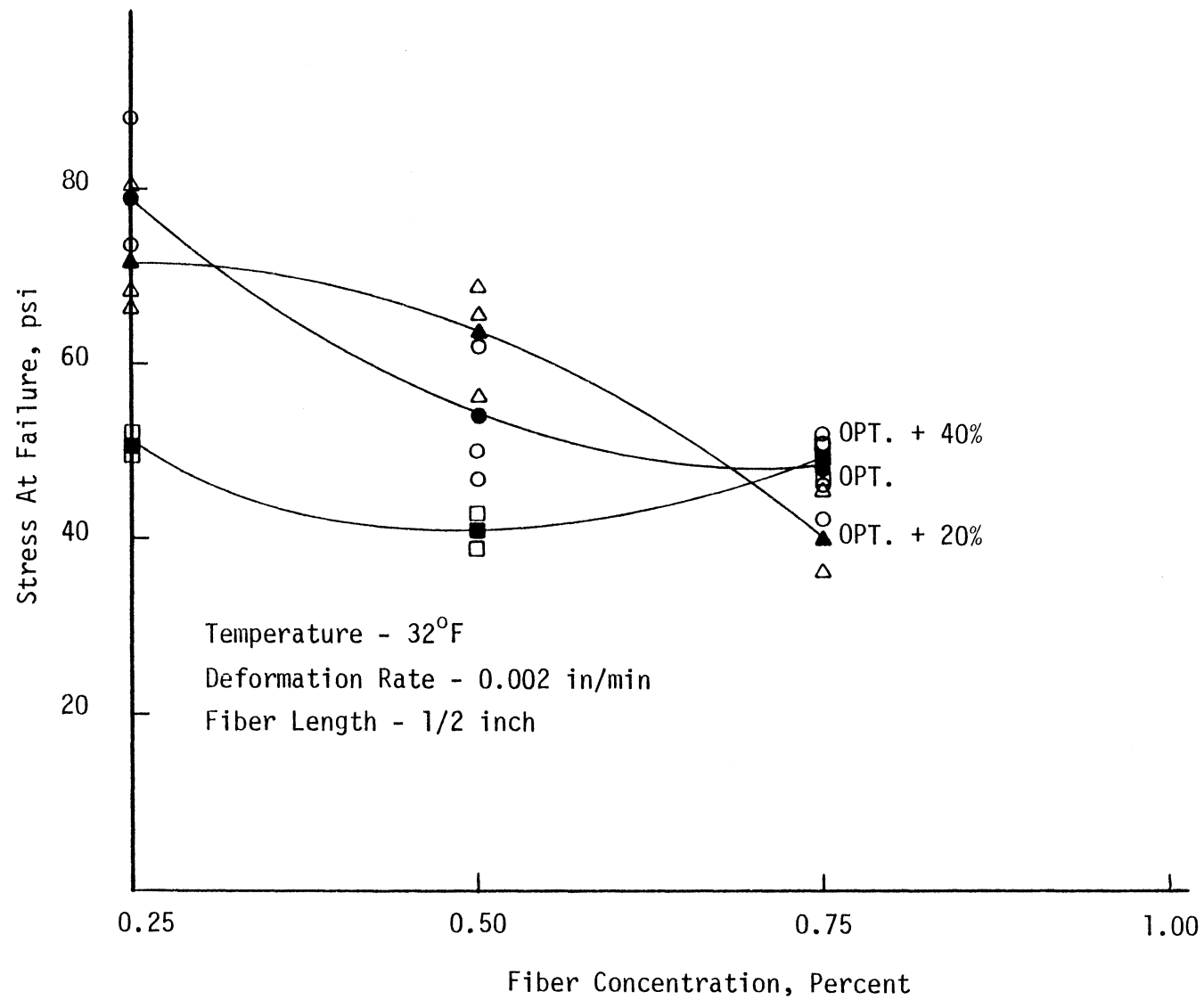


Figure 26. Relationship Between Fiber Concentration and Strength of Reinforced Asphalt Concrete Containing 1/2 inch Fibers.

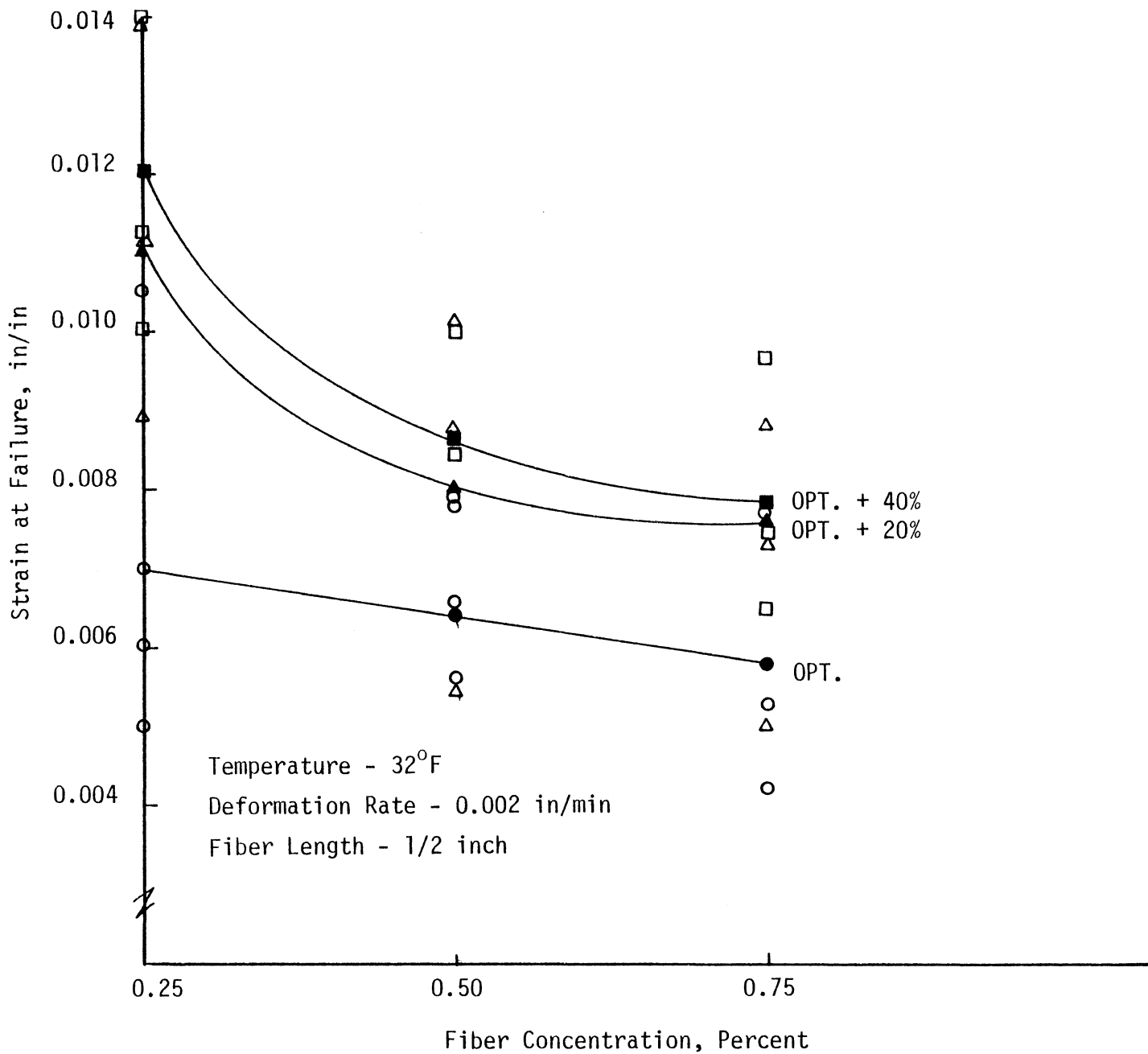


Figure 27. Relationship Between Fiber Concentration and Strain at Failure of Reinforced Asphalt Concrete Containing 1/2 inch Fibers.

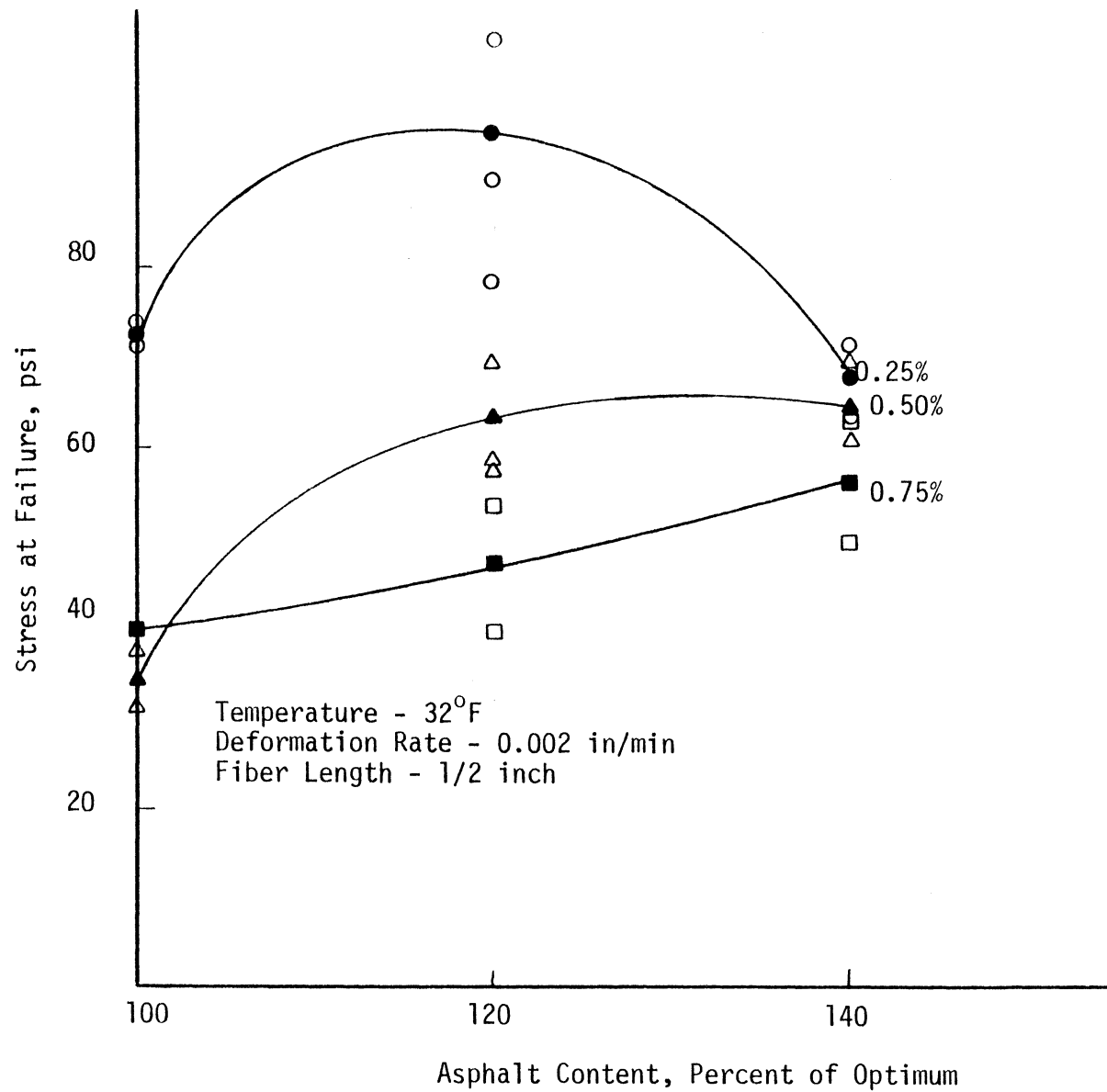


Figure 28. Relationship Between Asphalt Content and Strength of Reinforced Asphalt Concrete Containing 1/2 inch Fibers.

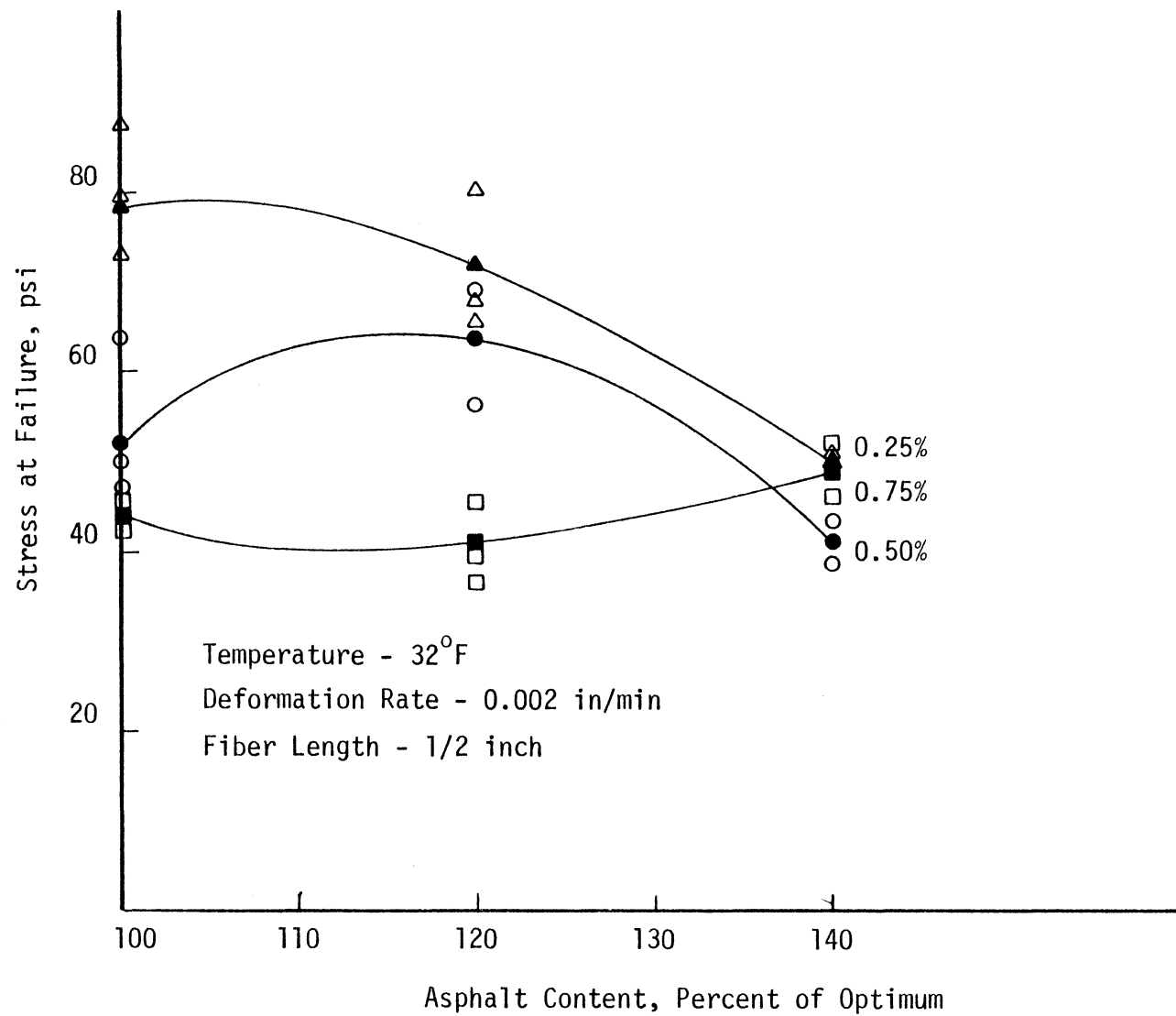


Figure 29. Relationship Between Asphalt Content and Strength of Reinforced Asphalt Concrete Containing 1/2 inch Fibers.

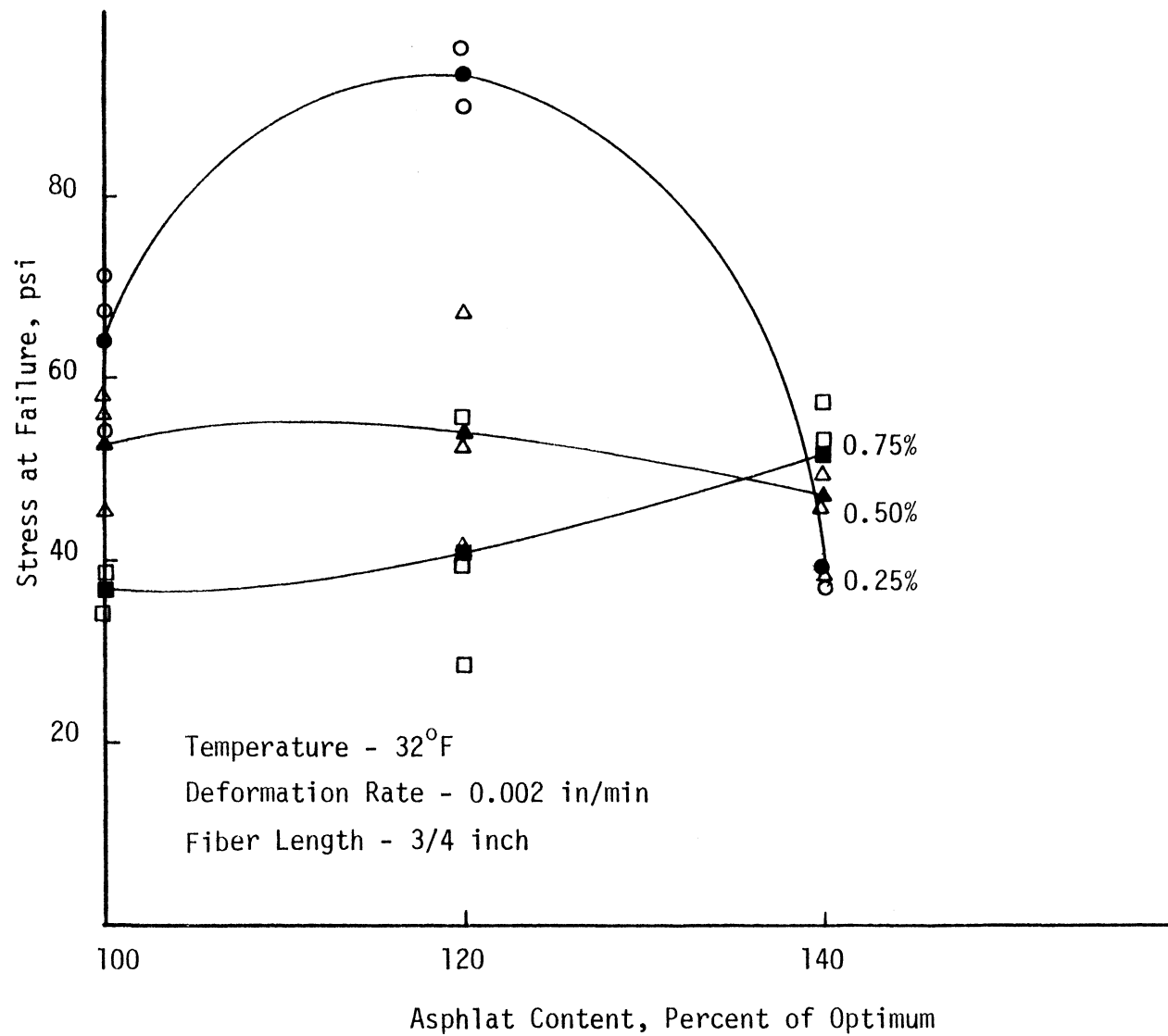


Figure 30. Relationship Between Asphalt Content and Strength of Reinforced Asphalt Concrete Containing 3/4 inch Fibers.

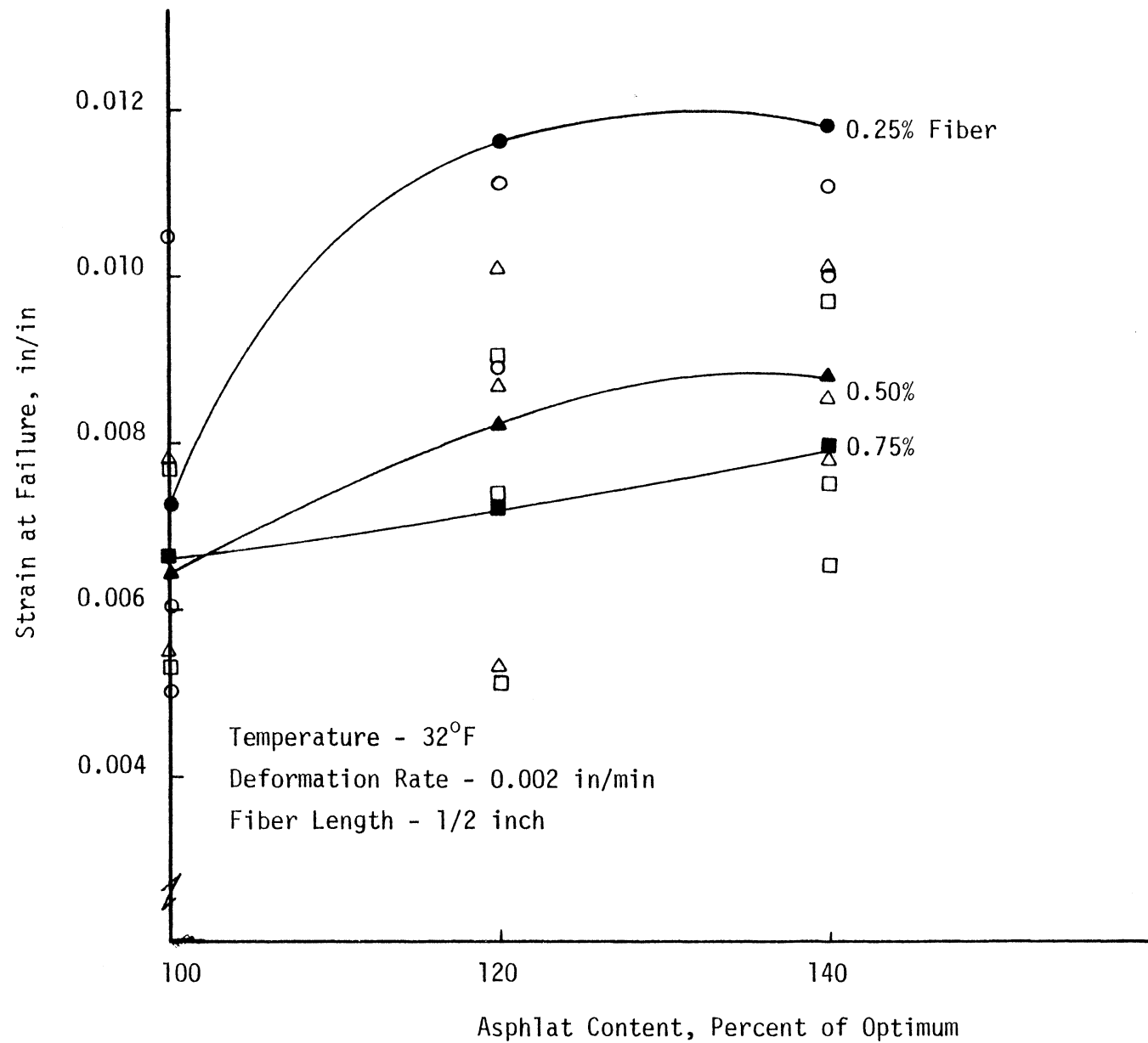


Figure 31. Relationship Between Asphalt Concrete and Strain at Failure of Reinforced Asphalt Containing 1/2 inch Fiber.

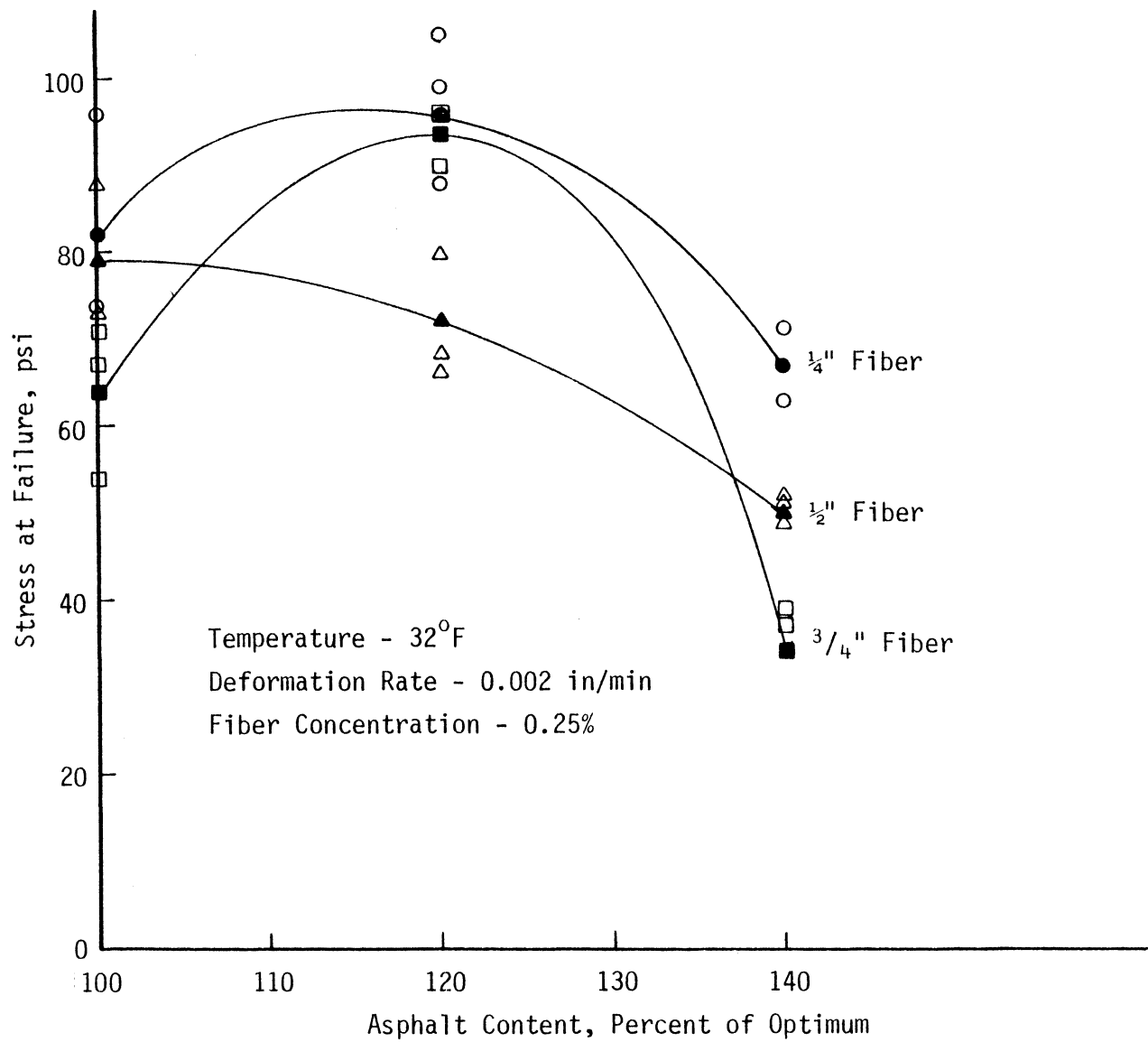


Figure 32. Relationship Between Asphalt Content and Strength of Reinforced Asphalt Concrete Containing 0.25 Percent Fibers.

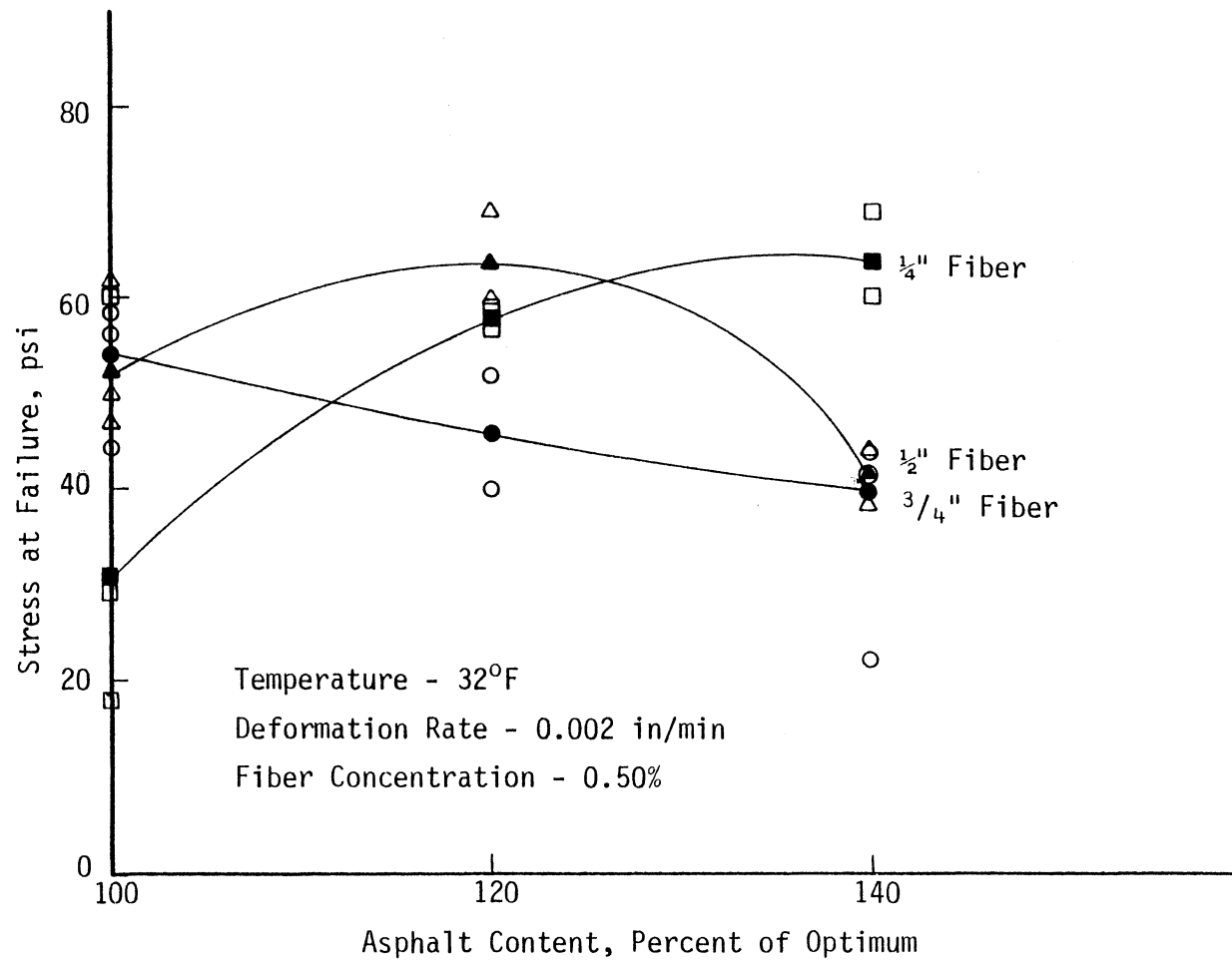


Figure 33. Relationship Between Asphalt Content and Strength of Reinforced Asphalt Concrete Containing 0.50 Percent Fibers.

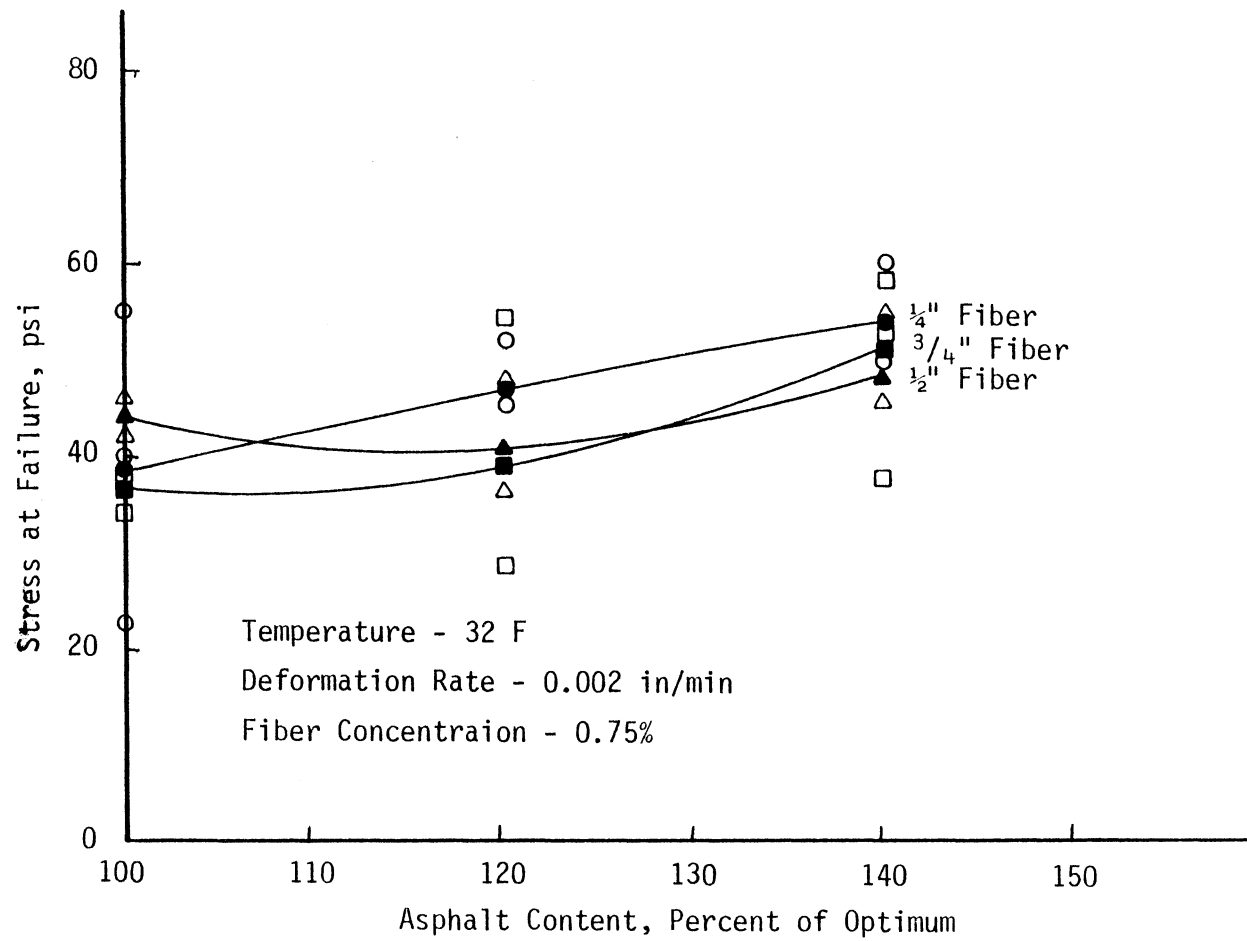


Figure 34. Relationship Between Asphalt Content and Strength of Reinforced Asphalt Concrete Containing 0.75 Percent Fibers.

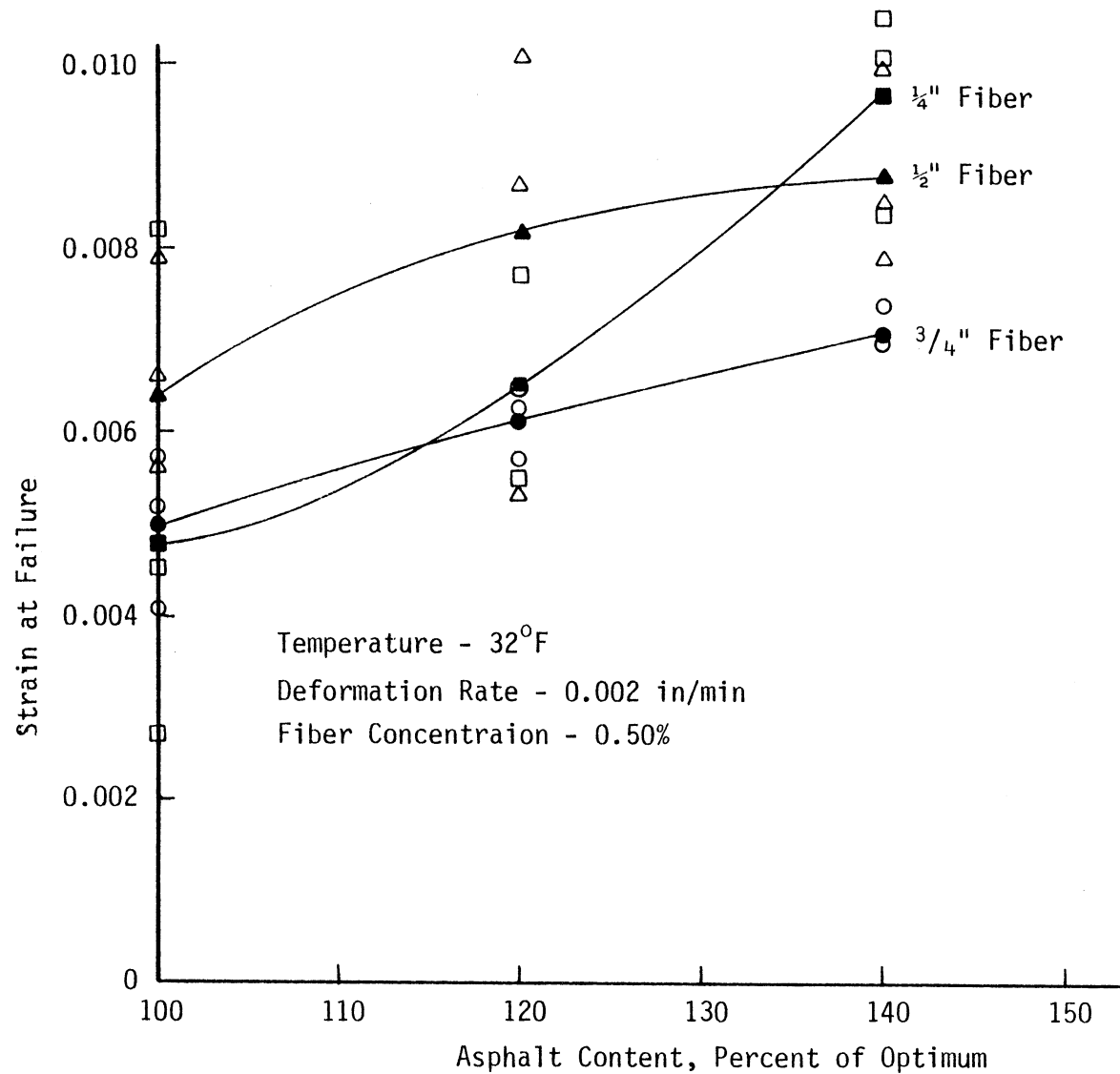


Figure 35. Relationship Between Asphalt Content and Strain at Failure of Reinforced Asphalt Concrete Containing 0.50 Percent Fibers.

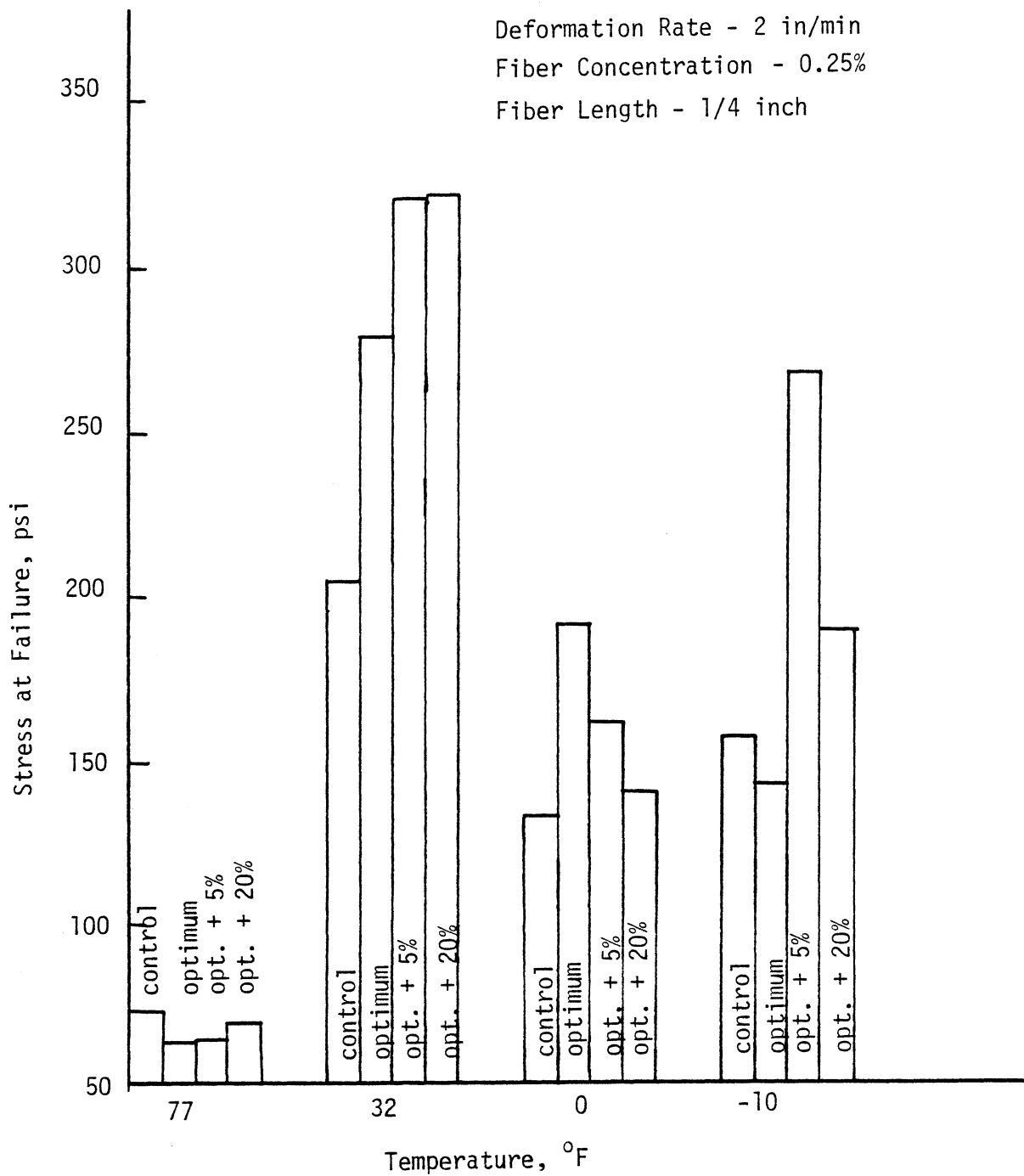


Figure 36. Effect of Temperature and Asphalt Content on Direct Tensile Strength of Asphalt Concrete Containing a One Fourth Inch Fiber at a Concentration of 0.25 Percent.

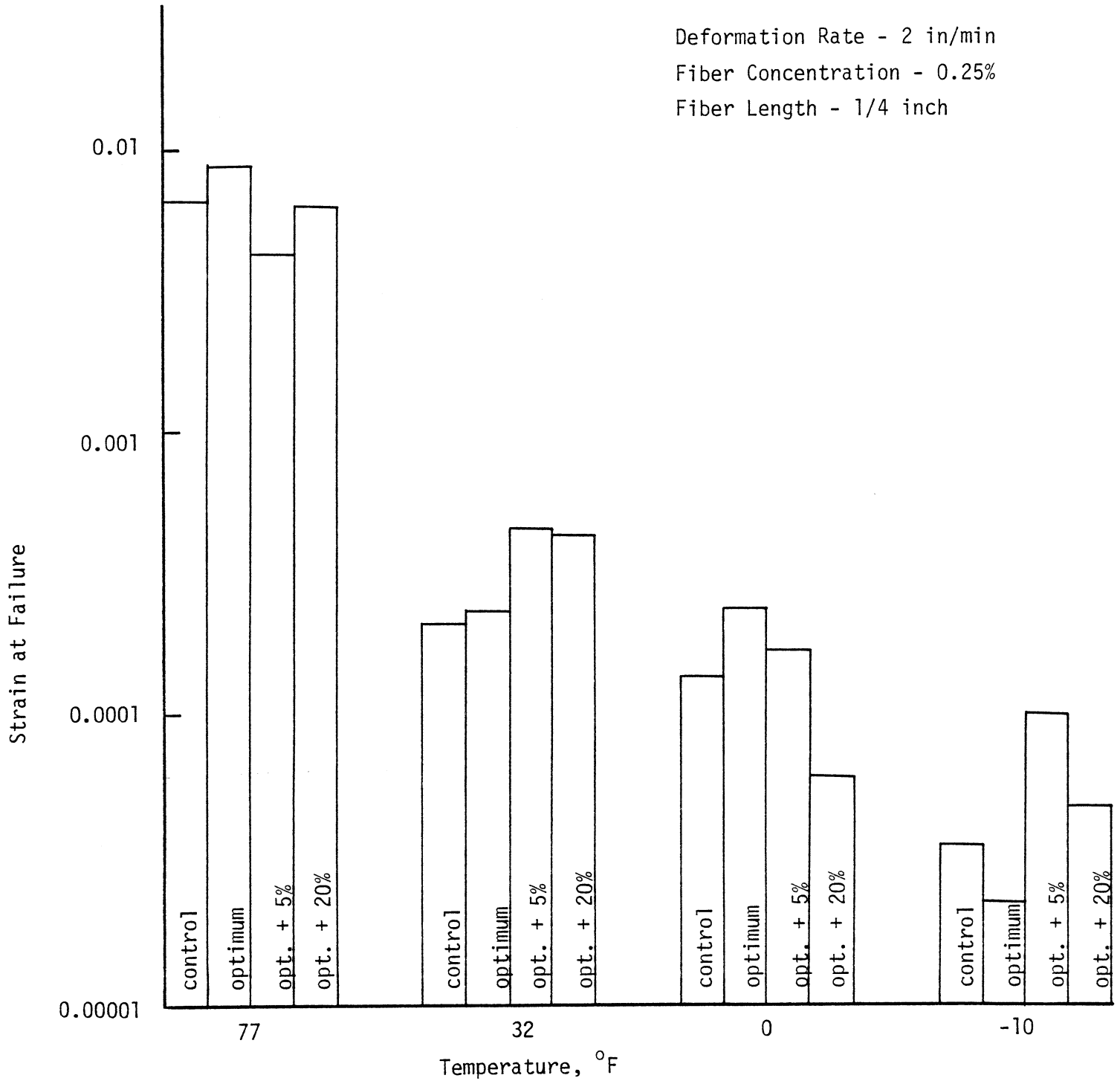


Figure 37. Effect of Temperature and Asphalt Content on Direct Tensile Strain at Failure of Asphalt Concrete Containing a One Fourth Inch Fiber at a Concentration of 0.25 Percent.

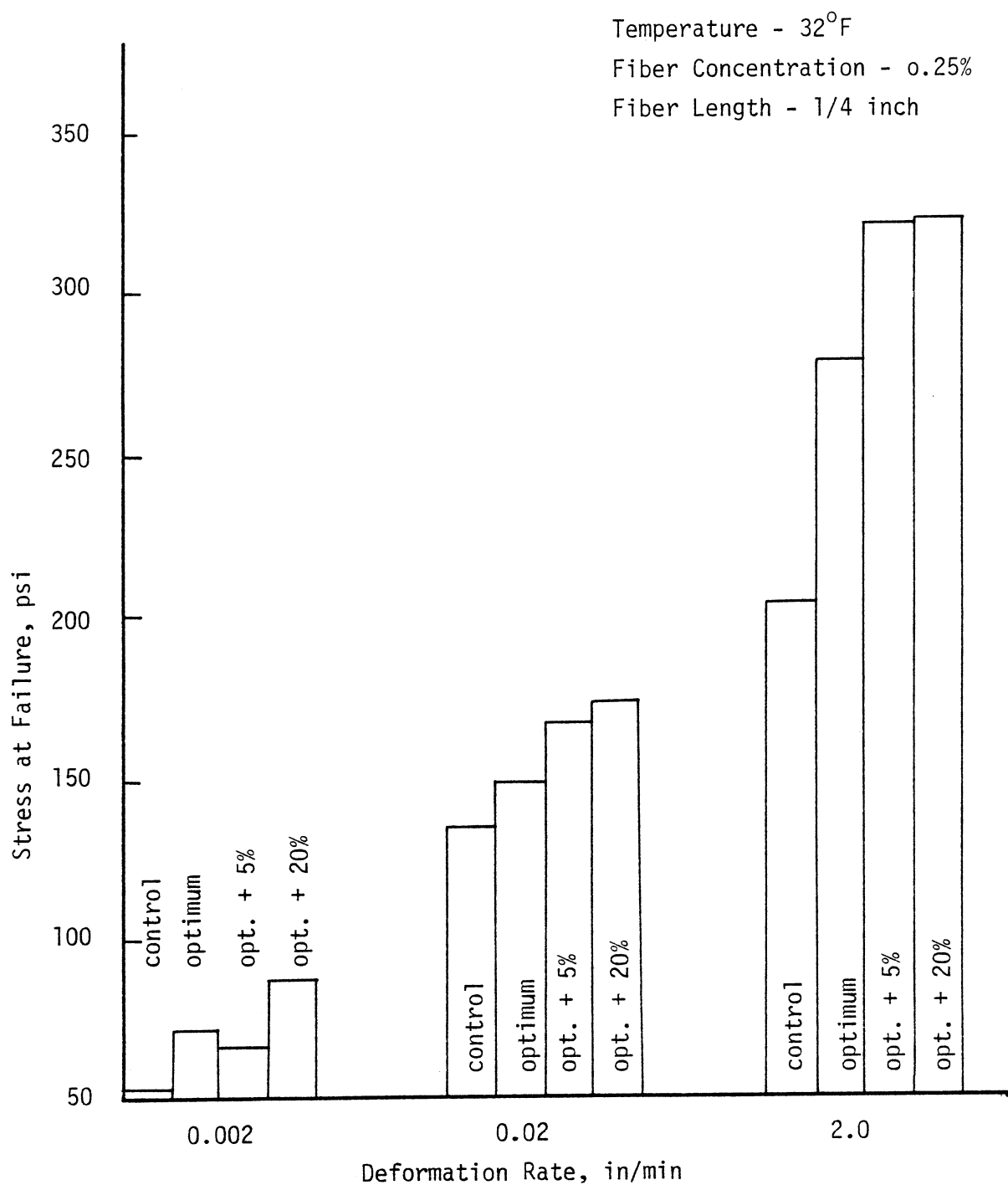


Figure 38. Effect of Deformation Rate and Asphalt Content on Direct Tensile Strength of Asphalt Concrete Containing a One Fourth Inch Fiber at a Concentration of 0.25 Percent.

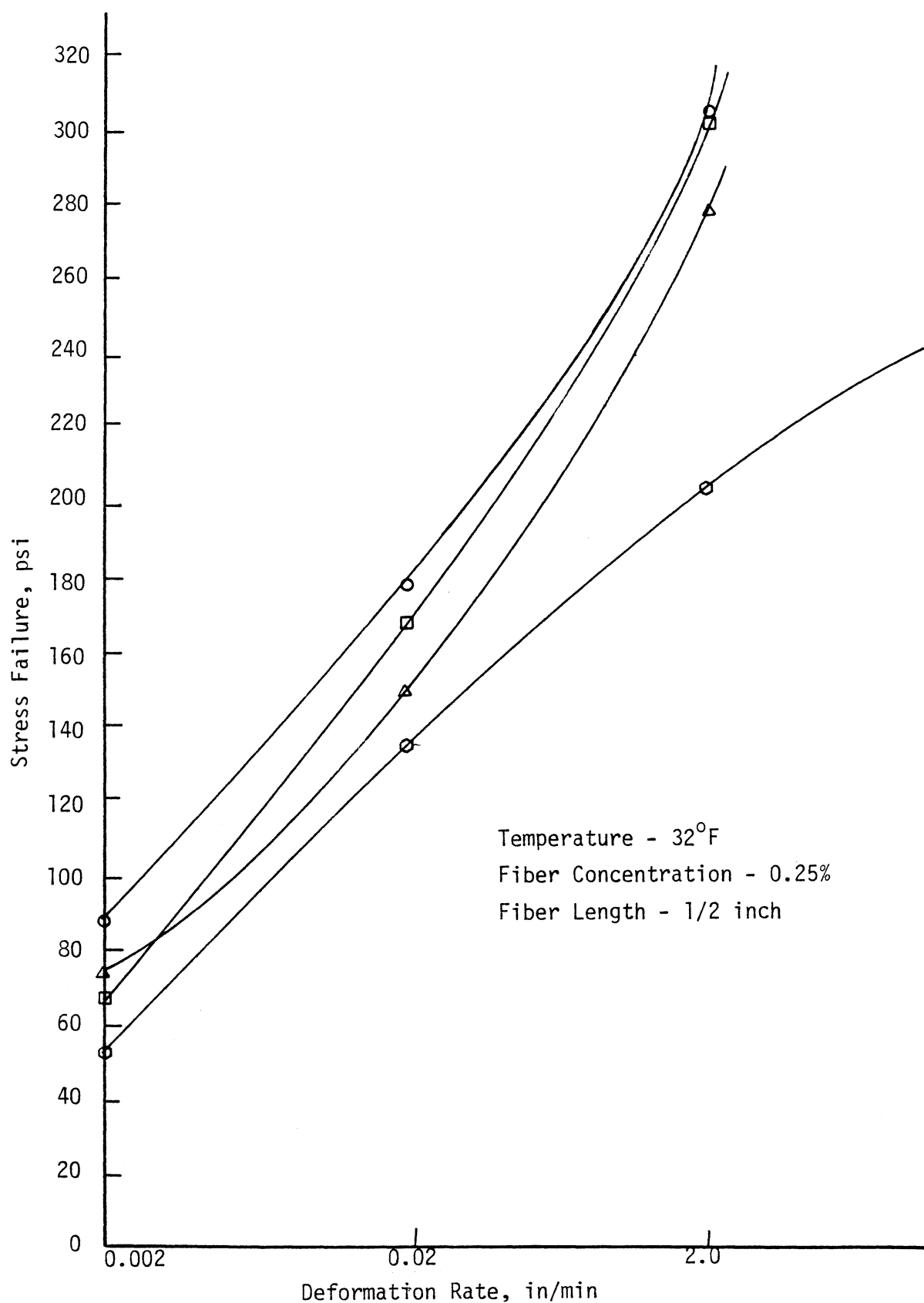


Figure 39. Effect of Deformation Rate and Asphalt Content on Direct Tensile Strength of Asphalt Concrete Containing a One Fourth Inch Fiber at a Concentration of 0.25 Percent.

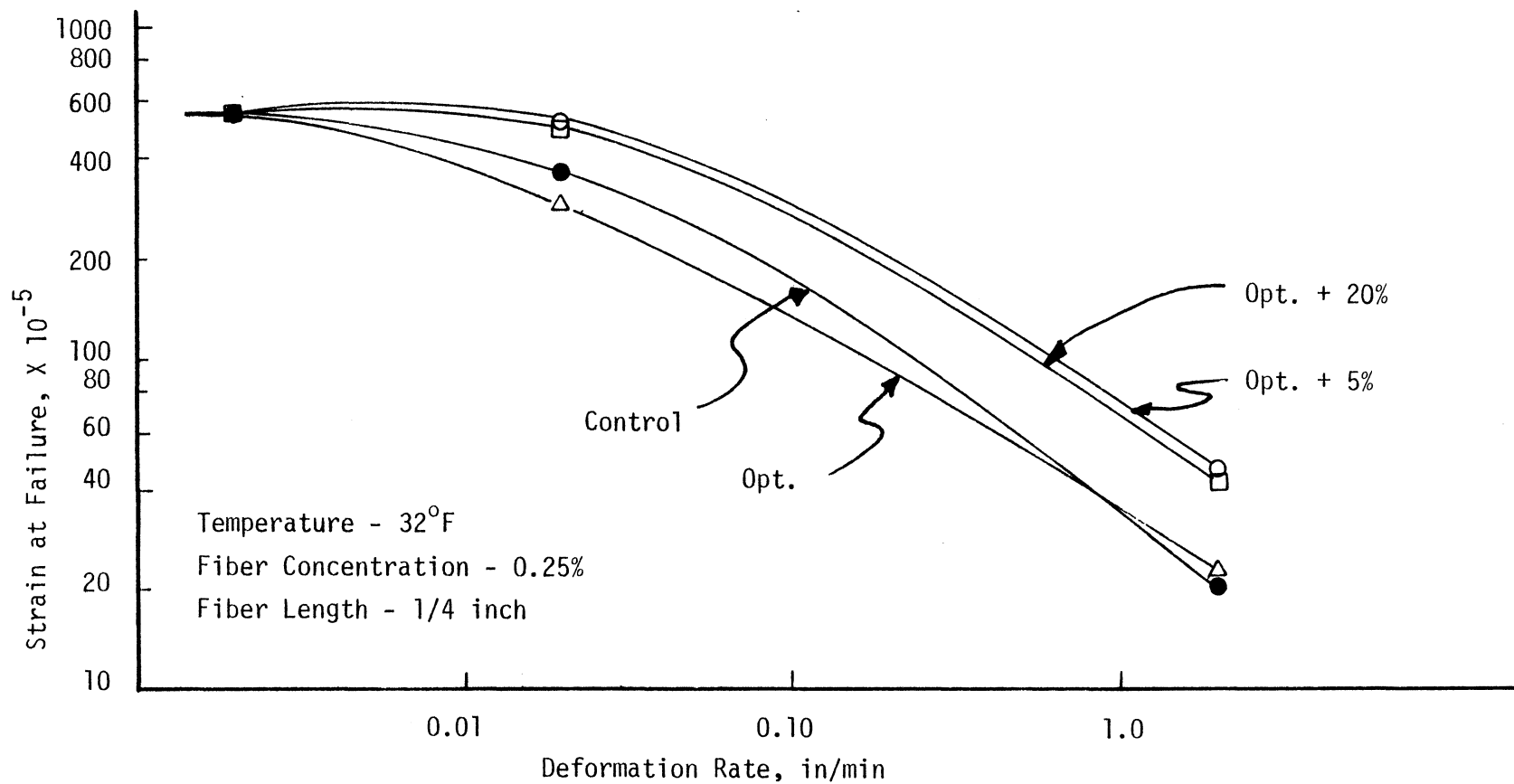


Figure 40. Effect of Deformation Rate and Asphalt Content on Direct Tensile Strength of Asphalt Concrete Containing One Fourth Inch Fiber at a Concentration of 0.25 Percent.

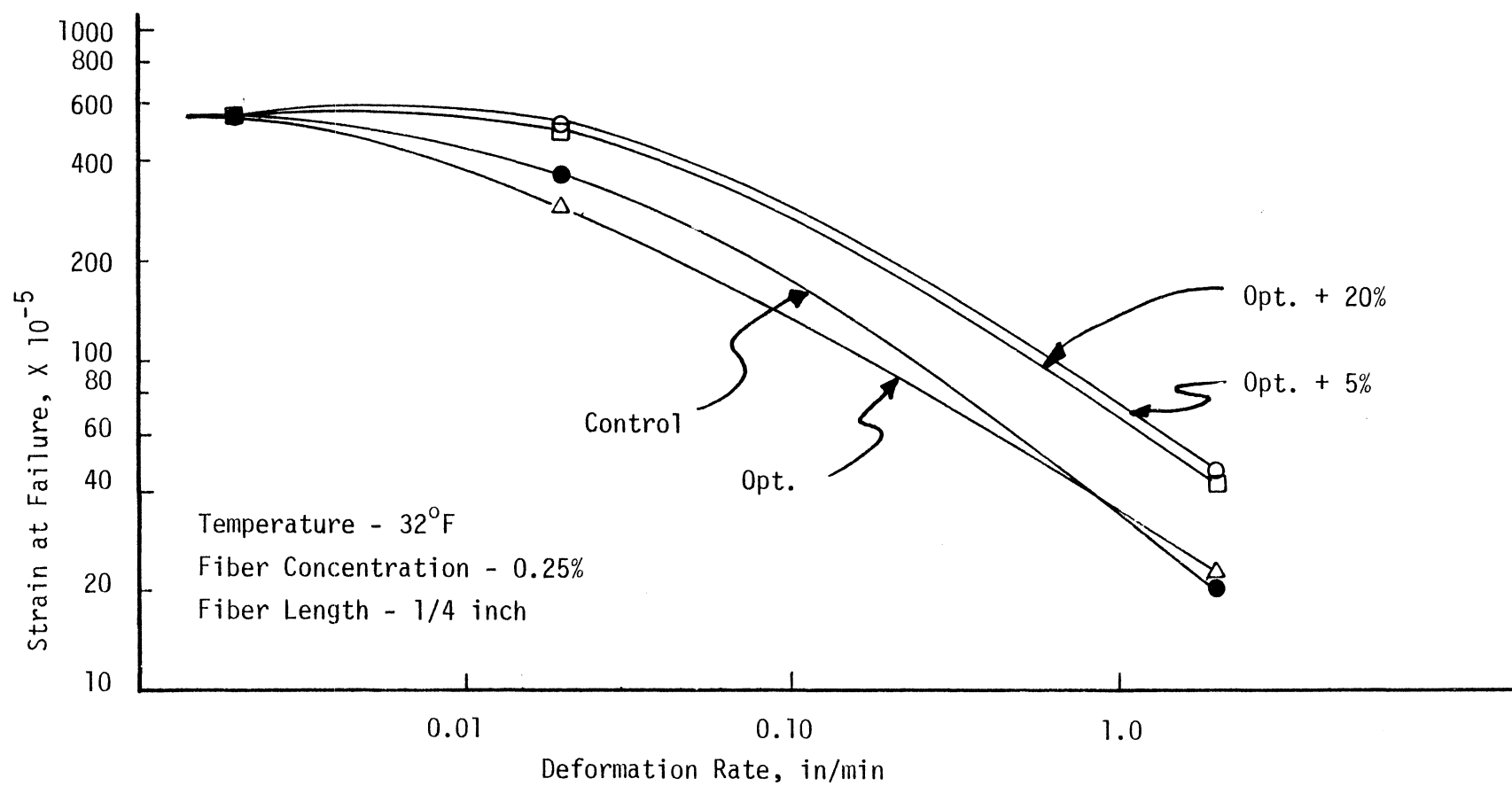


Figure 40. Effect of Deformation Rate and Asphalt Content on Direct Tensile Strength of Asphalt Concrete Containing One Fourth Inch Fiber at a Concentration of 0.25 Percent.

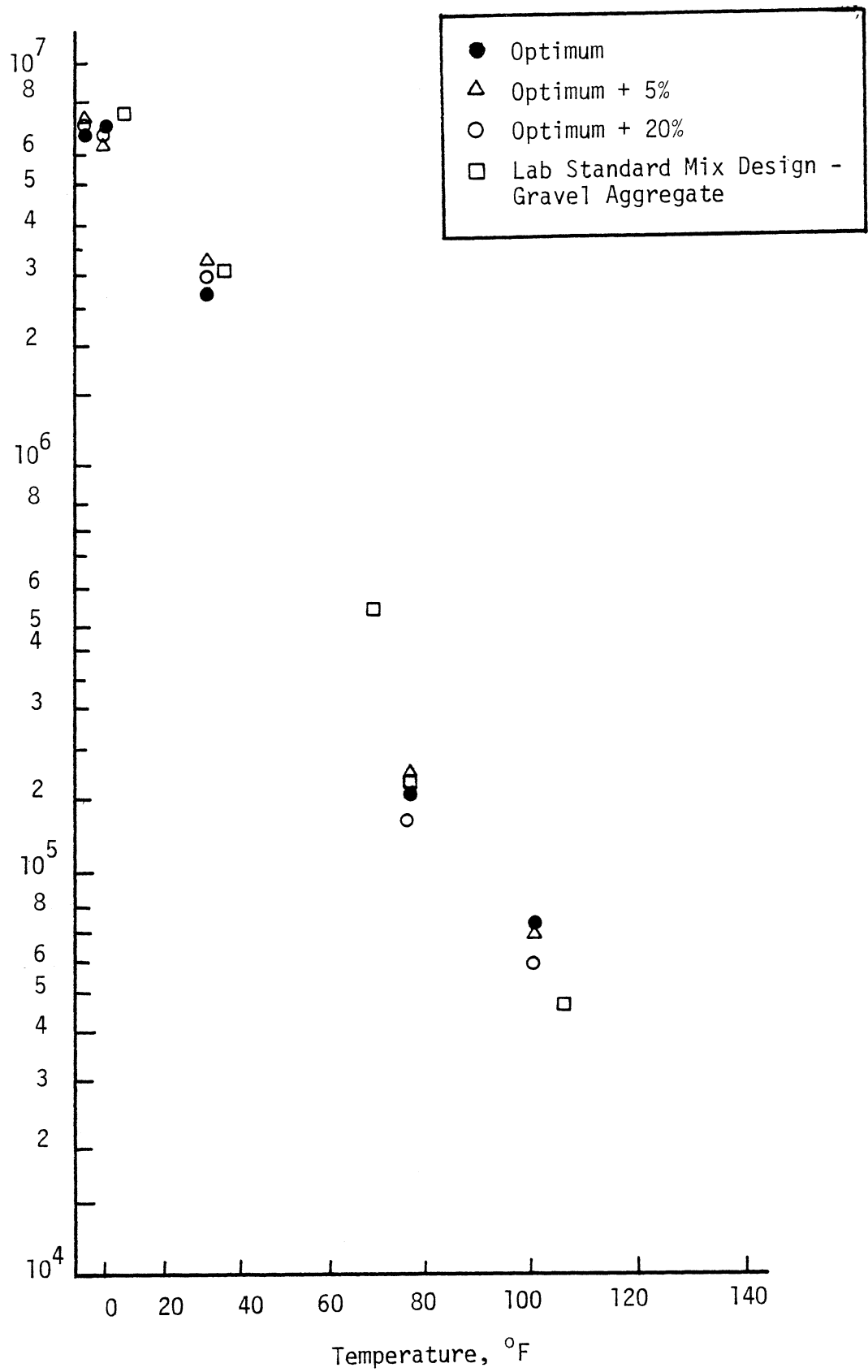


Figure 41. Effect of Temperature and Asphalt Content on Resilient Modulus of Asphalt Concrete Containing One Fourth Inch Fibers at a Concentration of 0.25%.

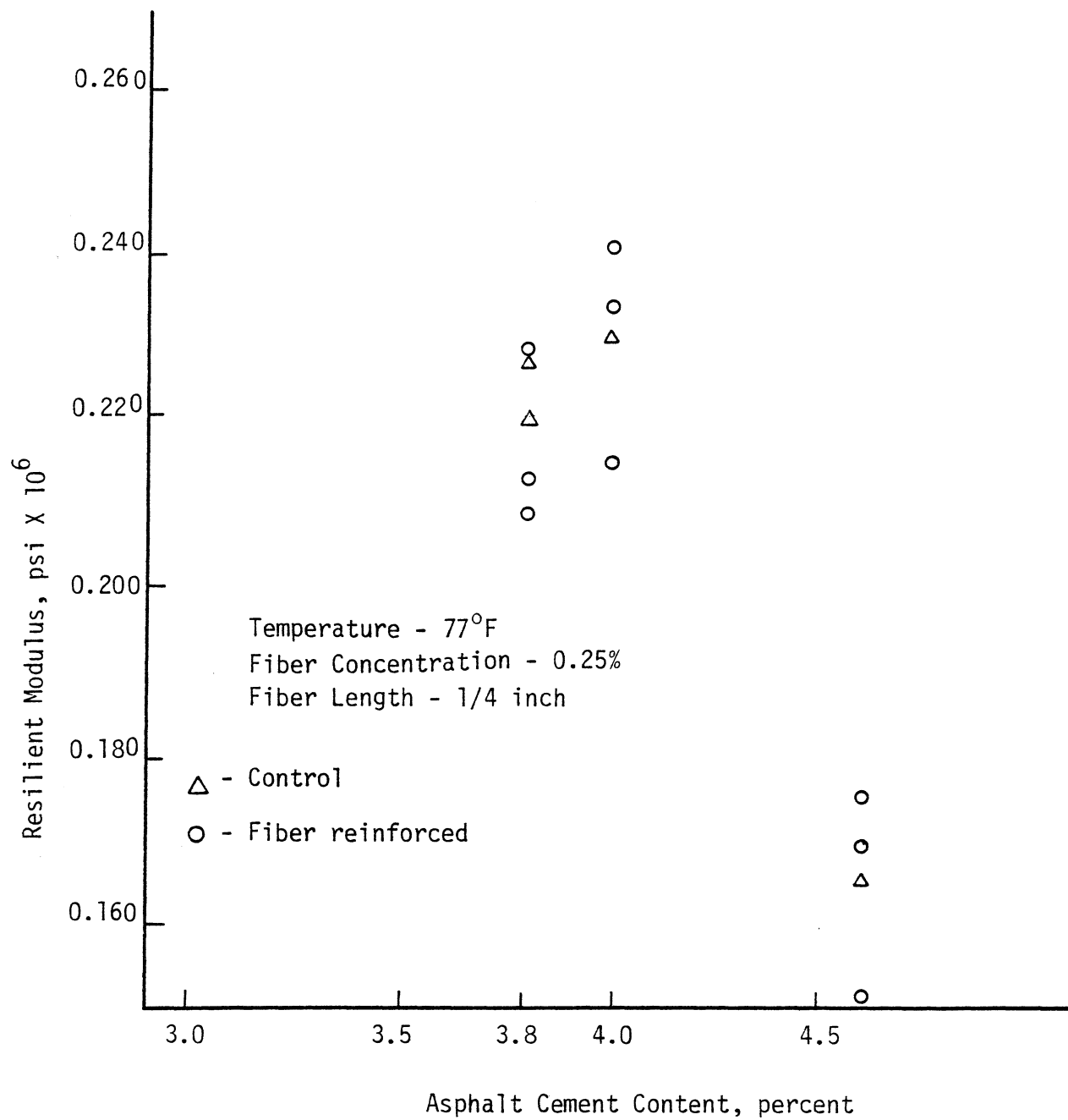


Figure 42. Effect of Asphalt Cement Content on Resilient Modulus of Asphalt Concrete Containing One Fourth Inch Fibers At a Concentration of 0.25 Percent.

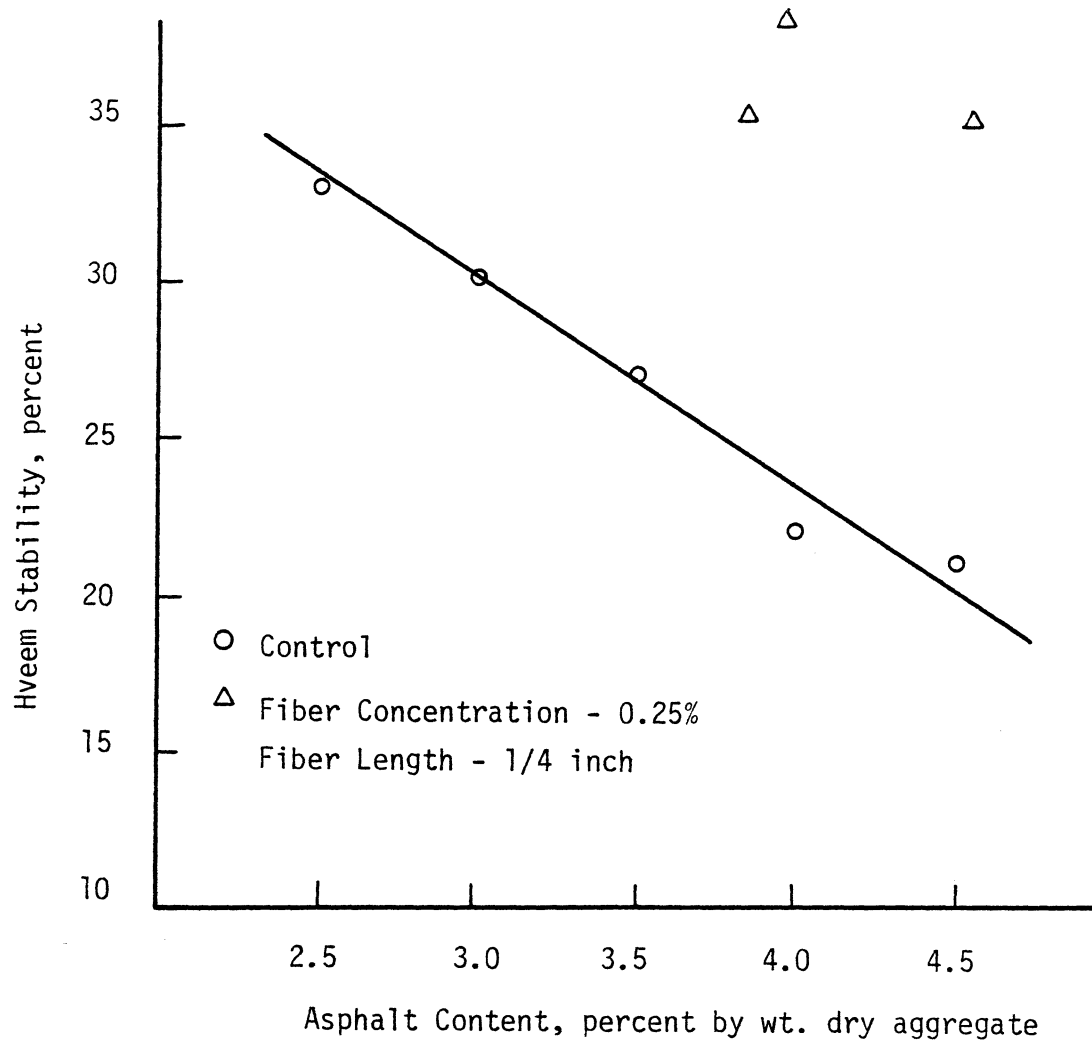


Figure 43. Hveem Stability of Samples Prepared With Gravel Aggregate.

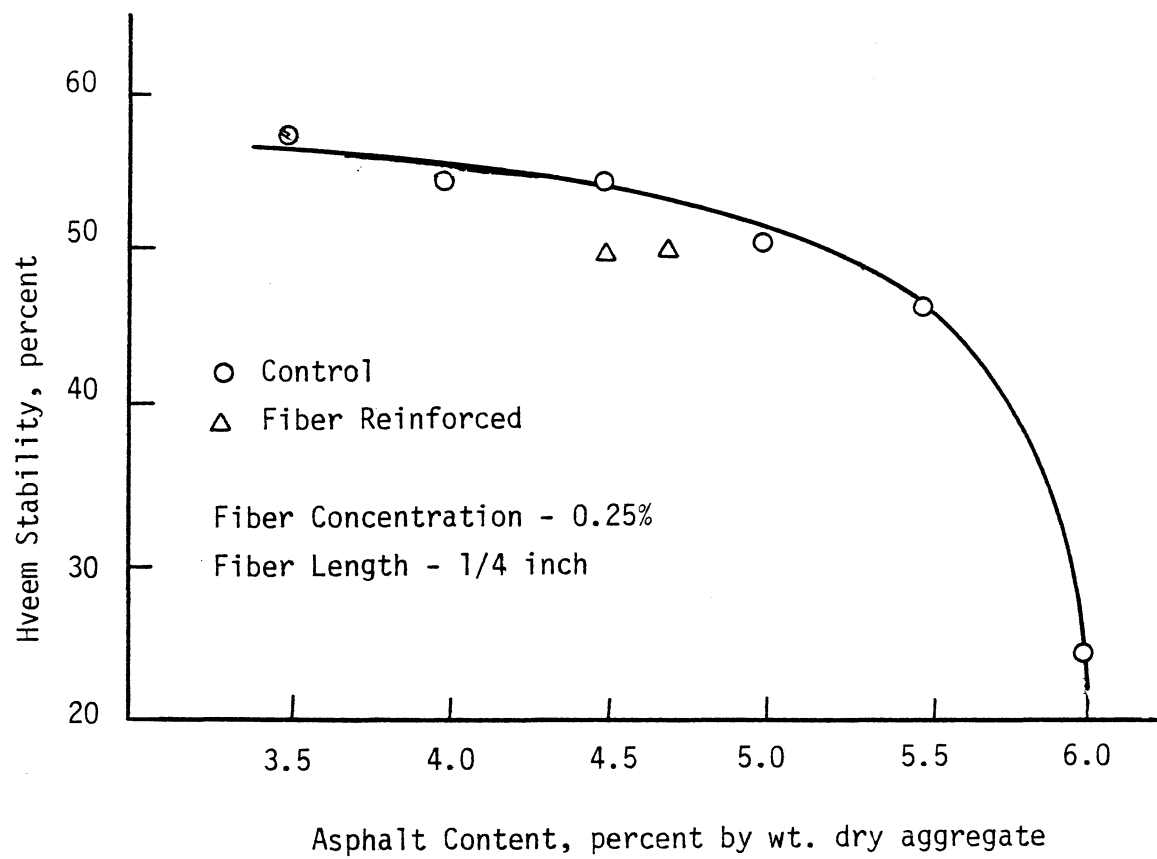


Figure 44. Hveem Stability of Samples Prepared With Crushed Limestone.

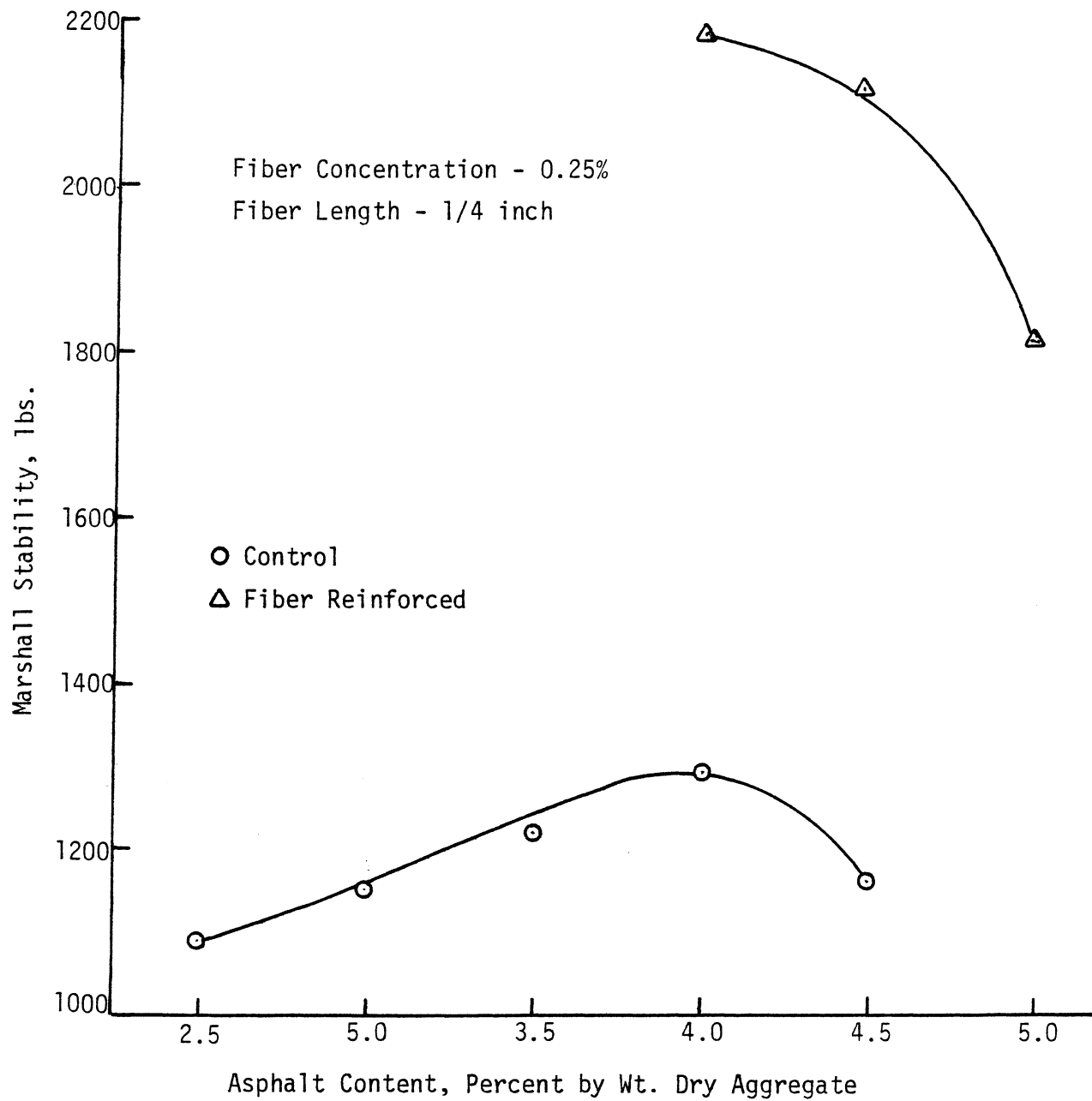


Figure 45. Marshall Stability of Specimens Using Rounded Gravel.

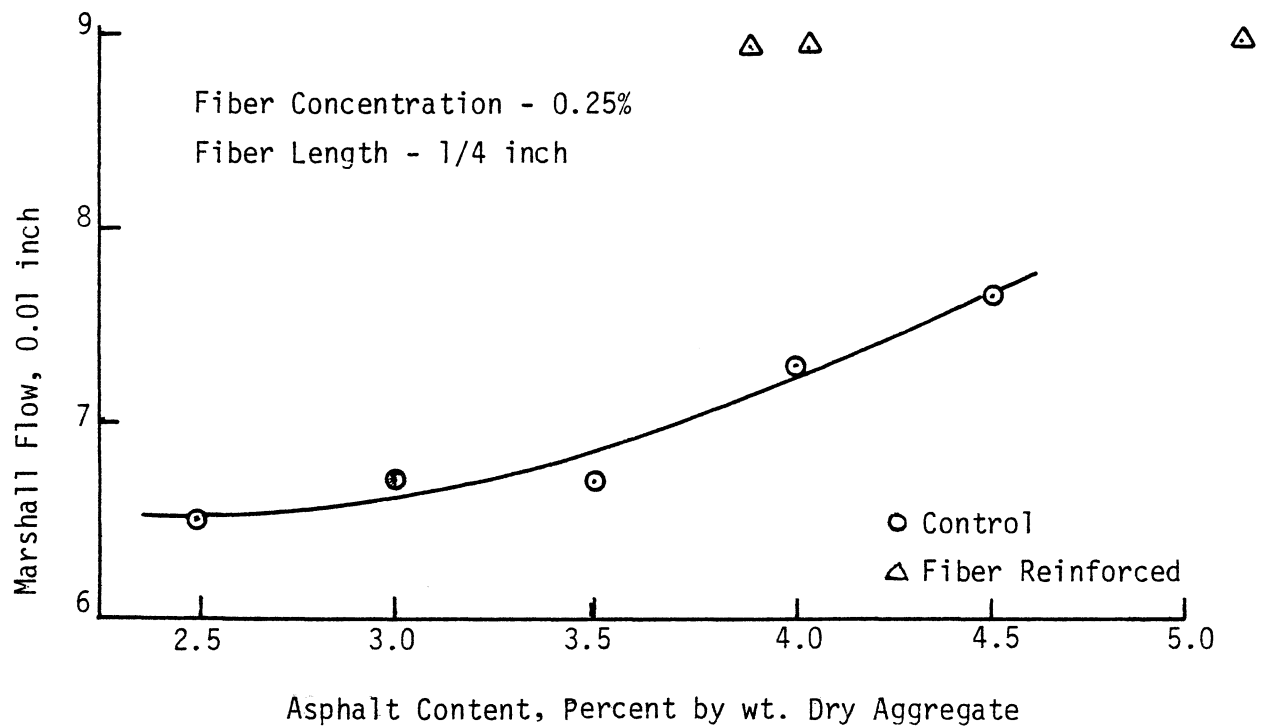


Figure 46. Marshall Flow of Specimens Using Rounded Gravel.

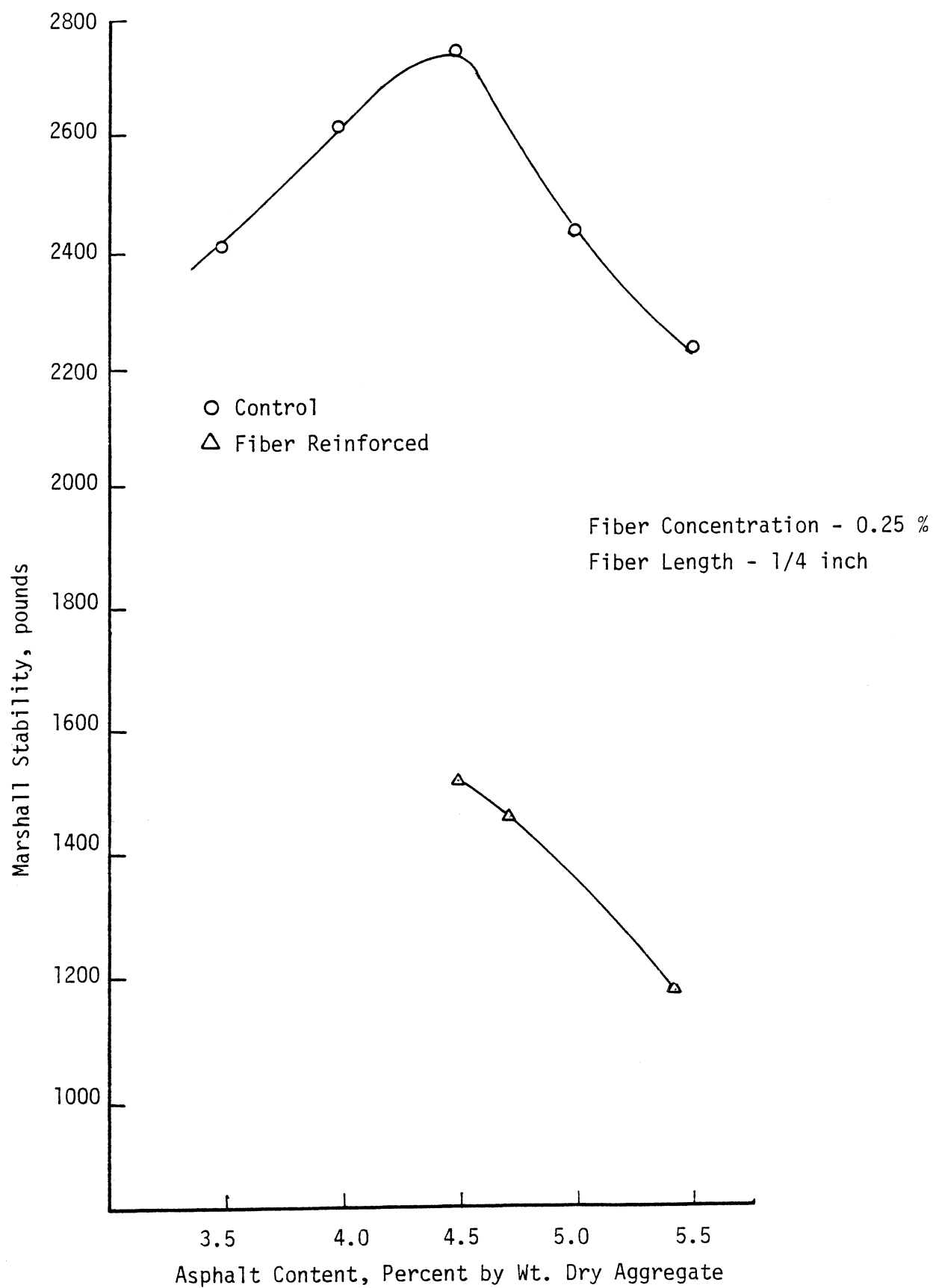


Figure 47. Marshall Stability of Specimens Using Crushed Limestone.

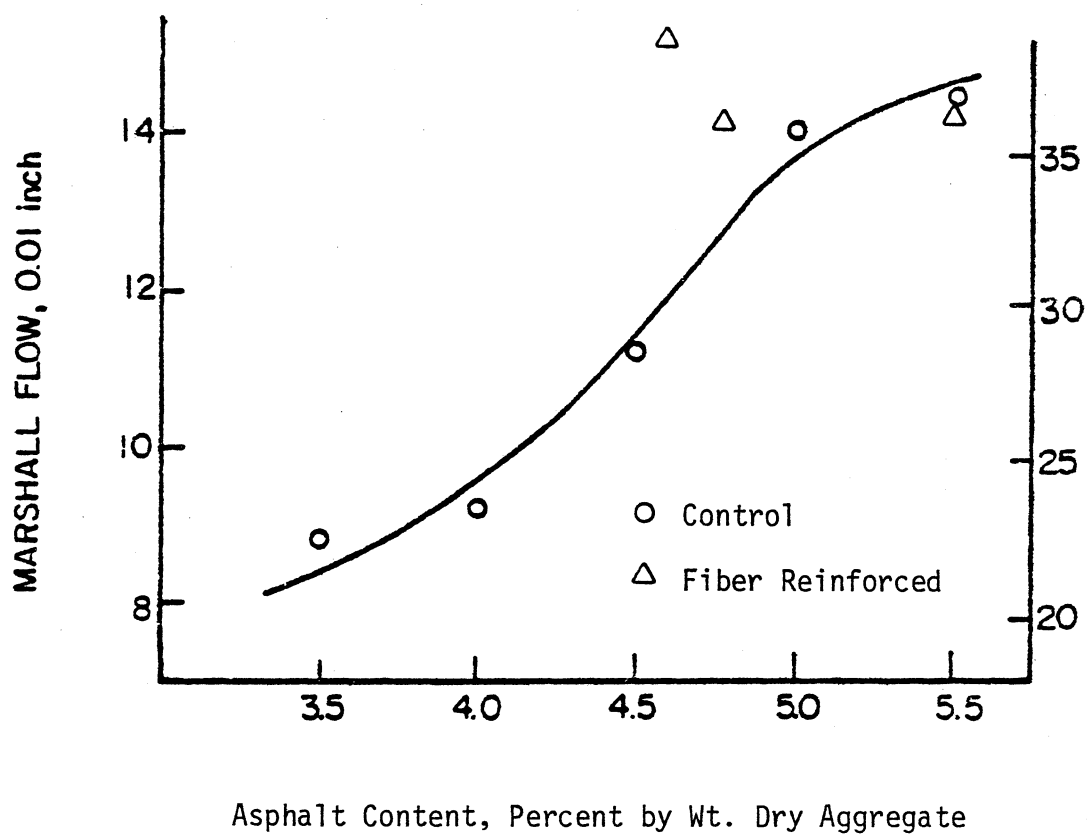


Figure 48. Marshall Flow of Specimens Using Crushed Limestone.

APPENDIX A

Stress-Strain Behavior of Fiber Reinforced Asphalt Concrete Mixtures

Table A-1. Stress, Strain and Modulus Values for Phase B for Deformation Rates of 0.020 in/min and 0.002 in/min for Individual Samples.

| Asphalt Content, Percent | Rate of Deformation, in/min | Stress at Failure, psi | Strain at Failure, in/in | Modulus at Failure $\text{psi} \times 10^3$ |
|--------------------------|-----------------------------|------------------------|--------------------------|---|
| Control | 0.020 | 123.2 | 0.0049 | 25,000 |
| | | 130.7 | 0.0039 | 33,900 |
| | | 150.1 | 0.0021 | 71,800 |
| Control | 0.002 | 59.2 | 0.0049 | 12,000 |
| | | 45.0 | 0.0041 | 11,000 |
| | | 52.4 | 0.0077 | 6,800 |
| Optimum | 0.020 | 169.8 | 0.0028 | 61,500 |
| | | 134.5 | 0.0019 | 70,000 |
| | | 141.0 | 0.0042 | 33,500 |
| Optimum | 0.002 | 72.9 | 0.0059 | 12,400 |
| | | 68.6 | 0.0056 | 12,100 |
| | | 79.5 | 0.0054 | 14,700 |
| Optimum Plus 5% | 0.020 | 184.0 | 0.0060 | 29,200 |
| | | 162.7 | 0.0042 | 38,700 |
| | | 151.5 | 0.0051 | 26,300 |
| Optimum Plus 5% | 0.002 | 65.4 | 0.0036 | 18,100 |
| | | 78.3 | 0.0064 | 12,300 |
| | | 57.2 | 0.0067 | 7,600 |
| Optimum Plus 20% | 0.020 | 165.5 | 0.0051 | 32,800 |
| | | 178.9 | 0.0057 | 31,700 |
| | | 175.1 | 0.0041 | 42,800 |
| Optimum Plus 20% | 0.002 | 93.7 | 0.0067 | 13,900 |
| | | 81.4 | 0.0052 | 1,600 |
| | | 88.6 | 0.0047 | 18,900 |

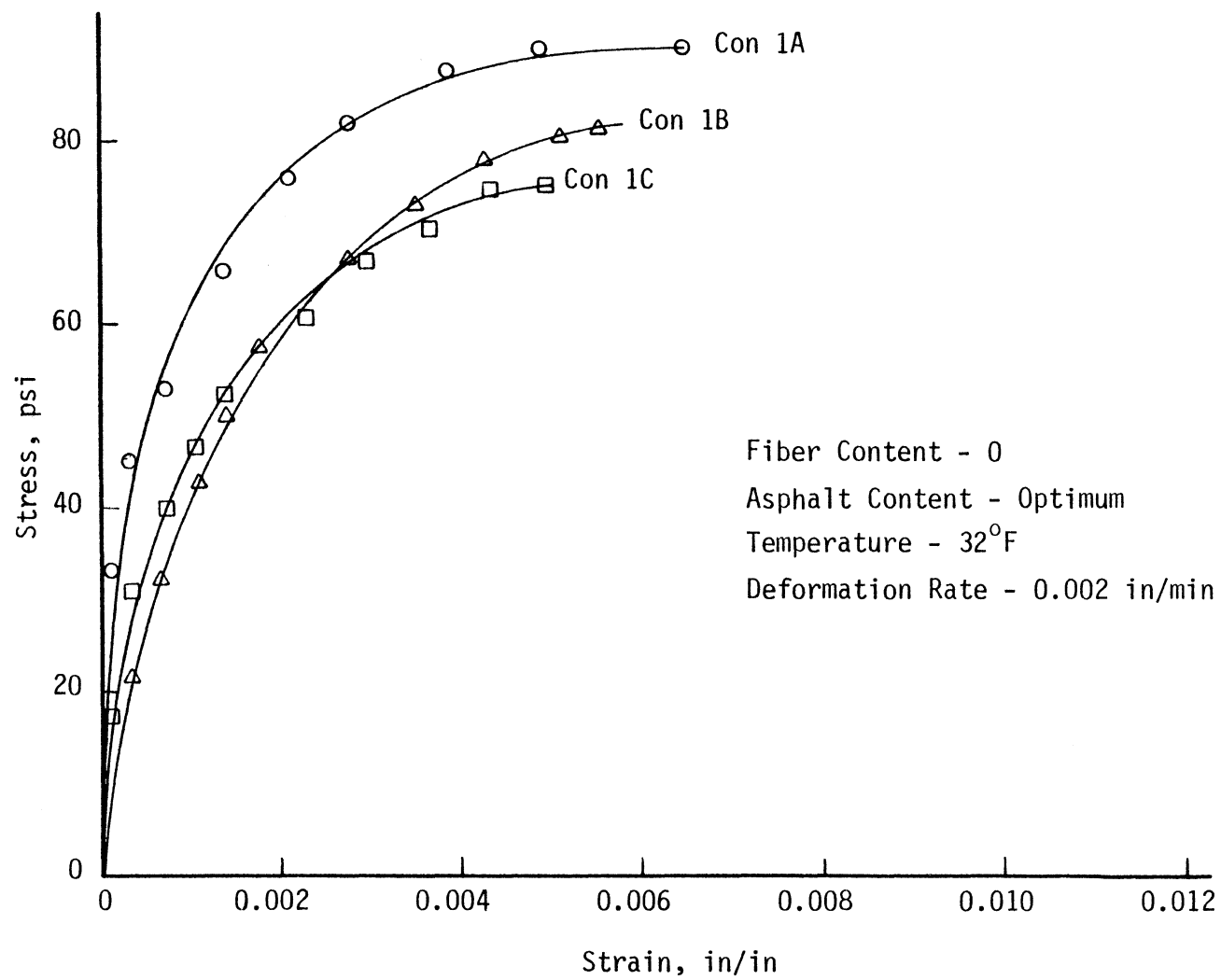


Figure A-1

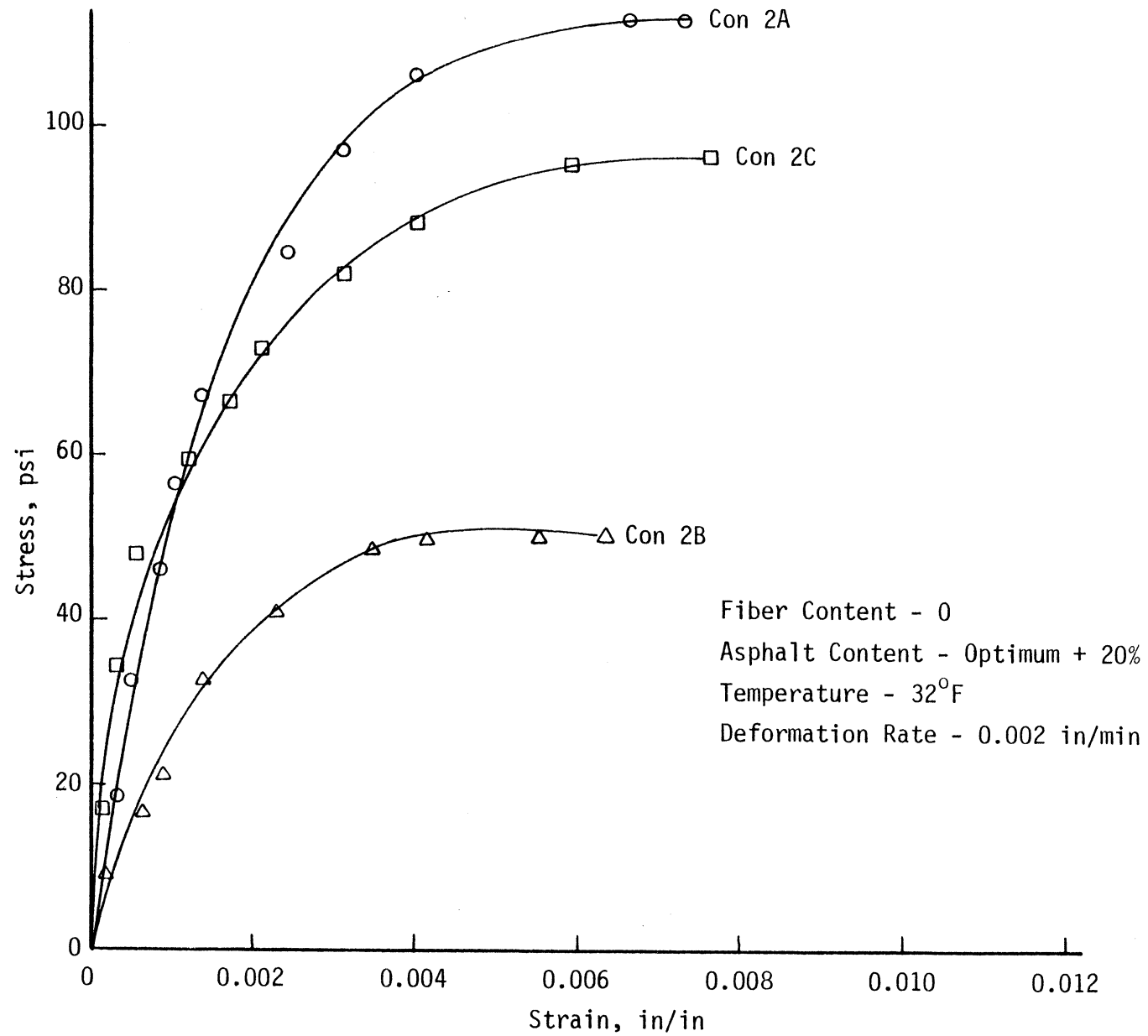


Figure A-2.

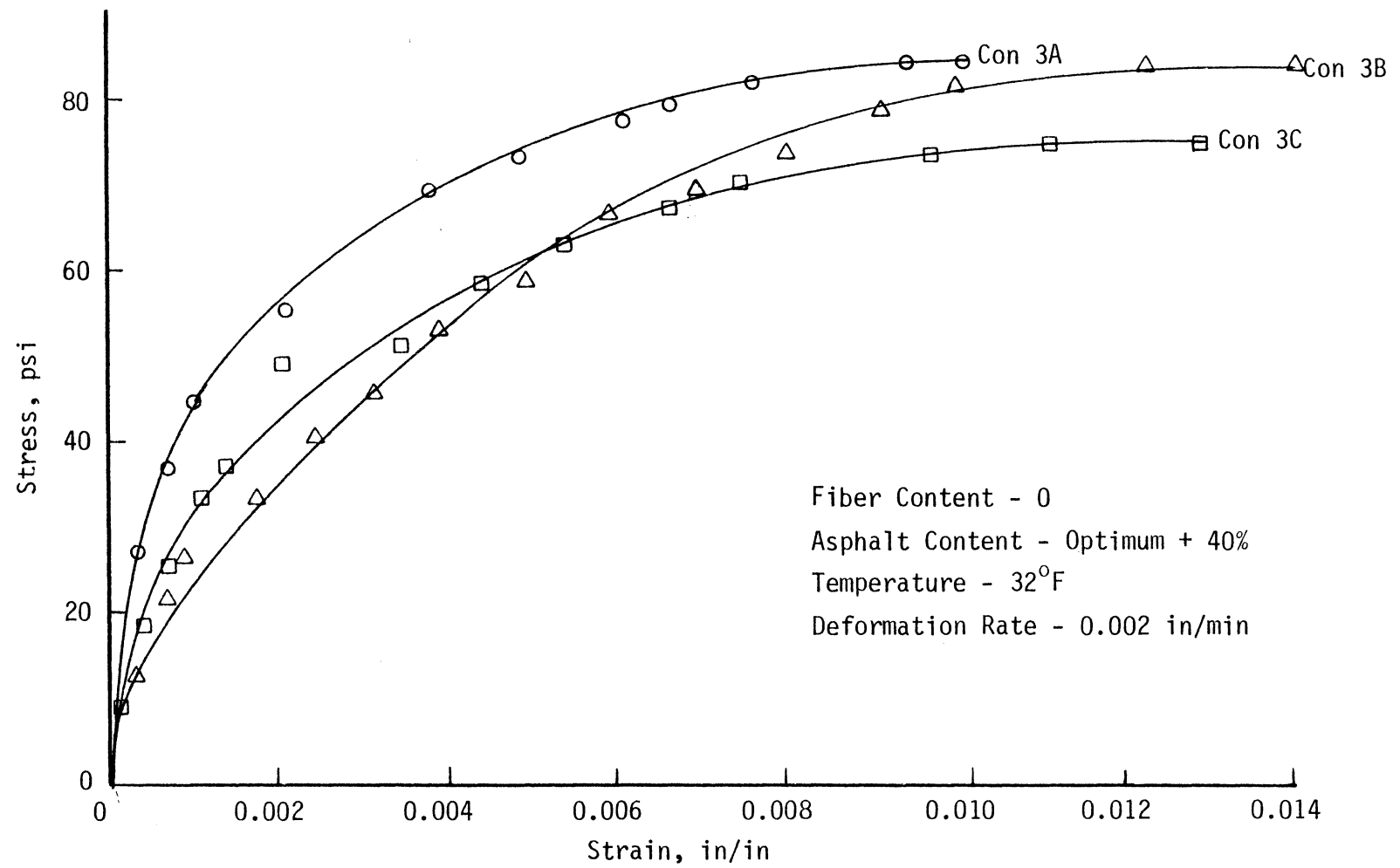


Figure A-3.

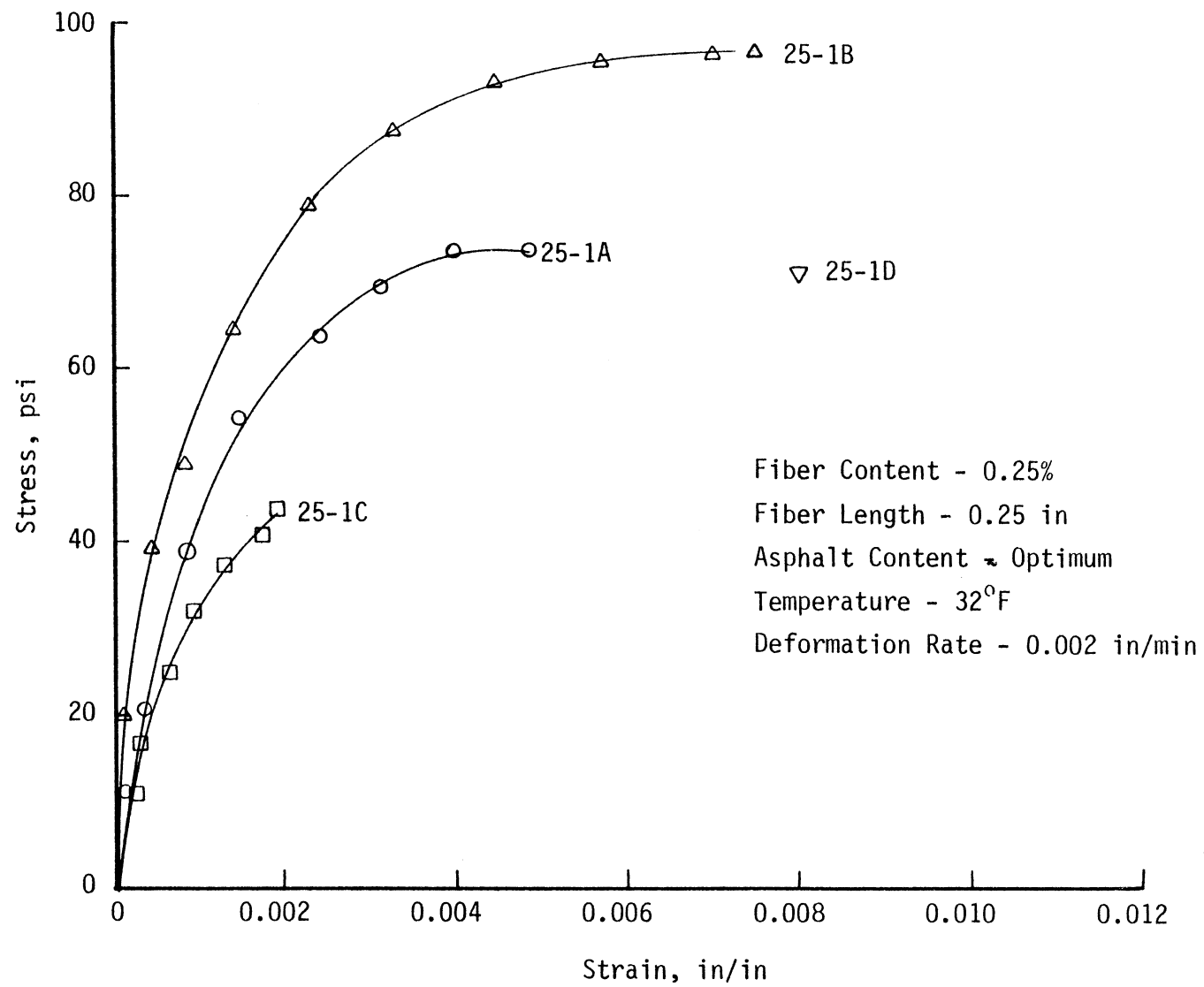


Figure A-4.

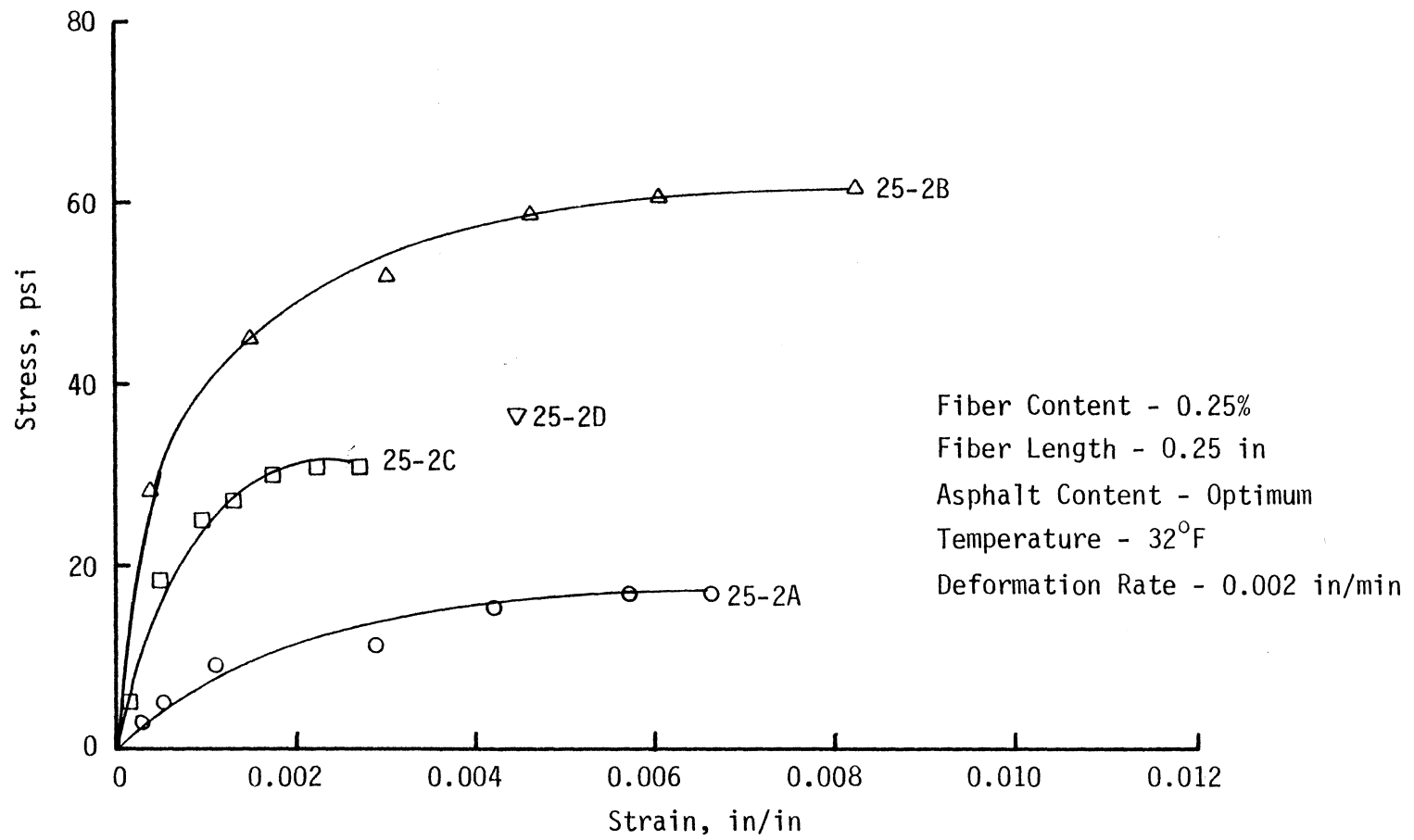


Figure A-5.

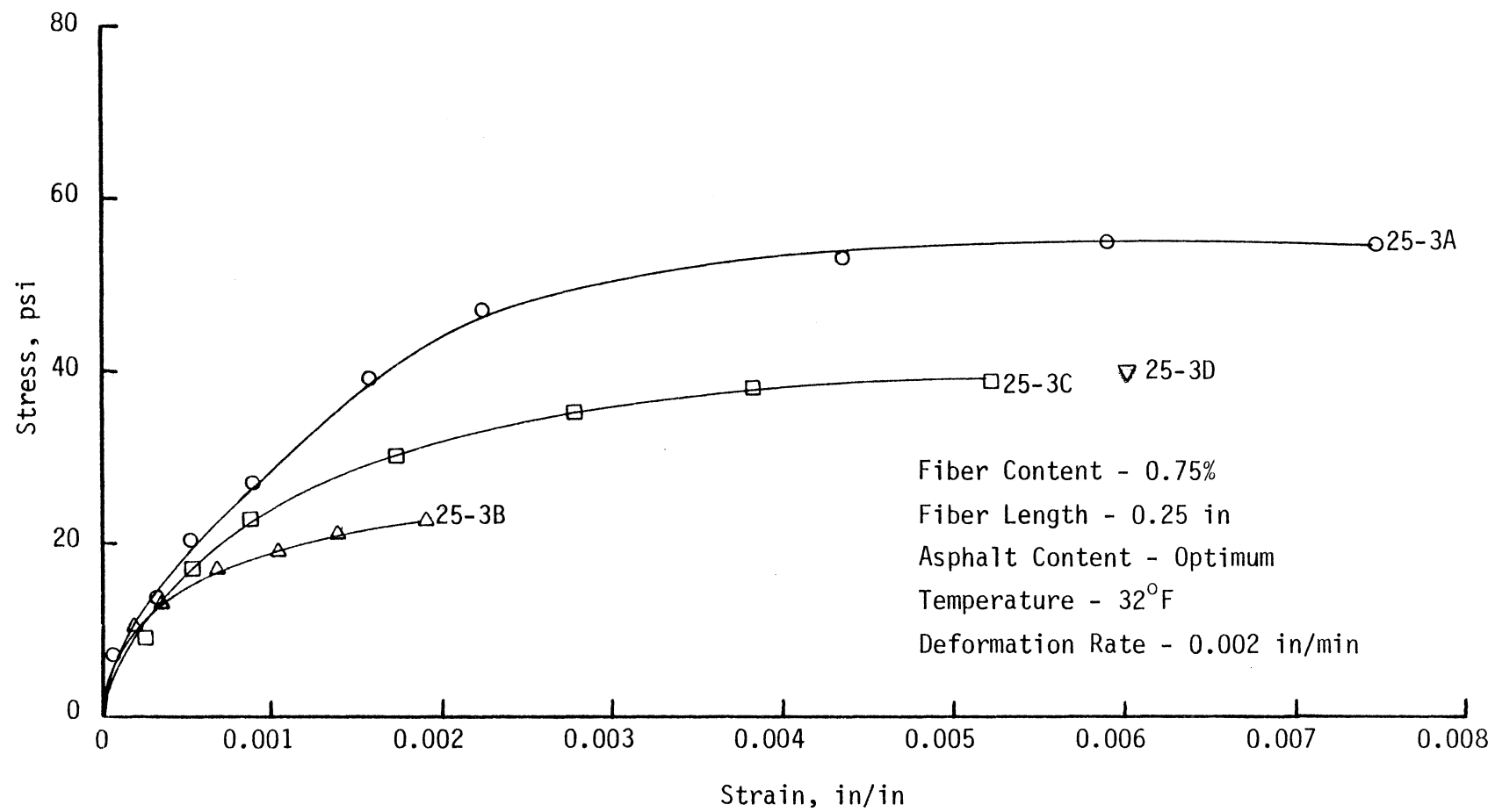


Figure A-6.

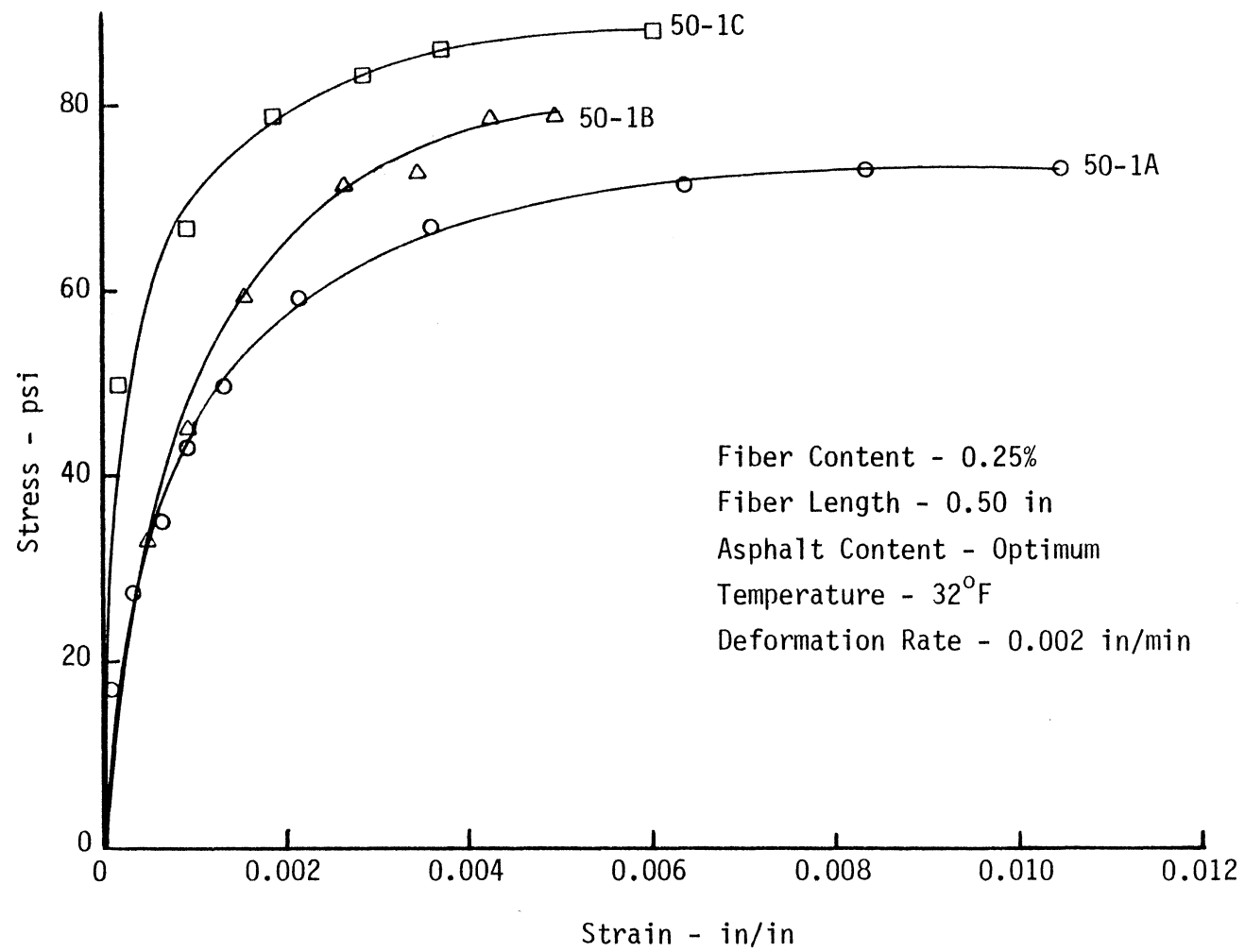


Figure A-7.

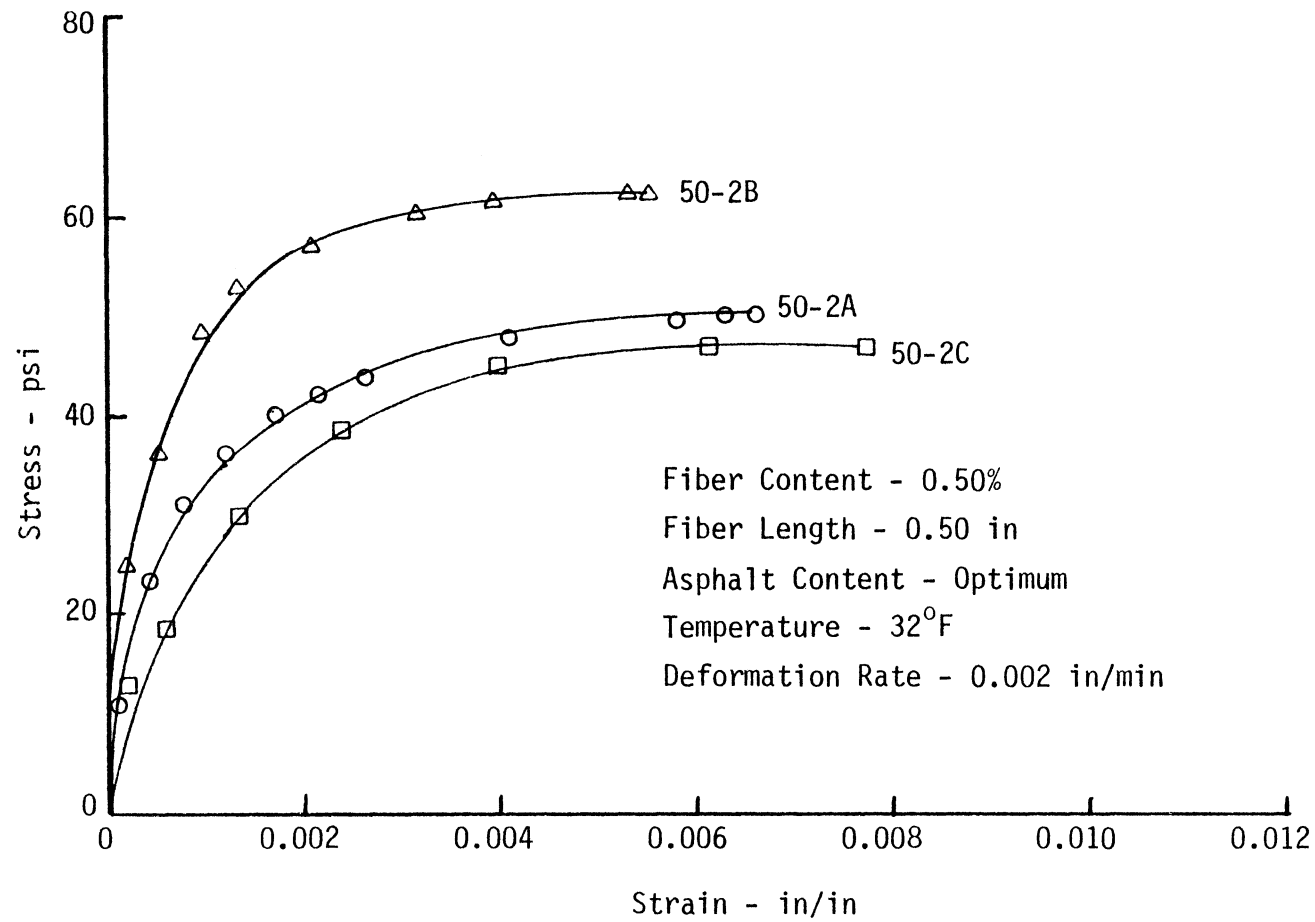


Figure A-8.

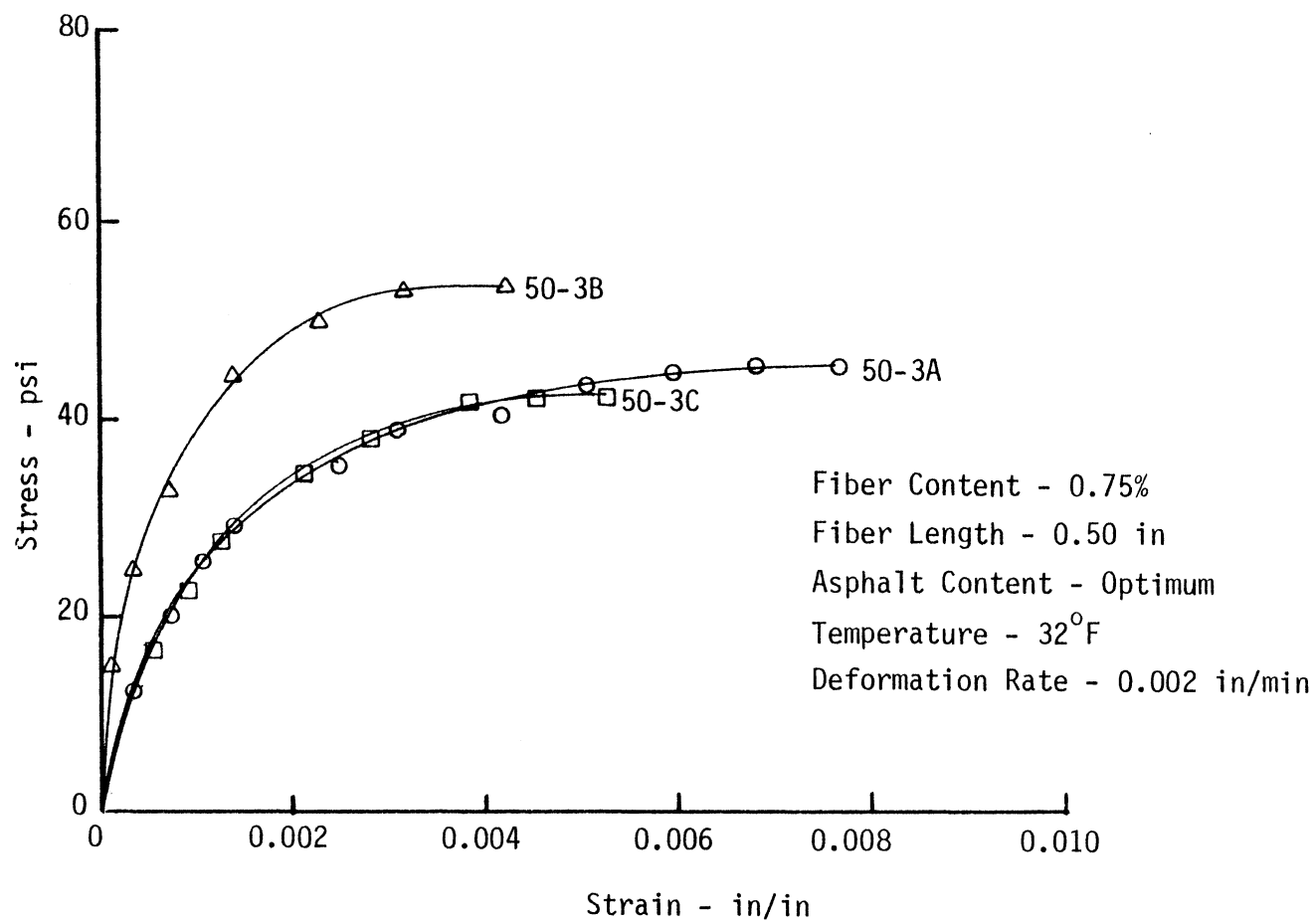


Figure A-9.

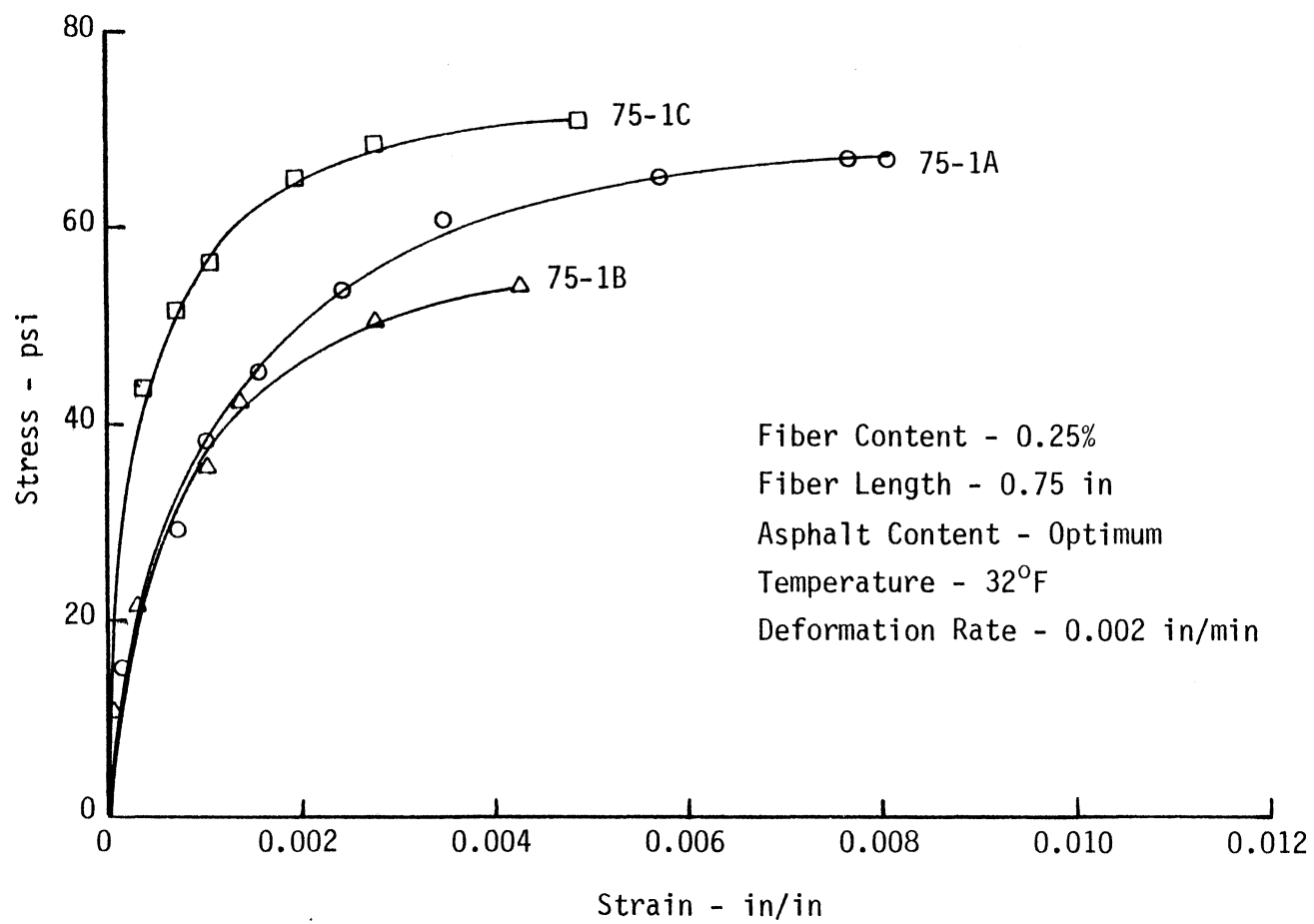


Figure A-10.

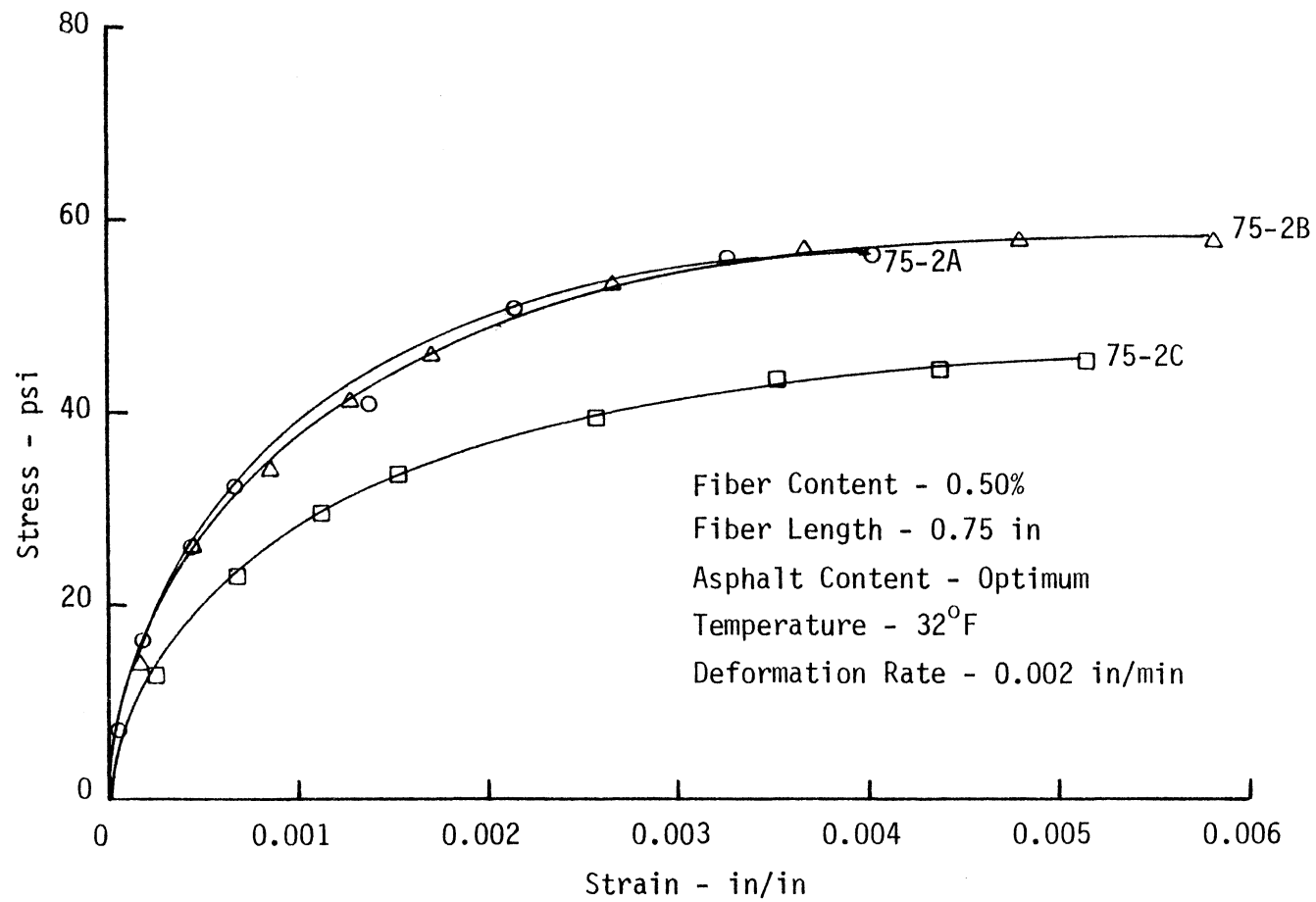


Figure A-11.

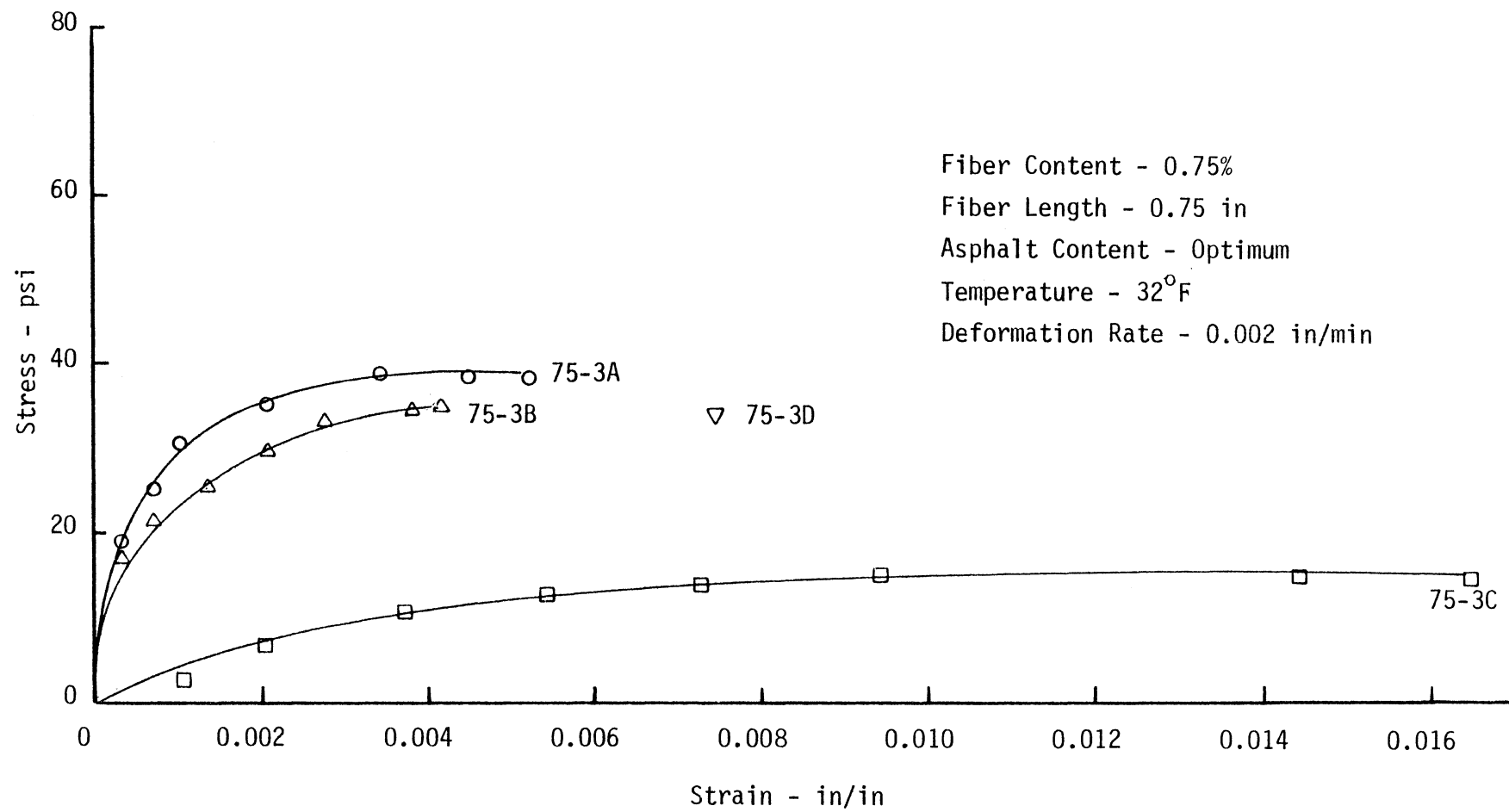


Figure A-12.

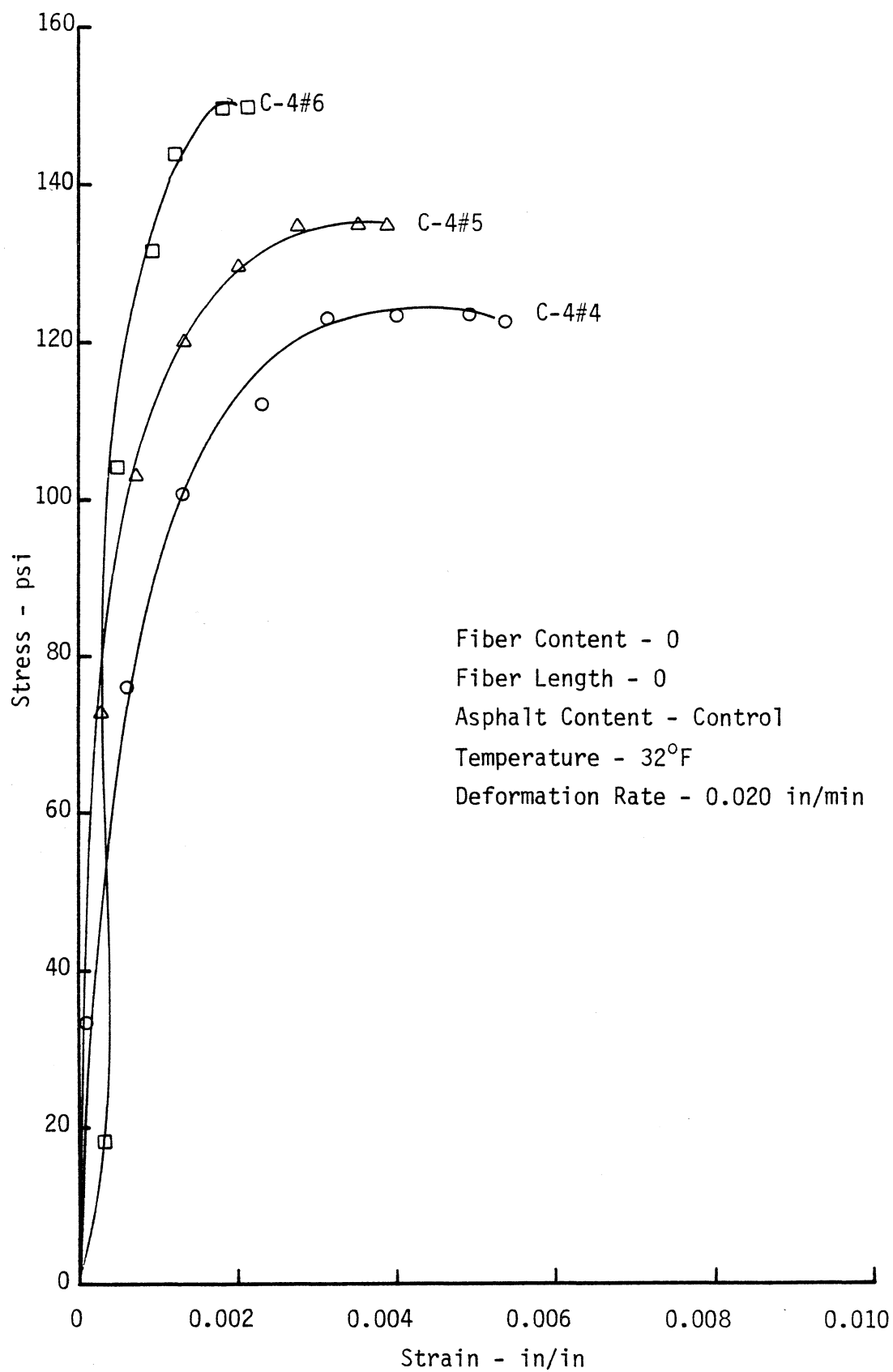


Figure A-13.

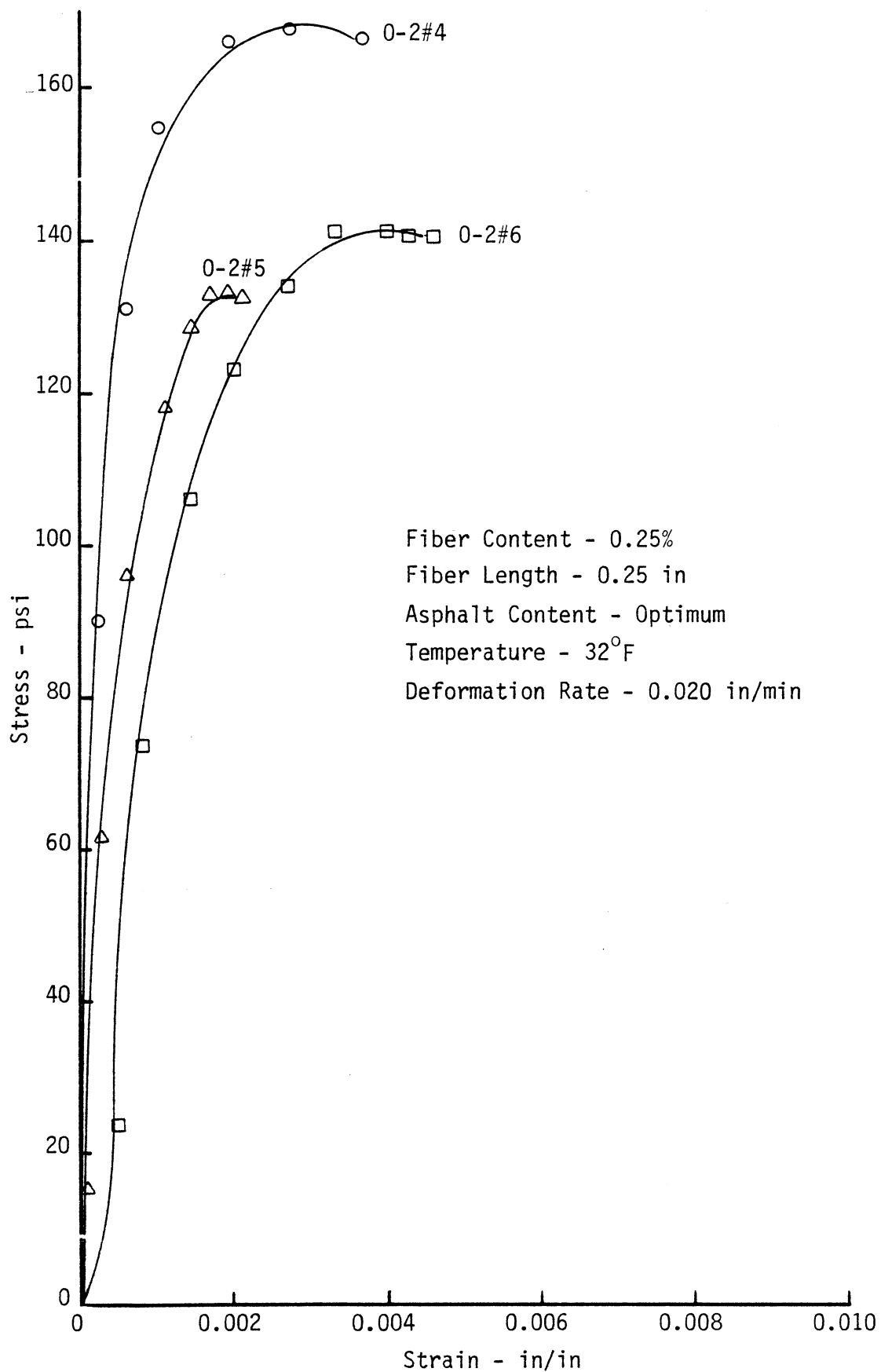


Figure A-14.

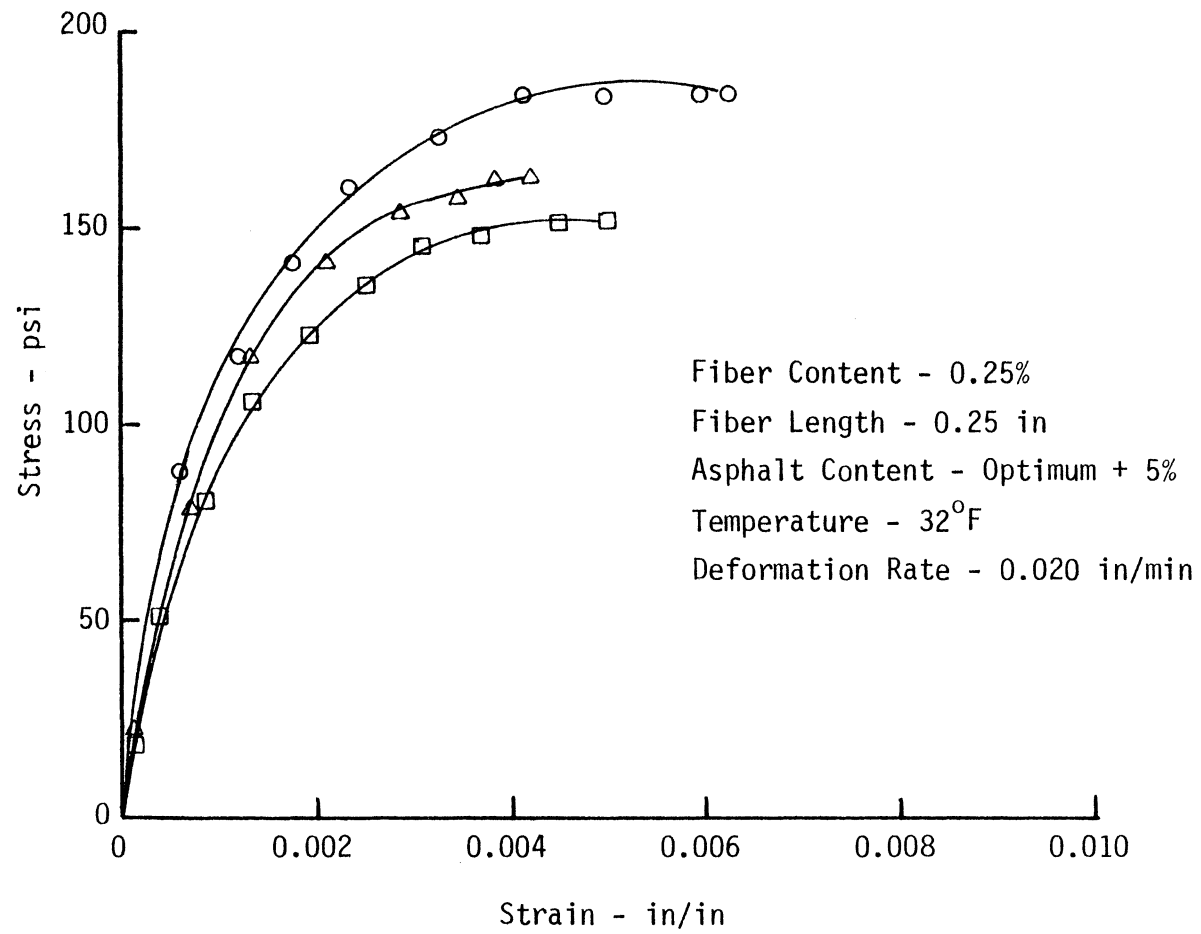


Figure A-15.

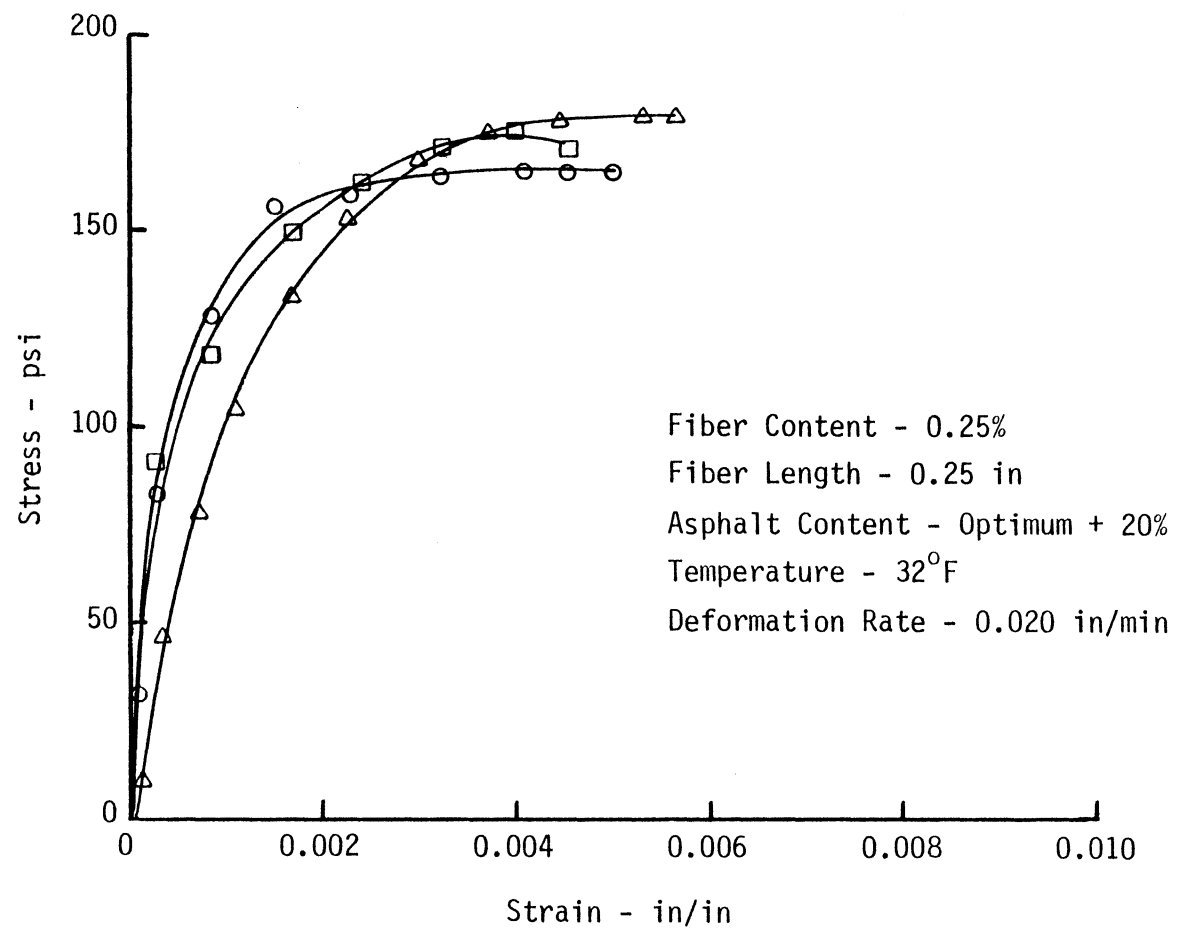


Figure A-16.

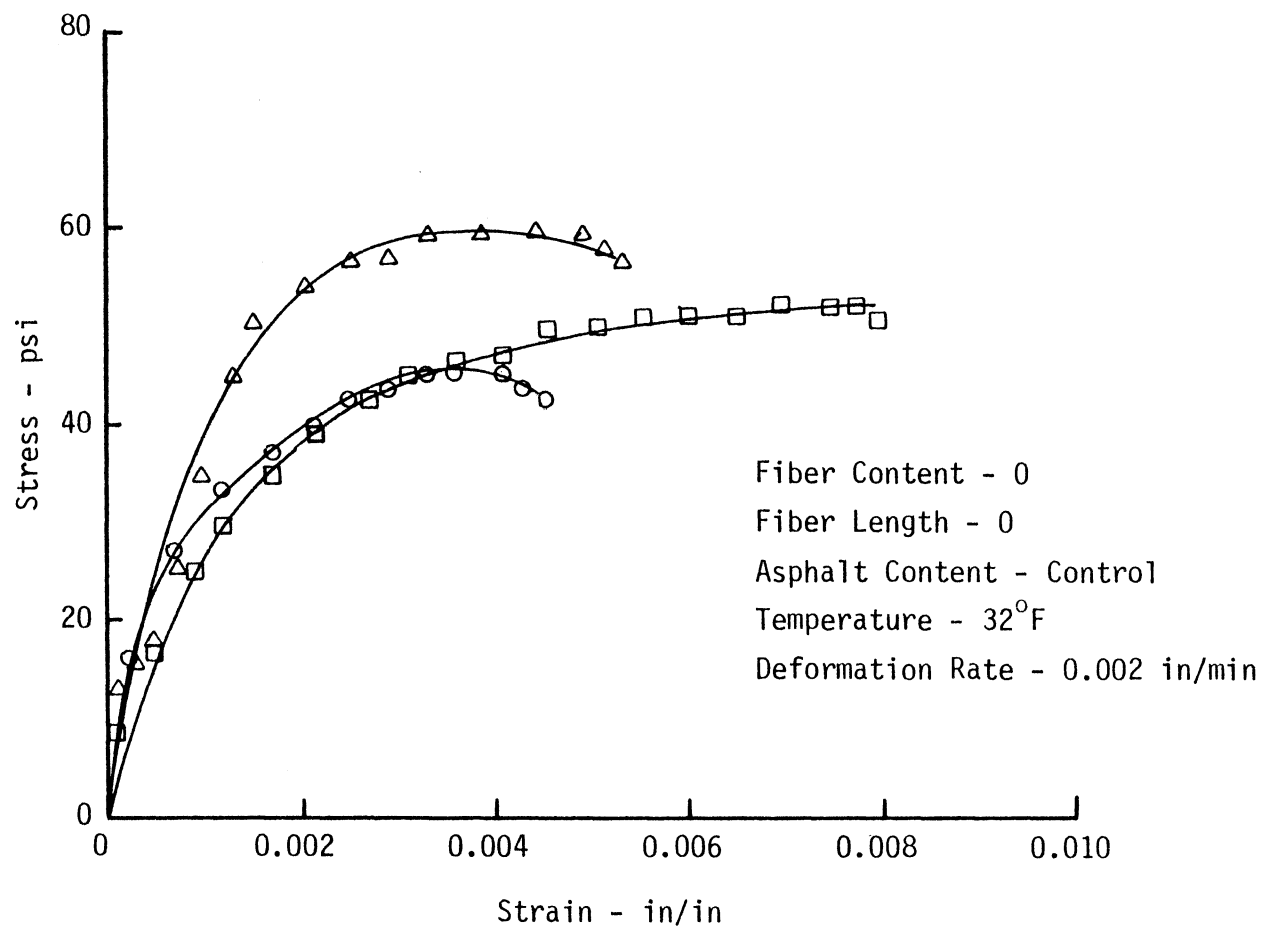


Figure A-17.

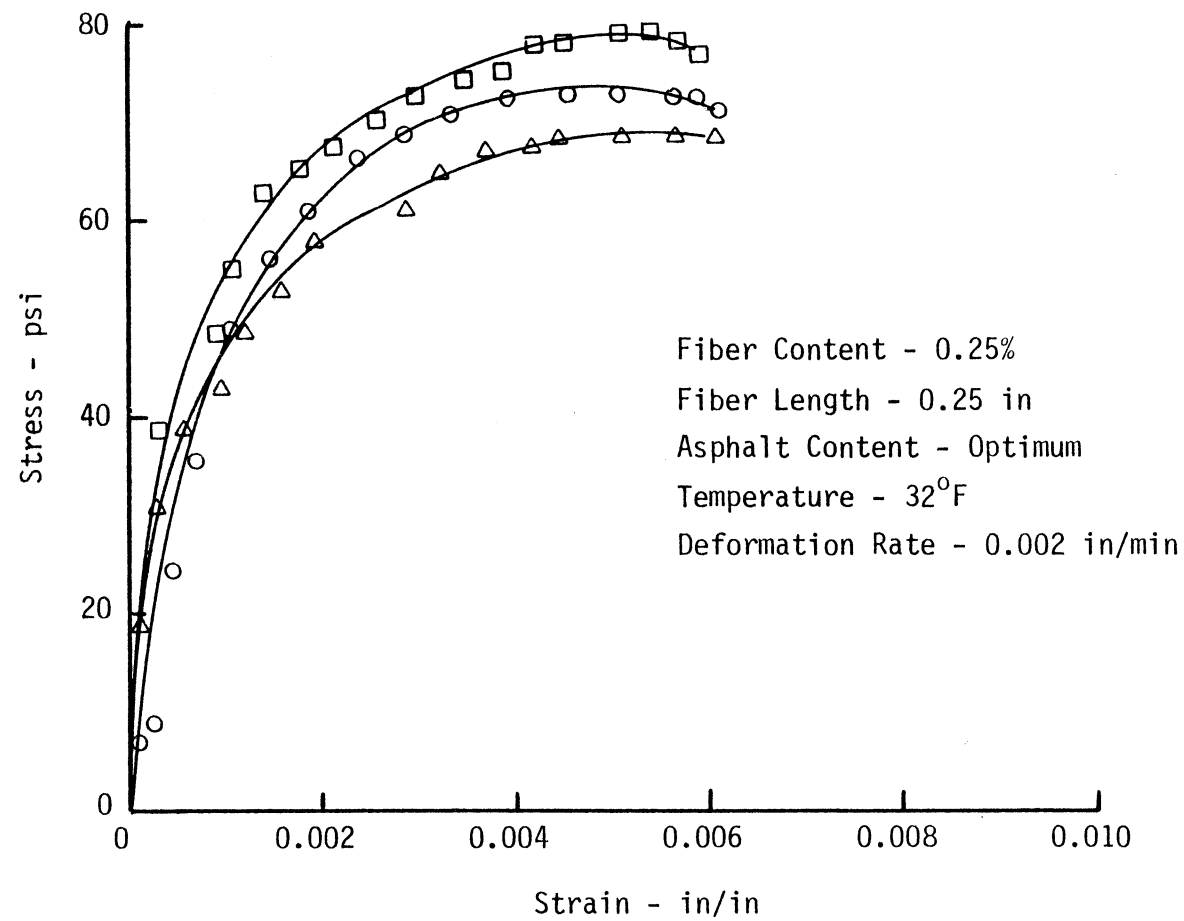


Figure A-18.

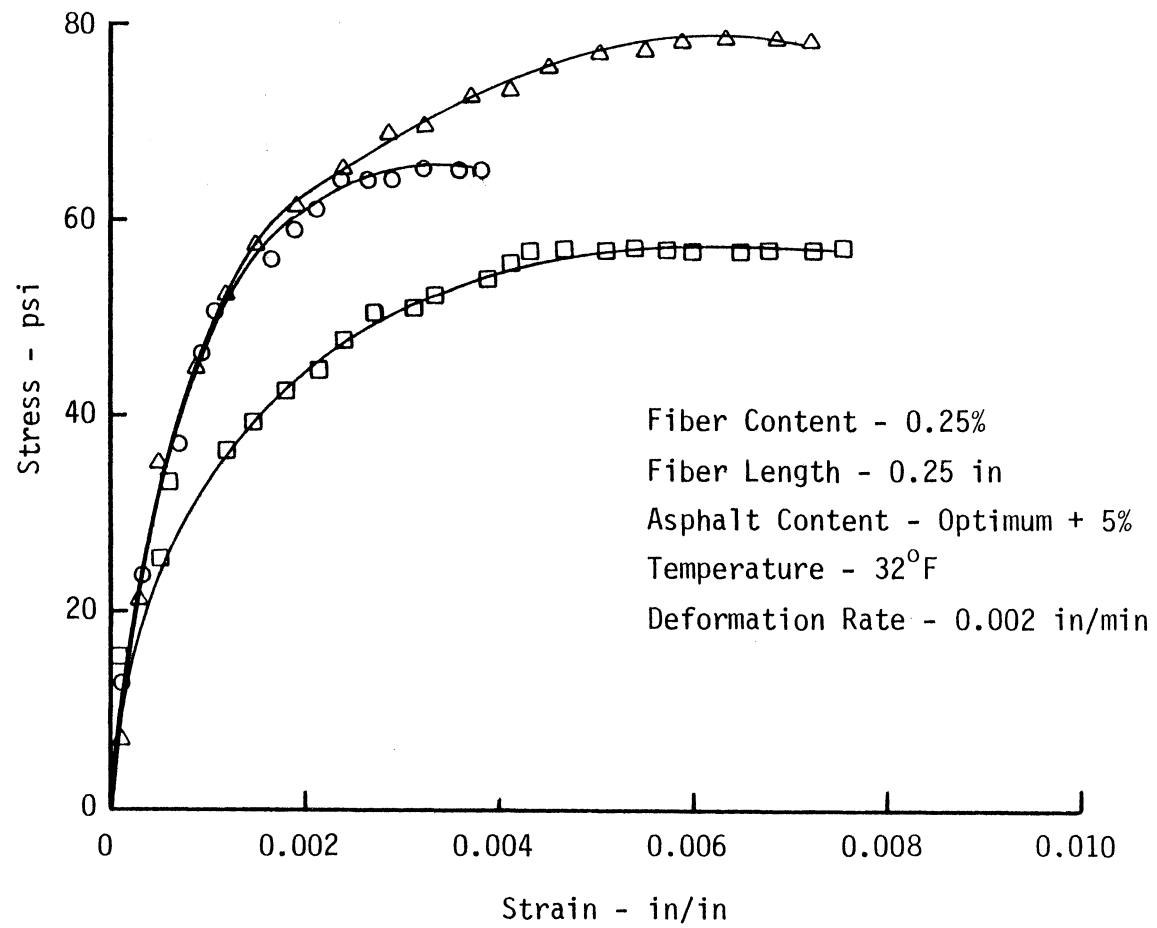


Figure A-19.

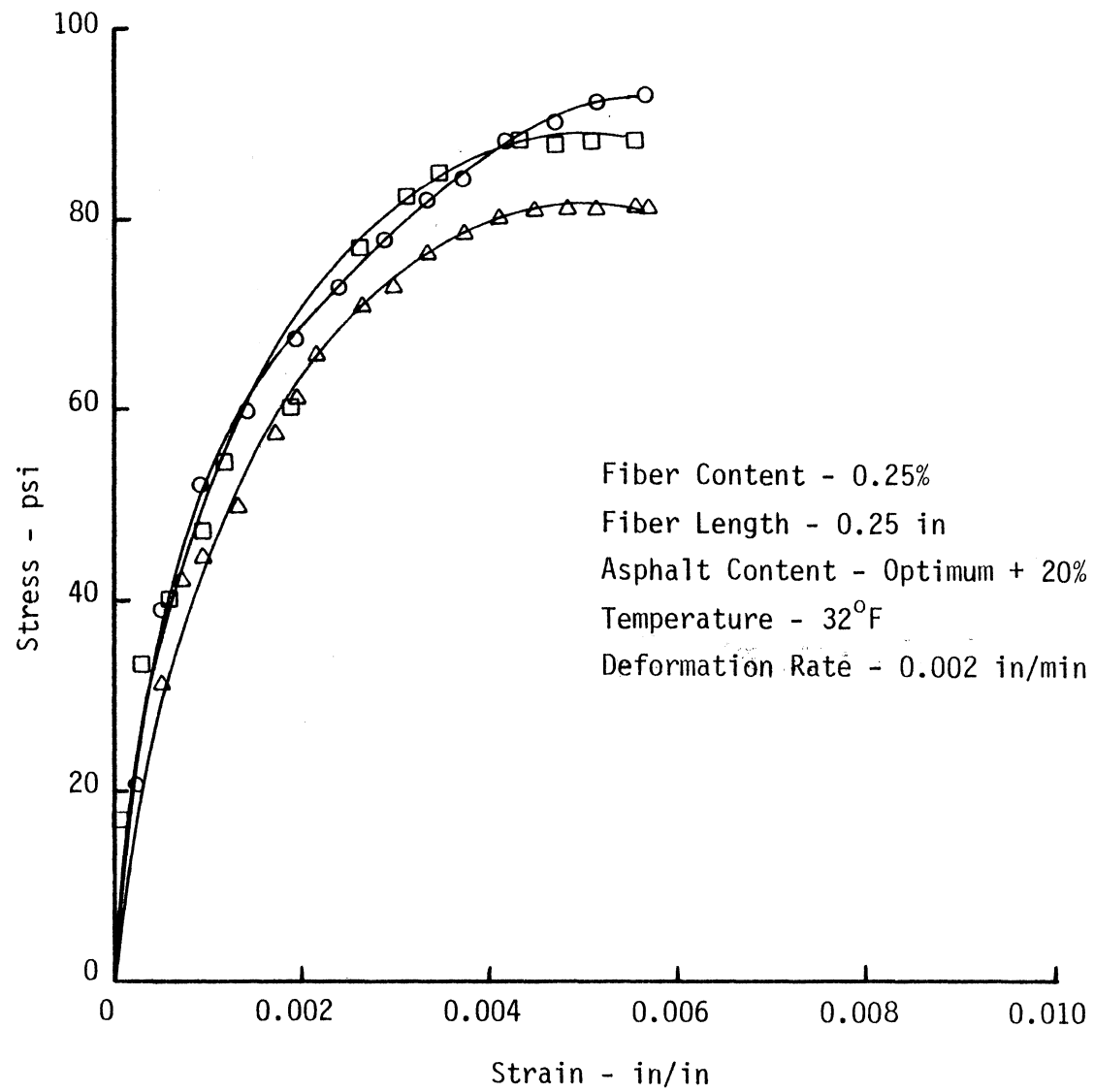


Figure A-20.

APPENDIX B

DETERMINATION OF OPTIMUM ASPHALT CONTENT

DETERMINATION OF OPTIMUM ASPHALT CONTENT

General

One of the first steps in producing asphalt-aggregate mixtures for paving purposes is to determine the optimum asphalt content. The optimum asphalt content for each of the two laboratory standard aggregates was determined using the laboratory standard asphalt. Determination of optimum asphalt content was accomplished in accordance with the test program shown by the flow chart in Figure B1.

Mixing of Laboratory Standard Asphalt With Aggregate

As mentioned earlier, the various aggregate fractions were recombined to meet specifications. The mixing and compacting temperatures for the asphalt-aggregate mixtures were determined to be $305 \pm 5^{\circ}\text{F}$ (152°C) and $283 \pm 5^{\circ}\text{F}$ (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 at 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 at $305 \pm 5^{\circ}\text{F}$. The asphalt cement was heated in the same oven a minimum of 3/4 hour and a maximum of two 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

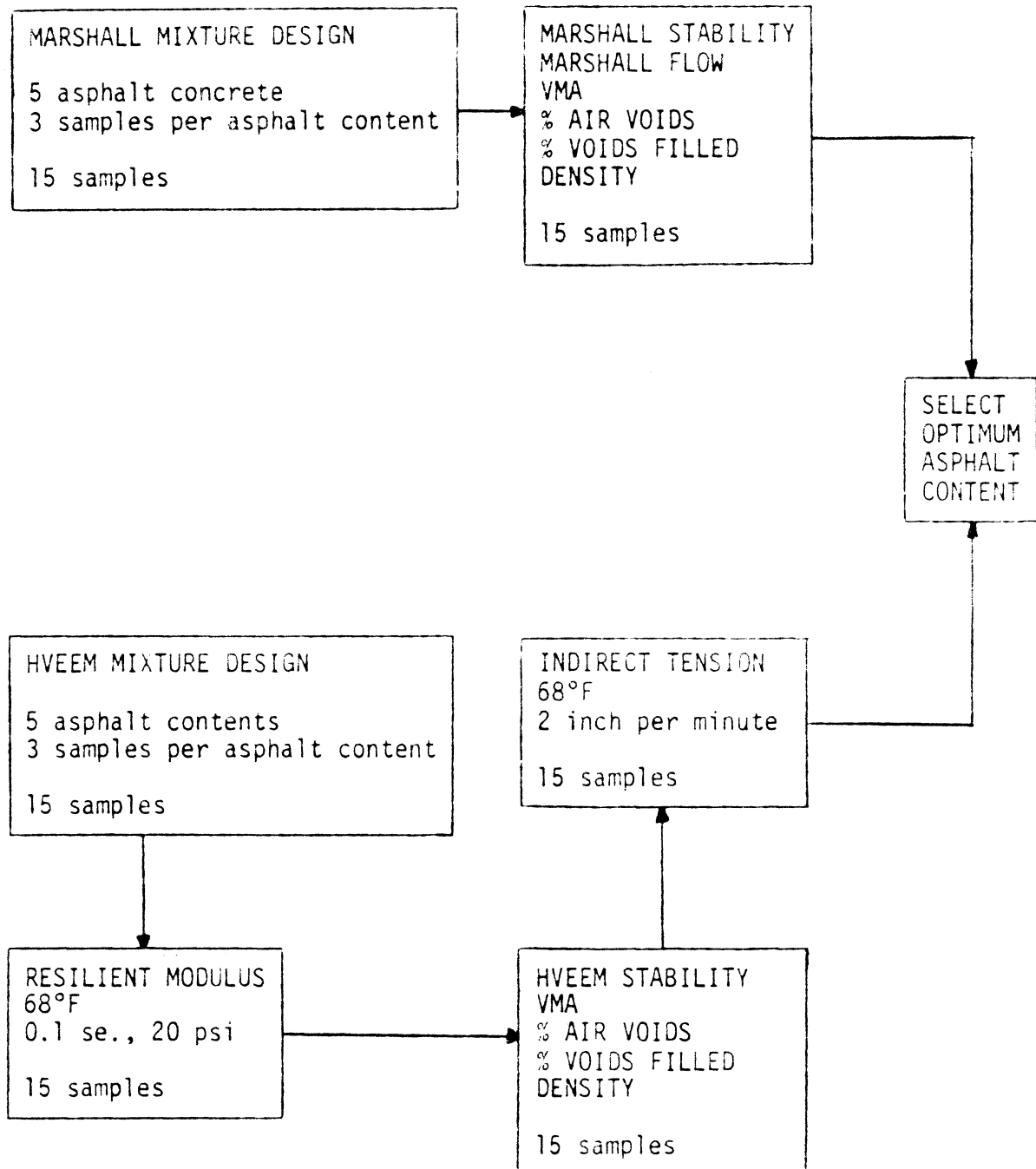


Figure B1. Test Program for Determination of Optimum Asphalt Content.

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 B1.

Marshall Compaction and Testing

Compaction and testing were conducted in accordance with ASTM D-1559, "Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus". As soon as the temperature of each batch reached $283 \pm 5^{\circ}\text{F}$ (140°C) they were compacted by applying 50 blows in each face of the specimen. When the specimens were sufficiently cool (less than 140°F) they were extruded from the molds. The weight and height of each specimen was accurately measured. The 4-inch (10.2 cm) diameter specimens are about 1200 grams in weight and 2.5-inches (6.4 cm) in height. The bulk specific gravity of each specimen was determined in accordance with ASTM D-2726, "Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens". Marshall stability tests were conducted on the day following compaction of the test specimens. Some of the previously failed specimens were reheated and finely divided in order to determine the maximum specific gravity of the mixture in accordance with ASTM D-2041, "Maximum Specific Gravity of Bituminous Paving Mixtures".

The Marshall compaction tests were accomplished as an aid to the determination of the optimum asphalt cement content for the given aggregate gradation. A summary of the test results for the Marshall Specimens containing gravel and limestone is presented in Tables B2 and B3, respectively. (Each value in the figures and tables represents an average for three tests unless otherwise indicated.)

Table B1. Data Summary of Asphalt-Aggregate Mixtures.

| | | | | | | | | |
|---|------|------|------|------|------|------|------|------|
| Asphalt Content, Percent by wt. Aggregate | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 |
| Asphalt Content, Percent by wt. Total Mix | 2.4 | 2.9 | 3.4 | 3.9 | 4.3 | 4.8 | 5.2 | 5.7 |
| Coarse Aggregate, Percent by wt. Total Mix | 41.5 | 41.3 | 41.1 | 40.9 | 40.7 | 40.5 | 40.3 | 40.1 |
| Fine Aggregate, Percent by wt. Total Mix | 50.7 | 50.5 | 50.2 | 50.0 | 49.8 | 49.5 | 49.3 | 49.1 |
| Mineral Filler, Percent by wt. Total Mix | 5.4 | 5.3 | 5.3 | 5.3 | 5.3 | 5.2 | 5.2 | 5.2 |
| Total Aggregate, Percent by wt. Total Mix | 97.6 | 97.1 | 96.6 | 96.2 | 95.7 | 95.2 | 94.8 | 94.3 |

Table B2. Summary of Test Results for Marshall Specimens Using Rounded Gravel.

| Asphalt Cement Content, Percent by wt. Aggregate | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 |
|---|------|------|------|------|------|
| Bulk Specific Gravity of Compacted Mix | 2.37 | 2.39 | 2.42 | 2.44 | 2.45 |
| Maximum Specific Gravity of Mixture | 2.53 | 2.52 | 2.50 | 2.48 | 2.46 |
| Effective Specific Gravity of Aggregate | 2.63 | 2.64 | 2.63 | 2.63 | 2.63 |
| Asphalt Absorption, Percent by wt. Aggregate | 0.72 | 0.83 | 0.81 | 0.76 | 0.71 |
| Effective Asphalt Content, Percent by Total Mix | 1.7 | 2.1 | 2.6 | 3.1 | 3.6 |
| Voids in Mineral Aggregate, Percent Bulk Volume | 10.5 | 10.0 | 9.4 | 9.0 | 9.3 |
| VMA Filled w/Asphalt, Percent VMA | 47 | 57 | 71 | 85 | 95 |
| Air Void Content, Percent Total Volume | 6.4 | 5.1 | 3.2 | 1.6 | 0.6 |
| Marshall Stability, lbs | 1190 | 1150 | 1220 | 1290 | 1160 |
| Marshall Flow, 0.01 in | 7 | 7 | 7 | 7 | 8 |

Table B3. Summary of Test Results for Marshall Specimens Using Crushed Limestone.

| Asphalt Cement Content, Percent by Wt. Aggregate | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 |
|--|------|------|------|------|------|
| Bulk Specific Gravity of Compacted Mix | 2.40 | 2.41 | 2.45 | 2.48 | 2.48 |
| Maximum Specific Gravity of Mixture | 2.55 | 2.55 | 2.53 | 2.50 | 2.49 |
| Effective Specific Gravity of Aggregate | 2.70 | 2.69 | 2.71 | 2.69 | 2.70 |
| Asphalt Absorption, Percent by wt. Aggregate | 1.6 | 1.5 | 1.8 | 1.5 | 1.6 |
| Effective Asphalt Content, Percent by wt. Total Mix | 1.8 | 2.4 | 2.6 | 3.4 | 3.7 |
| Voids in Mineral Aggregate, Percent Bulk Volume | 10.5 | 10.5 | 9.4 | 8.8 | 9.2 |
| VMA Filled with Asphalt, Percent VMA | 57 | 65 | 78 | 94 | 97 |
| Air Void Content, Percent Total Volume | 5.9 | 4.8 | 3.0 | 0.8 | 0.4 |
| Marshall Stability, lbs | 2410 | 2610 | 2740 | 2430 | 2230 |
| Marshall Flow, 0.01 in | 9 | 9 | 11 | 15 | 14 |

Gyratory Compaction and Testing

The aggregate gradation, asphalt and mixing procedure used in making the gyratory compacted specimens were identical to those used in making the Marshall specimens. However, compaction was conducted in accordance with Texas State Department of Highways and Public Transportation test method TEX-206-F, Part II, "Motorized Gyratory-Shear Molding Press Operating Procedure" (10).

Upon completion of mixing, each batch was placed in an oven and as soon as the required temperature was attained the mixtures were compacted. This test method required a compaction temperature of $250 \pm 5^{\circ}\text{F}$ (121°C) for all asphalt-aggregate mixtures. When the specimens were sufficiently cool, the weight and height of each were accurately determined. These 4-inch (10.2 cm) diameter specimens were approximately 1000 grams in weight and 2-inches (5.1 cm) in height. The bulk specific gravity of each specimen was determined in accordance with ASTM D-2726.

On the day following compaction the resilient modulus, M_R (a measure of stiffness), was determined for each specimen at 68°F (20°C) using the Mark III Resilient Modulus Device developed by Schmidt (11). A diametral load of approximately 72 lbs. (33 kg) was applied for a duration of 0.1 seconds while monitoring the lateral deformation.

The Hveem stability of the specimens was determined 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.

The final test performed on these specimens was the splitting tensile test (indirect tension), which is described in detail by Hadley, Hudson,

and Kennedy (13). The splitting tensile test was conducted at 68°F (20°C) with a loading rate of 2-inches per minute. Stress, strain and modulus of elasticity were computed for each specimen at the point of failure using a value of 0.35 for Poisson's ratio. A summary of the test results for the Hveem specimens containing gravel and limestone is given in Tables B4 and B5, respectively. (Each value in the figures and tables represents an average of three tests.)

Optimum Asphalt Content

The optimum asphalt cement content was selected for both types of aggregate to be used in all mixtures for further testing and evaluation of shale oil asphalts. The selection was based primarily on the results of the test series conducted on the Marshall specimens using the mixture design selection procedures described by The Asphalt Institute. However, the results of the test series conducted on the Hveem specimens and engineering judgement also entered into the final selection. The properties of the mixtures using rounded gravel and crushed limestone at optimum asphalt content are given in Table B6.

It should be noted that some of the properties of the compacted mixtures at optimum asphalt content did not meet the criteria established by The Asphalt Institute. For example, considering the rounded gravel mixtures, the average values for Marshall flow, air void content, VMA and Hveem stability were less than those specified. Considering the crushed limestone mixtures, the average values for air void content and VMA were also less than specified. The action of traffic on an asphalt concrete pavement with qualities such as those mentioned above is likely to display

plastic instability or, possibly flushing after a period of time. Undoubtedly, the quality of these mixtures could have been improved by adjusting the aggregate gradation and/or the asphalt content. However, since these mixtures were to be used as laboratory standards for test comparisons and not highway paving, no attempt was made to further adjust the mixture design.

Table B4. Data Summary of Hveem Specimens Using Rounded Gravel.

| Asphalt Content, Percent by wt. Dry Aggregate | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 |
|--|---------|---------|---------|---------|---------|
| Bulk Specific Gravity of Compacted Mix | 2.34 | 2.39 | 2.40 | 2.43 | 2.45 |
| Maximum Specific Gravity of Mixture | 2.53 | 2.52 | 2.50 | 2.48 | 2.46 |
| Effective Specific Gravity of Aggregate | 2.63 | 2.64 | 2.63 | 2.63 | 2.63 |
| Asphalt Absorption, Percent by wt. Aggregate | 0.72 | 0.83 | 0.81 | 0.77 | 0.71 |
| Effective Asphalt Content, Percent by wt. Total Mix | 1.7 | 2.1 | 2.6 | 3.1 | 3.6 |
| Voids in Mineral Aggregate, Percent Bulk Volume | 11.7 | 10.0 | 10.0 | 9.6 | 9.3 |
| VMA Filled with Asphalt, Percent VMA | 42 | 58 | 68 | 81 | 95 |
| Air Void Content, Percent Total Volume | 7.7 | 5.0 | 3.8 | 2.2 | 0.6 |
| Resilient Modulus (M_R), 68°F (20°C), psi | 407,000 | 515,000 | 513,000 | 562,000 | 477,000 |
| Hveem Stability, percent | 33 | 30 | 27 | 22 | 21 |
| Splitting Tensile Stress @ Failure, 68°F (20°C), psi | 92 | 103 | 121 | 114 | 119 |
| Splitting Tensile Strain @ Failure, 68°F (20°C), in/in | 0.0025 | 0.0027 | 0.0027 | 0.0032 | 0.0037 |
| Splitting Tensile Modulus (E) @ Failure, 69°F (20°C), psi | 36,500 | 38,400 | 44,100 | 36,100 | 33,100 |

Table B5. Data Summary of Hveem Specimens Using Crushed Limestone.

| Asphalt Content, Percent by Wt. Aggregate | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 |
|--|---------|---------|---------|---------|---------|---------|
| Bulk Specific Gravity of Compacted Mix | 2.44 | 2.45 | 2.46 | 2.44 | 2.47 | 2.47 |
| Maximum Specific Gravity of Mixture | 2.55 | 2.53 | 2.53 | 2.50 | 2.49 | 2.48 |
| Effective Specific Gravity of Aggregate | 2.70 | 2.69 | 2.71 | 2.69 | 2.70 | 2.71 |
| Asphalt Absorption, Percent by Wt. Aggregate | 1.6 | 1.5 | 1.8 | 1.5 | 1.6 | 1.8 |
| Effective Asphalt Content, Percent by Wt. Total Mix | 1.8 | 2.4 | 2.6 | 3.4 | 3.7 | 4.0 |
| Voids in Mineral Aggregate, Percent Bulk Volume | 9.0 | 9.0 | 9.1 | 10.3 | 9.6 | 10.0 |
| VMA Filled with Asphalt, Percent -VMA | 64 | 74 | 81 | 84 | 94 | 97 |
| Air Void Content, Percent Total Volume | 4.5 | 3.2 | 2.5 | 2.2 | 0.8 | 0.4 |
| Resilient Modulus (M_R), psi | 618,000 | 620,000 | 590,000 | 499,000 | 571,000 | 249,000 |
| Hveem Stability, Percent | 57 | 54 | 54 | 50 | 46 | 24 |
| Splitting Tensile Stress @ Failure 68°F (20°C), psi | 119 | 112 | 112 | 106 | 105 | 82 |
| Splitting Tensile Strain @ Failure 68°F (20°C), in/in | .0032 | .0032 | .0044 | .0041 | .0035 | .0069 |
| Splitting Tensile Modulus (E) @ Failure, 68°F (20°C), psi | 37,200 | 34,800 | 26,000 | 27,400 | 30,000 | 12,000 |

Table B6. Mixture Properties With Laboratory Standard Asphalt at Optimum Asphalt Content.

| Property | Rounded Gravel | Crushed Limestone |
|---|----------------|-------------------|
| Design Asphalt Content, Percent by wt. Aggregate | 3.8 | 4.5 |
| Marshall Specimens | | |
| Unit Weight, pcf | 152 | 153 |
| Air Void Content, Percent | 2.1 | 3.0 |
| VMA, Percent | 9.1 | 10.5 |
| VMA Filled with Asphalt, Percent | 80 | 78 |
| Marshall Stability, lbs | 1270 | 2740 |
| Marshall Flow, .01 inch | 7 | 11 |
| Hveem Specimens | | |
| Unit Weight, pcf | 151 | 154 |
| Air Void Content, Percent | 2.9 | 2.5 |
| VMA, Percent | 9.7 | 9.1 |
| VMA Filled with Asphalt, Percent | 76 | 81 |
| Hveem Stability, Percent | 25 | 54 |
| Resilient Modulus, psi | 570,000 | 590,000 |
| Elastic Modulus, @ Failure * | 39,000 | 26,000 |

* From Splitting Tensile Test