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TESTING OF ASPHALT-RUBBER AND AGGREGATE MIXTURES

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TESTING ASPHALT-RUBBER AND AGGREGATE MIXTURES

by

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16. Abstract

This report is concerned with the development of a mixture design procedure for asphalt-rubber and aggregate. The investigation was aimed at finding a method for (a) mixing the high-viscosity asphalt-rubber with aggregate, (b) forming of test specimens made with the resilient material, and (c) testing the specimens obtained from compaction of the mixtures. Each of the above factors is discussed along with the test results obtained for Hveem stability, Hveem cohesiometer value, axial tension, double-punch tension and dynamic modulus of elasticity, and double-punch durability. In general, it was found that a normal high shear rate mechanical mixing procedure yielded good aggregate coating; tamping foot (T.I.) compaction was not possible; specimens compacted by static double plunger and also by vibratory-kneading procedures required three days of aging in the mold; specimens had high air void contents; 140°F (60°C) testing temperature was not feasible, and field trials will be needed to establish design criteria for laboratory prepared specimens. Durability measurements indicated the critical need of clean aggregates and high asphalt content.

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Final Report

TESTING ASPHALT-RUBBER AND AGGREGATE MIXTURES

Synopsis

This report is concerned with the development of making and testing of mixtures asphalt-rubber and aggregate. The investigation was aimed at finding a method for (a) mixing the high-viscosity asphalt-rubber with aggregate, (b) forming of test specimens made with the resilient material, and (c) testing the specimens obtained from compaction of the mixtures. Each of the above factors is discussed along with test results obtained for Hveem stability, Hveem cohesiometer value, axial tension, double-punch tension and dynamic modulus of elasticity, and double-punch durability. In general, it was found that a normal high shear rate mechanical mixing procedure yielded good aggregate coating; tamping foot (T.I.) compaction was not possible; compacted specimens required three days of aging in the mold; specimens had high air void contents; 140°F (60°C) testing temperature was not feasible, and field trials will be needed to establish design criteria for laboratory prepared specimens.

INTRODUCTION

Asphalt-rubber (A-R) is a blend of asphalt and fine grindings from rubber tires. The mixture was investigated by McDonald and a specific formulation patented by him in the 1960's. A review of the development and usage of asphalt-rubber is given by both Jimenez (1) and Morris and McDonald(2).

Asphalt-rubber as used by the Arizona Department of Transportation (ADOT) and representing the principal blend in this report is composed of one part rubber granule and three parts asphalt; the characteristics of each component is usually fixed as will be presented. The main usage of the A-R blend has been as a binder in chip-seal construction. The chip seal has been placed as a surface course or as a strain-attenuating interlayer to minimize reflection cracking of a bituminous overlay. Of particular concern to the present study is the use of the strain-attenuating layer and its construction with asphalt-rubber and aggregate mixtures.

Chip seal construction has difficulties with uniformity in application and in providing consistently good performance. The use of kerosene in A-R would seem to present additional problems. The solution to the construction problems appears to be the replacement of the chip seal with a hot-mix asphalt-rubber concrete whereby proportioning of materials and construction can be readily controlled.

The objectives of the research were to obtain means for making and testing mixtures of A-R and aggregate so that physical characteristics of the specimens may be measured and related to performance of the mixture as a retardant to reflection cracking.

MATERIALS

Asphalt-Rubber

The majority of the spray applications of A-R by ADOT has made use of a blend of rubber grindings known as TP-044 and an asphalt of AR-1000 grade from Edgington Oil Company. The specification properties of these materials have been given by Jimenez (1), Morris and McDonald (2), and Green and Tolonen (3). Additionally, the amount of rubber in the blend has been held constant in the weight proportion of one-part rubber to three-parts asphalt.

These materials were used in the study in addition to including a finer grind of the same type of rubber. Where the TP-044 was essentially of one size passing the No. 16 and retained on the No. 25 sieves, the finer rubber, TP-0165, passed the No. 30 and was retained on the No. 200 sieves.

Aggregate

The A-R and aggregate mixture was contemplated to be placed as hot-mix asphaltic concrete; therefore, it was assumed that the aggregate maximum particle size be 3/8 of an inch (9.5 mm). Two aggregates were chosen for the study, one a standard 3/8-inch dense gradation ADOT MA7 (4), and a 3/8-inch open gradation, ADOT MA6. The open gradation was chosen because of its possible use as a hot plant seal for a replacement of a chip seal. Also, it was anticipated that coating difficulties might be overcome with a low surface area aggregate. Characteristics of the two aggregates are shown in Table 1 of the Appendix.

Making of the A-R blend was according to the procedure developed for the earlier work described in Reference 1 and a brief discussion of it is given in the next paragraph.

The batch size is held to about 1,000 grams (250 grams of rubber and 750 grams of asphalt). The asphalt is brought to a temperature of 375°F (191°C) in a stainless steel saucepan. The hot asphalt is stirred with a motorized mixer having a three-bladed three-inch (76 mm) propeller. The rubber grindings are added to the asphalt within a period of five minutes and then the mixture is stirred and held to the 375°F temperature for 30 minutes.

MIXING A-R AND AGGREGATE

In regular asphaltic concrete mixture design, it is customary to heat the aggregate and asphalt cement to some specified temperature. Because asphalt cements are semisolid at ambient temperature, it is necessary to heat the asphalt and aggregate in order to have a reduced asphalt viscosity for coating the aggregate during mixing and for lubricating the aggregate during compaction. Test method T245-74 of the American Association of State Highway and Transportation Officials (AASHTO) (5) specifies that the asphalt temperature should correspond to that at which the asphalt has a viscosity of about 170 centistokes and that for compaction the hot mixture be at a temperature corresponding to that at which the asphalt has a viscosity of about 280 centistokes.

For most paving asphalt cements, the laboratory mixing temperature is usually less than 325°F (163°C) and the compaction temperature is usually more than 230°F (110°C). In Reference 1, a temperature-viscosity relationship was established for the base AR-1000 asphalt; the equation is as shown:

$$\eta = 6.767 \times 10^{25} F^{-10.69} \qquad \ldots .1$$

where η is the viscosity in poise at a shear rate of 0.05 sec^{-1}

F is the temperature in degrees Fahrenheit.

The equation indicates that at a temperature of 250°F (121°C) the viscosity of the asphalt would be 1.6 poises or approximately 180 centistokes if we assume the hot asphalt has a density of 0.9 gram per cubic centimeter.

A similar equation for the A-R was obtained and was expressed as

$$\eta = 5.768 \times 10^{14} F^{-4.494} \qquad \ldots.2$$

If we enter into the above equation with a value of 1.53 poises (170 centistokes) we will obtain a temperature of 1721°F (938°C) -- which is certainly not a reasonable temperature for mixing. This unreasonable answer comes about from two sources of error -- one being in extrapolating the equation very much beyond the measured viscosities and secondly, being the unstated assumption that the shear rate at mixing is equal to 0.05 reciprocal second. It is not necessary to explain the discrepancies in the calculations yielding 1721°F (938°C) for the mixing temperature; however, it does seem reasonable to assume that a relatively high temperature and/or shear rate will be required for mixing A-R and aggregates. In making the A-R blend, it is observed that the viscosity of A-R at 375°F (190°C) is quite high and would seemingly be difficult to spray or mix with aggregates

Initial mixing trials of A-R and the dense-graded aggregate consisted of combining aggregate at 375°F (190°C) and the hot A-R immediately after the 30-minute holding period at 375°F (190°C). The hot A-R and aggregate were mixed in a ten-quart Hobart C-10 mixer using a type D wire whip and the highest mixing speed of the device for a period of approximately two minutes. The resulting mixture showed excellent coating of the aggregate.

Because the temperatures involved were considered excessive in that they were not comparable to hot-mix plant operation and because of the hard and rigid characteristics of specimens resulting from Triaxial Institute (TI) compaction, lower mixing temperature and slower mixing speeds were set to approach regular laboratory hot-mix design operation.

The regular mixing procedure for A-R and aggregate used in this research was to make the A-R and then immediately place the container of hot asphalt-rubber blend into a 250°F (121°C) circulating air oven until the mixture cooled to the oven temperature. Prior to making the A-R blend, the aggregate had been heated in an oven to a temperature of 300°F (149°C). The average batch size was of about 4,000 grams and it was mixed in the Hobart mixer at speed setting number 2 which gave a maximum free tangential speed of 8.35 feet per second (2.56 m/s). Mixing time was approximately two minutes, or less if the aggregate appeared to be completely coated. After machine mixing, the mixture was transferred to a large, hot metal pan to check for completeness of mixing and to facilitate the scooping of mixture for making individual test specimens.

Two other variations in the mixing procedure were included in the study; in one case, the fresh A-R was allowed to cool to ambient temperature for one day and then it was brought to the 250°F (121°C) mixing temperature; in the second case, the rubber granules at ambient temperature were added to the hot aggregate just before pouring the hot 250°-asphalt into the aggregate. Mixing time and speed were the same for all three rubberized mixtures as for the straight asphaltic concrete.

The laboratory trials with A-R served to demonstrate thixotropic characteristics at mixing temperatures as had been indicated by viscosity measurements that had been conducted at much lower temperatures and much lower shear rates (1).

Only a few variations in the mixing operations were examined because a prime objective was to produce a good coating of aggregate with reasonable temperature, energy, and mixing time. No attempt was made to duplicate any one hot plant mixing procedure since this may vary from the high temperature and high shear rate of a pug mill to a low temperature and low shear rate of a drum drier mixer.

Reducing the blending temperature of 375°F (190°C) of the A-R to a 250°F (121°C) mixing temperature is considered to be reasonable since the A-R in plant mixing will be pumped through a pipe and not through a nozzle as in chip seal construction; additionally, the lower temperature should reduce the detrimental oxidation of both the asphalt and the rubber.

COMPACTION OF MIXTURES

The concept of a strain-attenuating layer for minimizing reflection cracking is based on the layer having a relatively low resistance to deformation but also the elasticity to recover upon the release of stress. The rubber granules in the A-R and aggregate mixtures serve the necessary functions of strain-attenuating layers and thus would work against compactive efforts expended for making test specimens of the mixture. Also, because of the intermediate shear rate or strain rate during most standard compaction procedures, the A-R would have much higher viscosity than straight asphalt to resist the compaction effort.

Compaction temperature was arbitrarily set at 250°F (121°C) and two compaction procedures were utilized for making 4"D (102 mm) x $2\frac{1}{2}$"H (63 mm) specimens.

Static Compaction

The Triaxial Institute (T.I.) compactor, also known as the California kneading compactor, is used by ADOT for making test specimens (6) for testing by the Hveem procedure; the making and testing procedures are identified as Arizona test method ARIZ 803.

An initial mixing trial at a temperature of 375°F (190°C) was with a mixture containing rubber and five percent asphalt by total weight. After cooling the mixture to a temperature of 250°F (121°C) specimens were made using the T.I. compactor, the initial low tamping pressure of 250 psi (1.7 M Pa), and final densification was achieved with a double-plunger load of 40,000 pounds (177.9 kN). However, as mentioned earlier, these specimens did not have the desired low elastic characteristics -- perhaps due to oxidation of both the asphalt and rubber granules.

After fixing the mixing procedure for the study mixtures, the compaction procedure was set using a temperature of 250°F (121°C); no initial tamping at low pressures because at the higher asphalt content the A-R mixture could not reach any degree of compaction; and a final double-plunger load of 40,000 pounds (177.9 kN).

After compaction as described above, it was found necessary to leave the specimen in the mold for three days. Early experimentation with the compaction process, using mixtures with A-R and at asphalt contents of 6.0, 7.5, and 9.0 percent asphalt, had shown that if specimens were extruded after application of the 40,000 pounds (177.9 kN) the specimen would swell up to the point of cracking itself.

Even for those specimens that did not crack, radial swelling was such that the specimen could not be placed inside the stabilometer shell for testing.

Keeping the freshly compacted specimen in the mold for three days eliminated the radial swelling but not in the vertical direction which resulted in the end portions of the specimen being less dense than the middle portion. This difference was noted by feel, since measurements were not made to determine a density gradient along the length of a specimen.

At this time, it is pointed out that for the earlier experimentations in mixing and compaction, asphalt contents of four and five percent were used. During the second stage, asphalt contents of six to nine percent were used and as such differences in the characteristics of the loose, hot mixture and the resulting specimens were due to differences in asphalt content as well as to the high early mixing temperature. Also at this time, it is desired to point out the reason for defining binder content in terms of percent asphalt content by total weight. Variations in mixtures will be affected by (a) having no rubber; that is asphalt only; (b) having rubber as A-R in the binder; and (c) having the rubber added as an aggregate. In all cases, the variations in asphalt content will be 6.0, 7.5 and 9.0 percent which correspond to A-R contents of 8.0, 10.0, and 12.0 percent by total weight of mixture for those mixtures containing rubber. Additionally, when rubber was added as an aggregate, its amount was in the same ratio as for A-R; i.e., one part rubber to three parts asphalt.

Vibratory Kneading Compactor

In anticipation of lessening the elastic resistance to compaction of the A-R mixture by a static force, vibratory compaction was used to form standard specimens for the Hveem tests. Our vibratory kneading compactor (VKC) has been described elsewhere (7); however, it is believed to be appropriate to present a brief discussion here.

A four-inch (102 mm) diameter mold containing the hot mixture is secured to the compactor's turntable. The table can be tilted as well as rotated; the standard angle of tilt is one degree (0.02 rad) and rotation is 25 revolutions per minute. Vibratory loading is achieved by the counter rotation of mirror-imaged eccentric masses. The loading is applied through a four-inch (102 mm) diameter foot placed in the mold and at a frequency of 1,200 times per minute. The vibratory and impacting force is applied in a vertical direction while the mold is tilted and rotating; the mold is free to slide along the plane of the turntable. The combined vertical and rotational displacements cause a kneading action in the compaction process which is carried out for 2.5 minutes. After the 2.5 minutes of kneading action, the turntable is leveled and an additional 30 seconds of vibratory loading is given while the mold is being rotated. The final 30 seconds of compaction is for the purpose of squaring the specimen.

The actual contact pressure of compaction is not known since the vibratory force depends on the resistance given by the mixture which will vary and also the exact contact area is not known due to the tilt of the mold. However, it is estimated that the maximum contact pressure does not exceed 30 psi (0.20 M Pa).

A modification to the standard VKC procedure was required because of the resilient properties of the A-R mixtures. The modification consisted of an additional double-plunger load of 300 psi (2.0 M Pa) after vibratory compaction.

TESTS AND MEASUREMENTS ON COMPACTED SPECIMENS

The tests and measurements made to characterize physical properties of the compacted mixtures were selected for ease of implementation. It was deemed desirable for the initial study to utilize test methods that yielded recognizable result values, especially for ADOT personnel.

A brief description of measurements for density, Hveem tests, tensile strength, and resistance to debonding will follow.

Density and Air Void Contents

The density of compacted specimens was obtained after the three-day curing period for all specimens including the non-rubberized mixtures. After extruding the specimen, it was measured for height and diameter. For the open-graded specimens, these dimensions plus the weight-in-air were used for calculating the density. It has been our experience that density values obtained through this procedure are generally less than when the specimen's volume is obtained by displacement of water, whether or not it is coated with paraffin.

The density of the compacted dense graded specimens was obtained by weighing the specimen in air and also submerged in water. All weighing operations were made at ambient temperature and using a balance graduated to 0.1 gram.

It was not anticipated that these A-R mixtures would be used in courses with thinknesses greater than one-half inch (12.7 mm), and because of the resiliency of the mixtures, density values would not have as much significance as air void content would have. Air void content value was calculated with a so-called effective-specific-gravity (ESG) of the aggregate which accounts for the asphalt absorbed by the aggregate. The ESG of the aggregate was "calculated" following the "measured" loose-asphalt coated specific gravity of mixtures of varying asphalt content with and without rubber. The loose-asphalt coated specific gravity of the mixture was obtained using a quart (0.9 l) jar for a pycnometer, a weak aerosol solution, and vacuum to remove air from the system. With this "measured" specific gravity, and knowing the specific gravity values for the asphalt, the rubber, and A-R and their weight proportions, the ESG of the aggregate was computed. For completely coated aggregate, the ESG should be constant regardless of amount of asphalt if mixing asphalt viscosity is the same for all mixtures. Measurements and calculations for ESG on mixtures with asphalt only, with A-R, and with the rubber granules as aggregate, yielded a constant value. The implication of this finding is that apparently only asphalt is absorbed into the surface pores of the aggregates used and that there is no significant effect from the composition of the asphalt that was absorved, In the second inference, we are considering the selective absorption of the aromatic fraction of asphalt by the rubber.

Hveem Tests

The frictional and cohesive components of shear strength of the compacted mixtures were characterized with the Hveem stability and cohesiometer tests. These tests were performed at 77°F (25°C) using the basic procedures of ARIZ 803 and ARIZ 804 methods (6). The stability test had to be slightly modified since the initial 5 psi (34.5 k Pa) confining pressure could not be held without preloading the specimen. Modification of the test consisted of preloading the specimen in the stabilometer with 100 pounds (0.44 kN) and then obtaining the required confining pressure before the preload fell to 60 pounds (0.27 kN). Following the setting of the initial 5 psi (34.5 k Pa) confining pressure, the specimen was loaded at the prescribed rate up to 6,000 pounds (26.7 kN) and recording the gauge pressures corresponding to loads of 3,000; 4,000; 5,000; and 6,000 pounds (13.3, 17.8, 22.3, and 26.7 kN). As anticipated from the rubberiness of the specimens, final displacement values were relatively high.

There was a modification to the standard cohesiometer test which followed the stability test in that testing was done at 77°F (25°C).

Earlier experimentation with performing the double-punch tension test after the cohesiometer test indicated that the results perhaps were not affected by the prior cohesiometer test; especially for flexible mixtures such as produced with rubber granules. Because of this earlier experience the double-punch test as described in Reference 8 was performed at 77°F (25°C) on specimens produced by both compaction procedures.

The double-punch test is an indirect tensile test in which a specimen is loaded in compression with an axial one-inch (25.4 mm) diameter steel punch on each flat surface. The testing machine crosshead speed was one inch (25.4 mm) per minute. The maximum load applied was considered the failure load.

Elastic and Deformation Measurements

Elastic and deformation measurements were made on specimens made with the 3/8-inch dense gradation and formed with the vibratory kneading compactor.

These measurements were made under static axial tension and also under a new procedure in which a repeated load is applied to a specimen using the double-punch system.

Static Axial Tension

As mentioned, specimens were compacted by VKC; however, the compacted height was 3.25 inches (82.5 mm) so that 0.375 inch (9.5 mm) could be cut from each end with a diamond tipped masonry circular saw. The ends of the specimens were glued to four-inch (102 mm) diameter by 3/4-inch (190 mm) thick steel plates with Devcon plastic steel B and the glue was allowed to cure for one day. As a consequence, the static axial tension test was performed four days after compaction rather than three days as was the case for all other tests.

The test set-up was made of ball joints and chain so that an axial load be applied with the testing machine. Tests were performed at temperatures of 77°F (25°C) and 39.2°F (4°C) and at a crosshead speed of one inch (25.4 mm) per minute. A linear variable differential transformer (LVDT) was used to graph load versus crosshead movement.

Dynamic Modulus of Elasticity

The dynamic modulus of elasticity (E_D) was obtained using a double-punch procedure (9) which has shown excellent correlation with resilient modulus (M_R) values obtained by Chevron, U.S.A., and also by ADOT (10). In this test the specimen is subjected to a repeated double-punch load and radial displacements are obtained at mid-height and at three points 120 degrees (2.1 rad) apart. For a standard specimen 2.5 inches (63.5 mm) in height, the loading results in stresses fluctuating from a low value of 5 psi (34.5 k Pa) to a high value of 19 psi (131.1 k Pa). The low tensile strength of the A-R specimens required that the stress level range be 2.9 psi (20.0 k Pa) to 12.0 psi (82.8 k Pa). The frequency of sinusoidal loading was a 690 cycles per minute. The radial dilations were obtained using dial extensometers graduated to 0.0001 inch (0.0025 mm).

Resistance to Debonding

Up to this point we have been discussing general strength measurement. As important as strength of a paving mixture is its durability, and a measure of this property is given by the resistance to debonding of the asphalt from the aggregate caused by the action of water in the pavement.

The test procedure used for evaluating a mixture's resistance to debonding is fully described in Reference 8. The test concept is similar to the AASHTO immersion-compression test T165-55 (5) in that a retained strength after exposure to a test environment is a measure of durability. In our procedure, the exposure environment is a repeated pore water pressure of 5 to 30 psi (34.5 to 207.0 k Pa) at 122°F (50°C) for a specified number of repetitions.

The evaluation for resistance to debonding was performed on three mixtures of the dense graded aggregate and on two mixtures of the open graded aggregate.

RESULTS AND DISCUSSIONS OF THE EVALUATION PROGRAM

The results of the tests performed are listed in the tables of Appendix A. Graphs of selected data will also be presented in the appendix to facilitate the interpretation of the results or effects.

Materials

Asphalt Cement and Rubber Granules

The physical characteristics of the asphalt cement and of the rubber granules were fixed with respect to grade and source. The asphalt was of grade AR-1000 and was obtained from the Edgington Oil Company with unaged penetration of 120 and a 140°F (60°C) viscosity of 744 poises (7.4 PaS).

The rubber granules were obtained from Atlos Rubber Inc. and were essentially of uniform size equal to about 1 mm. A very limited use was made of a finer rubber granule with a size of 0.4 mm.

Aggregate Blends

The two aggregate blends used in the study met gradation limits of ADOT 703 (4) for MA6 open graded and MA7 dense graded. Other characteristics of the aggregates are shown on Table 1 in which special note should be taken of the sand equivalent value of 28 for the dense graded material. As discussed earlier the effective specific gravity values shown account for absorption of the asphalt used.

Plots of the particle size distribution for the rubber granules and also aggregates are shown in Figure 1.

The reader is reminded that the mixtures under investigation are not intended to have strength properties comparable to asphaltic concrete that would impart structural strength to a pavement. In order for the study material to serve as a strain-attenuating layer to minimize reflection cracking it must be pliable and elastic, that is, it must deform easily and then have elastic recovery upon release of stress.

Hveem and Double Punch Tests

The results of the tests performed are listed in Tables 2 - 5, in Appendix A. The variations in type of binder, amount of asphalt, aggregate gradation, and compaction procedure are to be discussed relative to their effects on void content, Hveem stability, cohesiometer value, and double-punch tension. For convenience, the definitions of the variables shown in the tables are repeated below:

1. Type of binder
   a. AC-1000 No Rubber - means that the mixture had no rubber and would serve as the control mixture. The prefix AC (asphalt cement) is used instead of AR (aged residue) in order to minimize confusion with A-R (asphalt-rubber).
   b. A-R Immediate - means the fresh blend of asphalt-rubber was mixed with hot aggregate soon after its formulation.
   c. A-R 1-Day - means the fresh A-R was allowed to cool for one day and then reheated for mixing with the hot aggregate.
   d. AC-1000+ Rubber Aggregate - means that the rubber at ambient temperature was added to the hot aggregate just before adding the hot asphalt for mixing.

2. Amount of asphalt

   a. A.C. Content, % - means that the asphalt cement was expressed as a percent of total weight.

3. Aggregate gradation - is self explanatory.

4. Compaction procedure - is self explanatory.

Effects of Asphalt Content on Air Voids

As can be anticipated an increase in asphalt content would decrease the amount of air voids in the compacted specimens. However, the relative amounts of air voids did depend on type of binder, aggregate gradation, and compaction procedure.

3/8-Inch Dense Gradation. From Figures 2 and 3, it is evident that the void content is quite high for all specimens except for those containing asphalt without rubber and compacted by VKC. The two main effects are due to compaction procedure and the addition of rubber to the mixture. The data show the VKC is more efficient than compaction with the static double-plunger method. From Figure 2, it appears that the rubber binder type did not have a significant effect on void content (or density) when static compaction was used. However, rubber binder type did affect the void content when the VKC was used for making the specimens, in that the greatest resistance to compaction came when rubber was introduced as an aggregate and the least when introduced to the mix immediately as A-R.

3/8-Inch Open Gradation. Plots for the void characteristics for these mixtures are shown in Figures 4 and 5. As expected for this gradation and from the way density was calculated, the air void content for these mixtures was high but not necessarily higher than for the dense gradation. The response to compaction method was opposite to that of the dense gradation in that static compaction yielded lower void content than did the VKC procedure, even for the dense gradation. It is reasoned that for the open gradation, the binder in effect filled the void space and thus offered less resistance to compaction. This concept follows also from the indications that binder type generally had a small effect on void content. The relatively high void contents of the A-R mixtures is apparently due to the energy absorbing characteristics of the rubber granules.

Tables 2 to 5 in Appendix A indicate that air void content variability resulting from binder type, aggregate, and compaction procedure is essentially the same for all sets of specimens.

Effects of Asphalt Content on Stability Value

The reader is reminded of the variations in performing the Hveem stability test; these are concerned with the application of the initial confining pressure and testing at 77°F (25°C). Because of the relatively high void contents and rubberiness of specimens, high values were not expected nor felt to be needed.

3/8-Inch Dense Gradation. The stability data of Figures 2 and 3 follow effects of binder and compactor type similar to that found for density as indicated by air void content. Stability values were higher for those specimens compacted by VKC and for those having asphalt only as the binder. The plots do not show significant differences in stability caused by the type of rubber binder.

3/8-Inch Open Gradation. Examination of Figures 4 and 5 show low values of stability especially for specimens compacted by the static procedure. Even though the specimens compacted by VKC had higher void contents, they did have higher stability values than for those compacted by the static procedure. This difference appears to be due principally to the difference in surface voids resulting from the compaction procedure. Static compaction resulted in higher surface voids which yielded higher "final displacement" and thus lower stability.

At this time the significance of the magnitude of the stability is not known since we do not know the requirements for service conditions.

As for air void contents, variability in stability values do not seem to be affected by asphalt content, binder type, nor compaction procedure.

Effects of Asphalt Content on Cohesiometer Value

Because of the 3/8-inch maximum particle size and also the open gradation it was generally found, as expected, that the cohesiometer value increased as asphalt content increased. As mentioned above, the significance of the magnitude of the cohesiometer value does not have much specific meaning with reference to field performance; however, this characteristic can be compared with values obtained for regular asphaltic concrete.

3/8-Inch Dense Gradation. It is to be noted that static compaction generally resulted in higher cohesion values than for specimens compacted by VKC, except for the mixtures containing no rubber and A-R mixed immediately upon formulation. The effect of the use of rubber or no rubber depended on the compaction procedure. In most cases, but not all, the use of rubber caused the specimens to have high air void content and thus lower cohesion value.

3/8-Inch Open Gradation. In Figures 4 and 5 it is seen that compaction procedure did not have a great effect on cohesion value and that the use of rubber resulted in a lowering of the cohesion value, especially when introduced as aggregate.

The reduction in cohesiometer value by the addition of rubber is not considered to be a detrimental effect since increased pliability is desired for a strain attenuating material.

Variability in the cohesiometer value was affected most by the aggregate gradation. The coefficient of variation, C_v, averaged around 11 percent for static compaction and 12 percent for VKC compaction which is common for dense graded asphaltic concrete. The corresponding average for the open graded specimens was 16 percent and 17 percent respectively for static and VKC compaction.

Effects of Asphalt Content on Double-Punch Tension

Earlier it was mentioned that the double-punch test was performed on the specimen after the cohesiometer test. The stressed plane of the cohesiometer test was marked and so it was possible to note that the tensile crack resulting from the double-punch test did not generally coincide with the bending plane of the cohesiometer test.

Both tests yield a measure of tensile strength; therefore, similar effects from the variable were noted for both.

3/8-Inch Dense Gradation. The curves of Figures 2 and 3 show that the straight asphalt specimens had the highest strength and the VKC produced specimens with higher strength. The effects of rubber binder type are not discernible.

3/8-Inch Open Gradation. Figures 4 and 5 do not show much of a compactor effect on the double-punch tension; however, there does seem to be a definite effect from the type of binder. As expected this gradation yields a lower strength than the dense gradation.

It is of interest to note the similarity of binder type effect on the cohesiometer and double-punch test; the lowest strength is attributed to the addition of rubber as an aggregate in the open gradation and to A-R immediate in the dense gradation.

The double-punch test results indicated the same responses as did the cohesiometer test results. The variability of the double-punch test is comparable to that of the cohesiometer; however, it must be considered that it was performed after two other tests. Another study (8) showed the coefficient of variation for the double-punch test is around 5 percent. Our experiences indicate that the double-punch test yields a more repeatable measure of tensile strength than does the cohesiometer test and that it is a much quicker and much simpler test.

Effects of Rubber Fineness on Hveem Properties

The reference rubber granule had a uniform size of about 1 mm. A finer rubber granule of about 0.40 mm size was added to the study program and tested in a mixture with the 3/8-inch dense gradation; compaction was with the vibratory compactor.

3/8-Inch Dense Gradation. Figure 6 in Appendix A shows a plot of the data listed in Table 6. The trends of the measurements as affected by asphalt content are similar to those observed when using the standard rubber size (see Figure 2). However, a comparison with the magnitude of measured values shows that the finer rubber resulted in the following improvements:

1. Higher density was obtained with the finer rubber
2. Higher stability was obtained with the finer rubber
3. Higher cohesion was obtained with the finer rubber
4. Higher double-punch tension was obtained with the finer rubber

The type of rubber binder had greater effects when using the finer rubber and, as for the standard, the lowest and most desirable values were obtained when rubber was added as aggregate.

Table 6 in the Appendix shows that the repeatability of the various tests as demonstrated by C_v was not affected by using the finer rubber granules.

Tensile Characteristics of 3/8-Inch Dense Mixtures

Mixtures of the 3/8-inch dense gradation with asphalt and rubber variables were compacted with the vibratory kneading compactor. Specimens were tested at 39.2°F (4°C) and 77°F (25°C) under axial and double-punch conditions. As indicated earlier, the specimen for the axial tensile test had the ends trimmed so that end conditions would be improved for strength and bonding to the steel caps.

Listing of test results appear in Tables 7, 8, and 9.

Modulus and Tensile Properties at 39.2°F (4°C)

Figure 7 displays the effects of asphalt content and rubber binder on modulus of elasticity and tensile strength at 4°C of the compacted specimens. It is noted that the modulus, E_D, obtained by the double-punch procedure is much higher than the modulus obtained by axial loading. At the test temperature of 39.2°F (4°C) and the crosshead speed of one inch (25.4 mm) per minute, the load-displacement graph for the axial test was quite straight so that this modulus is in essence a tangent modulus. The differences in modulus values are related to the lower repeated stress and the faster rate of load application in the double-punch procedure.

It is noted that rubber as aggregate yielded the highest E_D values and lowest E values under axial loading; the opposite relation is seen for the mixtures containing no rubber.

The dynamic modulus E_D was obtained at low strains while the axial static modulus was obtained at relatively large strains; as a consequence, the effects of variables on these two values cannot be directly compared.

The effects of asphalt content and binder type on tensile strength are similar for both methods of testing; however, the axial tension values were generally higher than those obtained by the double-punch method.

Values for dynamic modulus E_D were in the neighborhood of 100-200,000 psi (0.7 - 1.4 G Pa) while the static modulus values were in the range of 10-12,000 psi (70 - 82 M Pa). It is noted that the variability on the replicate measurements for modulus was quite high for the double-punch procedure and of average value for the static loading method.

Modulus and Tensile Properties at 77°F (25°C)

The results obtained from testing at 77°F (25°C) are listed in Tables 7 - 9 and appear plotted in Figure 8. In the axial tension test the load-elongation graph was quite curved and thus a constant tangent modulus was not obtainable. In Figure 8 a plot of a secant modulus does not appear since it was not believed to be appropriate and because the strain at maximum stress seemed to be a better indicator of relative pliability of the specimen.

The curves of Figure 8 show that the straight asphalt mixtures had much higher tensile strength than the rubberized ones; however, the rubberized specimens had higher E_D values and comparable strain values at the maximum axial stress.

The inference of these data is that the rubberized mixtures will have better strain attenuating properties at low temperatures and at high strain levels.

Resistance to Debonding

As important as strength properties of a paving mixture is its resistance to debonding of the asphalt binder from the aggregate. The environmental condition considered in our test was a saturated specimen undergoing repeated pore pressure at 122°F (50°C). The effect of this exposure is the amount of the original strength retained, S_R, expressed as a percentage.

Variables in the mixtures evaluated in the debonding test were asphalt content and binder type as shown in Tables 10 and 11 in the Appendix A.

Debonding of 3/8-Inch Dense Grade Mixtures

The curves of Figure 9 show that the resistance to debonding increases as asphalt content increases. The low values of "wet" strength and retained strength, S_R, are due principally to the aggregate's low sand equivalent value of 28 and the high void content of the specimens. Note should be taken of the relatively high values for the dry strength of the mixtures and especially that the rubberized mixtures had higher S_R values than the specimens containing straight asphalt.

The data of Table 10 indicate the repeatability of the test procedure was somewhat lower than found in previous work; however, the variability could be attributed to the addition of rubber, especially at the low asphalt content.

Debonding of 3/8-Inch Open Graded Mixtures

Variables for this gradation were asphalt content and rubber or no rubber. Data from the tests for retained strength are shown plotted in Figure 10. These curves show very high values of retained strength, meaning good resistance to debonding. However, there was not much difference between the two binders.

The relatively low dry strength values would be due to the high air void content and low viscosity of the base asphalt.

Reference 8 reported on a comparison of retained strength as obtained by the double-punch procedure and the immersion-compression method. That comparison showed that the two methods gave equal values when these were below 35 percent retained strength; above S_R's of 35, the double-punch values were higher than that for the immersion-compression method. An S_R value of 70 by double-punch was equal to a value of about 60 for the immersion-compression procedure.

(Following the initial review of this report, additional work was performed on a new asphalt-rubber and aggregate mixture. Discussion and data on this work appear in Appendix B.)

CONCLUSIONS AND RECOMMENDATIONS

It was stated earlier that the objectives of the research were to investigate and/or develop (a) methods for the mixing of A-R and aggregate, (b) procedures for making standard laboratory specimens for testing, and (c) the use of various test procedures for the characterization of compacted specimens. Within the bounds of the experimentation the following conclusions and recommendations are warranted for the making and evaluation of A-R and aggregate mixture.

1. It is not difficult to mix hot A-R and hot aggregate as is done for regular asphaltic concrete. Visual estimation of A-R's viscosity at 375°F (191°C) is misleading with reference to its coating capability of hot aggregate. It is recommended that the aggregate be heated to 300°F (149°C) and the A-R to 250°F (121°C) for standardizing the laboratory mixing procedure.
2. The above temperatures recommended for the mixing procedure were found to be adequate for coating the aggregate for the conditions when the A-R was added immediately after formulation, brought to mixing temperature after one day of cooling at ambient temperature, and when the cold rubber was added to the hot aggregate just prior to introducing the hot asphalt.
3. Although only one mechanical mixer was used and at only its medium mixing speed, it is recommended that a comparable speed and mixing speed be standard for laboratory mixing.

Hand mixing is not recommended because of the excessive time and incomplete coating in this study for the 3/8-inch dense graded aggregate.

4. Compaction temperature of 250°F (121°C) is recommended since it was found to be efficient for compacting with the static and vibratory procedures used. Compaction follows mixing when the mixture comes to temperature.
5. The study showed that suitable specimens could be made from mixtures compacted by the static double-plunger method and also by the University's vibratory kneading compactor. ADOT has such a compactor. The A-R mixtures could not be "semi-densified" with the T.I. compactor and 250 psi (1.7 M Pa). Both procedures for compaction were suitable for both the 3/8-inch dense and open aggregate gradations. Because of unknown service requirements for air voids and strength, one method cannot be specified at this time; however, the kneading action of the VKC compactor is preferred.
6. The standard sized specimen 2-1/2 inches (64 mm) high by 4 inches (102 mm) in diameter has to be kept in the mold at ambient temperature for three days to prevent unconfined swelling which could crack the specimen. After extrusion from the mold, the specimen can be handled for density measurement and measurements at ambient temperature or lower.
7. Hveem stability and cohesiometer tests were performed at 77°F (25°C) because A-R specimens were found to be soft, swollen, and cracked when stored in a 140°F (60°C) oven.

These tests were performed four days after compaction. Thus, the recommended Hveem test temperature is 77°F (25°C).

8. The data from the Hveem tests indicated that the specimens of both aggregates had higher stability, cohesion, and double-punch tension when compacted by the VKC procedure. However, static compaction yielded higher densities for the open graded aggregate mixtures. The method of introducing rubber into the mixture did not seem to influence test values for the dense gradation; however, the lowest test values for the open gradation were obtained when rubber was added as an aggregate.
9. The use of the finer rubber resulted in higher values of density and strength for the 3/8-inch dense gradation mixtures.
10. Static tensile strength and modulus at 39.2°F (4°C) were generally lower for the rubberized mixtures than for those containing straight asphalt. However, the dynamic modulus E_D was higher for the rubberized specimens. Dynamic moduli were higher than those obtained by the axial loading procedure. These differences are presumed to be due to the lower strains used in the dynamic procedure.
11. The same effects as noted above were found for tests performed at 77°F (25°C). The method of adding rubber to the mixture did not affect the test results at this temperature.
12. Although criteria for tensile characteristics of these mixtures cannot as yet be set, it is recommended that dynamic modulus or resilient modulus measurements be made at the two reported temperatures of 4° and 25°C for all laboratory specimens.

13. The inferences of the strength and modulus measurements are that the rubberized mixtures will have better strain attenuating properties at low temperatures and high strain levels.
14. Durability characteristics as determined by the debonding double-punch procedure indicated that the 3/8-inch dense graded mixtures were poor. This poor performance was attributed to the low sand equivalent value of 28 and high void content of the specimens. It was noted that the rubberized mixtures had an insignificantly higher retained strength, S_R, than the straight asphalt specimens. The method of introducing rubber did not affect significantly the retained strength value, S_R.
15. Debonding tests on the open graded mixtures showed excellent values for retained strength. There was not much difference in S_R values between the asphalt only and rubberized specimens.
16. Because of the anticipated high air void contents of the rubberized mixtures, it is imperative that the aggregate sand equivalent value be above 50 and that asphalt content be at least 7.5 percent for aggregate gradations comparable to those of this study.
17. It is recommended that a field trial using both the dense and open gradation be constructed and monitored.

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APPENDIX A

Tables and Figures

TABLE 1 - CHARACTERISTICS OF THE AGGREGATES

	Sieve Size	3/8" Dense-MA7 Test	3/8" Dense-MA7 Spec.*	3/8" Open-MA6 Test	3/8" Open-MA6 Spec.*
		Percent Passing			
Gradation	3/8"	100	100	100	100
	#4	87	70-85	55	30-60
	8	68	45-70	12	7-15
	16	49		4	
	30	34		1	
	40		20-40	1	
	50	21		1	
	100	13	5-15		
	200	8	3- 8		0- 4
Surface Area, $ft^2/16$		42		2	
Sand Equivalent, %		28			
CKE Oil Ratio, %		4.3		2.6	
Effective Specific Gravity** 72°/77°F		2.614		2.588	

* ADOT - 703

** Accounts for absorption of AR 1000

TABLE 2 - EFFECTS OF RUBBER GRANULES ON PHYSICAL CHARACTERISTICS OF DENSE GRADED SPECIMENS FORMED BY STATIC COMPACTION

BINDER		AC-1000 No Rubber			A-R Immediate			A-R 1-Day			AC-1000 + Rubber Aggregate		
A.C. Content, %		6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0
Void Content, %		11.0	8.5	5.5	24.5	23.5	23.0	25.5	22.0	20.0	27.0	26.5	17.5
		10.5	8.0	5.5	20.5	21.5	22.5	26.0	21.0	18.5	25.0	29.0	21.0
		11.0	8.0	5.0	23.5	18.0	17.5	26.0	21.0	21.0	26.0	28.0	21.0
	$\overline{X}$	11.0	8.0	5.5	23.0	21.0	21.0	26.0	21.0	20.0	26.0	28.0	20.0
	$\%C_v$	3	4	6	9	13	14	1	0	6	4	6	10
Hveem Stability, %		39	44	50	18	13	8	18	22	17	17.5	18.5	-
		38	44	50	21	13	10	19	20	16	17.5	15.5	-
		39	43	47	19	14	10	18	21	16	17.5	17.0	-
	$\overline{X}$	39	44	49	19	13	9	18	21	16	17.5	17.0	-
	$\%C_v$	1	1	4	8	4	13	4	5	4	0	10	-
Cohesiometer Value		390	350	360	190	210	270	300	540	670	380	630	490
		300	330	380	150	220	280	250	530	520	460	500	650
		340	320	370	130	280	210	280	540	640	330	500	460
	$\overline{X}$	340	330	370	160	240	290	280	540	610	390	540	530
	$\%C_v$	13	5	3	19	16	7	9	1	13	17	14	19
D.P. Tension, psi		55	57	60	13	10	12						
		50	57	59	11	11	13						
		47	56	55	9	13	17						
	$\overline{X}$	51	57	58	11	11	14						
	$\%C_v$	8	1	5	18	13	19						

1 psi = 6.89 k Pa

TABLE 3 - EFFECTS OF RUBBER GRANULES ON PHYSICAL CHARACTERISTICS OF DENSE GRADED SPECIMENS FORMED BY VIBRATORY KNEADING COMPACTION

BINDER		AC-1000 No Rubber			A-R Immediate			A-R 1-Day			AC-1000 + Rubber Aggregate		
A.C. Content, %		6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0
Void Content, %		9.5	4.0	2.0	17.5	14.0	15.0	20.5	22.0	15.0	18.0	17.0	16.0
		8.5	4.0	2.0	18.0	16.5	14.0	17.0	21.0	15.0	17.0	16.0	17.0
		10.0	4.5	1.0	18.0	15.0	14.0	19.0	21.5	15.0	17.0	17.0	14.0
	$\overline{X}$	9.5	4.0	2.0	18.0	15.0	14.5	19.0	21.5	15.0	17.5	17.0	16.0
	$\%C_V$	8	9	35	2	8	4	5	2	0	4	4	10
Hveem Stability, %		55	52	36	32	24	16	27	28	19	25	22	17
		55	45	35	33	22	17	28	29	23	29	24	19
		49	50	35	38	23	16	28	26	24	28	21	19
	$\overline{X}$	53	49	35	35	23	16	28	28	22	27	22	18
	$\%C_V$	7	7	2	7	6	4	4	6	12	8	7	6
Cohesiometer Value		310	330	350	210	240	210	180	210	230	190	150	200
		360	390	340	200	200	190	170	190	330	200	160	230
		340	350	270	180	220	200	180	190	260	230	150	260
	$\overline{X}$	340	360	320	200	220	200	180	200	270	210	150	230
	$\%C_V$	7	8	13	8	13	5	6	6	19	10	4	13
D.P. Tension, psi		69	88	67	34	35	27	23	21	28	30	20	25
		83	85	62	28	31	31	22	23	37	32	27	24
		72	88	65	30	33	30	28	25	35	28	24	29
	$\overline{X}$	75	87	65	31	33	29	24	23	33	30	24	26
	$\%C_V$	10	2	4	10	9	7	14	9	14	7	15	10

1 psi = 6.89 k Pa

TABLE 4 - EFFECTS OF RUBBER GRANULES ON PHYSICAL CHARACTERISTICS OF OPEN GRADED SPECIMENS FORMED BY STATIC COMPACTION

BINDER		AC-1000 No Rubber			A-R Immediate			A-R 1-Day			AC-1000 + Rubber Aggregate		
A.C. Content, %		6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0
Void Content, %		18.0	15.0	11.0	16.0	13.5	9.5	16.5	15.5	15.0	27.5	25.0	20.0
		17.0	14.5	11.5	17.0	16.5	12.0	15.0	12.5	11.0	28.5	24.5	20.5
		17.0	14.0	13.0	16.0	13.0	12.5	17.5	16.0	12.5	25.0	22.0	20.5
	$\overline{X}$	17.5	14.5	12.0	16.5	14.5	11.5	16.5	14.5	13.0	27.0	24.0	20.5
	$\%C_v$	3	3	9	4	13	14	8	13	16	7	7	1
Hveem Stability, %		24	22	22	23	21	17	21	27	9	11	10	-
		23	26	24	21	16	13	25	21	15	12	11	-
		23	25	25	21	22	15	20	24	14	12	12	-
	$\overline{X}$	23	24	24	22	20	15	22	24	13	12	11	-
	$\%C_v$	3	9	7	6	16	13	12	12	25	6	9	-
Cohesiometer Value		200	190	230	150	210	190	170	140	120	100	130	150
		230	260	280	150	170	210	200	190	140	130	120	120
		250	270	240	200	200	180	160	170	140	120	120	110
	$\overline{X}$	230	240	250	170	190	190	180	170	130	120	120	130
	$\%C_v$	11	18	11	17	11	8	12	15	9	13	6	16
D.P. Tension, psi		20	24	29	10	14	18	17	18	16	3	4	4
		22	27	28	9	10	16	19	23	22	3	4	6
		24	27	27	11	18	17	16	21	18	3	4	5
	$\overline{X}$	22	26	28	10	14	17	17	21	19	3	4	5
	$\%C_v$	9	7	4	10	29	6	9	12	16	0	0	20

1 psi = 6.89 k Pa

TABLE 5 - EFFECTS OF RUBBER GRANULES ON PHYSICAL CHARACTERISTICS OF OPEN GRADED SPECIMENS FORMED BY VIBRATORY KNEADING COMPACTION

BINDER	AC-1000 No Rubber			A-R Immediate			A-R 1-Day			AC-1000 + Rubber Aggregate		
A.C. Content, %	6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0
Void Content, %	23.5	19.5	17.5	22.0	18.0	15.0	21.5	17.0	15.0	20.5	19.5	14.0
	24.5	20.0	22.0	23.0	19.5	15.0	22.5	17.5	15.5	19.5	17.0	15.0
	25.0	19.5	16.0	25.5	19.0	15.0	22.0	18.0	14.5	25.0	17.5	14.0
$\overline{X}$	24.5	19.5	18.5	23.5	19.0	15.0	22.0	17.5	15.0	21.5	18.0	14.5
$\%C_v$	3	1	17	8	4	0	1	3	3	14	7	4
Hveem Stability, %	37	31	29	25	27	24	22	23	20	30	26	14
	32	34	16	24	24	23	20	20	21	29	24	14
	16	35	34	16	24	19	23	20	20	30	29	13
$\overline{X}$	28	33	26	22	25	22	22	21	20	30	26	14
$\%C_v$	39	6	36	22	7	12	7	8	4	2	10	5
Cohesiometer Value	220	220	240	160	160	160	150	150	200	140	110	100
	220	260	220	140	130	170	160	220	170	120	130	130
	150	230	260	100	180	170	150	190	160	110	130	120
$\overline{X}$	200	240	240	130	160	170	150	190	180	120	120	120
$\%C_v$	20	9	8	24	16	4	5	19	12	13	10	13
D.P. Tension, psi	24	24	20	11	14	18	14	15	15	9	9	10
	20	28	12	12	14	19	10	18	14	12	11	9
	13	23	26	12	15	18	12	16	15	11	15	10
$\overline{X}$	19	25	19	12	14	18	12	16	15	11	12	10
$\%C_v$	29	11	37	6	5	4	17	10	5	14	26	7

1 psi = 6.89 k Pa

TABLE 6 - EFFECTS OF THE FINER RUBBER GRANULES (TP-0165) ON PHYSICAL CHARACTERISTICS OF DENSE GRADED SPECIMENS FORMED BY VIBRATORY KNEADING COMPACTION

BINDER	AC-1000 No Rubber			A-R Immediate			AC-1000 + Rubber Aggregate		
A.C. Content, %	6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0
Void Content, %	9.5	4.0	2.0	6.5	4.5	1.5	13.0	11.5	8.5
	8.5	4.0	2.0	7.0	4.0	1.5	12.5	10.5	8.0
	10.0	4.5	1.0	7.0	3.0	2.5	11.0	10.5	8.0
$\overline{X}$	9.5	4.0	2.0	7.0	4.0	2.0	12.0	11.0	8.5
$\%C_v$	8	9	35	4	20	32	9	5	3
Hveem Stability, %	55	52	36	40	48	34	43	37	30
	55	45	35	40	62	37	42	34	24
	49	50	35	43	60	28	39	39	23
$\overline{X}$	53	49	35	41	57	33	41	37	26
$\%C_v$	7	7	2	4	13	14	5	7	15
Cohesiometer Value	310	330	350	410	400	440	230	210	200
	360	390	340	340	410	490	230	220	200
	340	350	270	380	590	510	230	240	240
$\overline{X}$	340	360	320	380	470	480	230	220	210
$\%C_v$	7	8	13	9	22	7	0	7	11
D.P. Tension, psi	69	88	67	53	58	52	30	30	33
	83	85	62	43	60	54	31	32	30
	72	88	65	47	66	45	32	34	32
$\overline{X}$	75	87	65	48	60	50	31	32	32
$\%C_v$	10	2	4	11	7	9	3	6	4

1 psi = 6.89 k Pa

TABLE 7 - TENSILE CHARACTERISTICS OF AC-1000 NO RUBBER ON DENSE GRADED SPECIMENS FORMED BY VIBRATORY KNEADING COMPACTION

TENSILE TEST	Static - Axial						Repeated Double Punch					
Test Temp. °F (°C)	39.2 (4)			77 (25)			39.2 (4)			77 (25)		
A.C. Content, %	6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0
Void Content, %	9.5	5.5	2.0	11.0	5.5	3.0	12.0	5.0	4.0	11.5	4.5	3.5
	11.0	6.0	2.5	10.5	4.5	3.5	12.0	5.5	3.5	13.0	5.0	3.5
	10.0	5.5	2.0	10.5	4.5	2.5	12.0	5.5	4.0	13.0	6.5	5.5
$\overline{X}$	10.0	5.5	2.0	10.5	5.0	3.0	12.0	5.5	4.0	12.5	5.5	4.0
$\%C_V$	8	5	13	3	12	17	0	5	8	7	20	27
Modulus of Elasticity, psi 10^{-3}--static 10^{-5}--D.P.	11.1	12.1	10.7				1.2	1.4	1.2	1.8	1.9	1.7
	11.1	11.1	11.1				1.4	1.1	1.7	2.6	2.0	1.7
	11.0	10.6	11.1				1.1	0.9	2.3	2.0	2.4	1.3
$\overline{X}$	11.1	11.3	11.1				1.2	1.1	1.7	2.1	2.1	1.6
$\%C_V$	1	7	3				13	23	32	20	13	14
Strength, psi	425	469	516	58	84	77	303	388	298	97	96	105
	429	493	533	61	96	82	287	400	313	67	114	100
	422	486	508	67	96	76	296	402	290	74	92	72
$\overline{X}$	425	483	519	62	92	78	296	397	300	79	100	93
$\%C_V$	1	3	3	7	8	4	2	2	4	20	12	20
Strain at Max. Stress, %				1.5	2.5	2.5						
				2.0	2.0	2.5						
				1.5	2.5	2.5						
$\overline{X}$				1.5	2.5	2.5						
$\%C_V$				17	12	0						

1 psi = 6.89 k Pa

TABLE 8 - TENSILE CHARACTERISTICS OF A-R IMMEDIATE, DENSE GRADED SPECIMENS FORMED BY VIBRATORY KNEADING COMPACTION

TENSILE TEST	Static - Axial						Repeated Double Punch					
Test Temp. °F (°C)	39.2 (4)			77 (25)			39.2 (4)			77 (25)		
A.C. Content, %	6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0
Void Content, %	14.5	15.0	15.0	12.0	15.0	13.0	17.5	15.0	16.5	18.0	15.0	17.0
	15.5	17.5	14.0	18.0	14.5	14.5	19.5	14.5	15.5	19.0	13.5	18.5
	13.0	13.5	15.5	15.0	14.0	16.5	17.5	15.0	15.0	20.0	16.0	19.0
$\overline{X}$	14.5	15.5	15.0	15.0	14.5	14.5	18.0	15.0	15.0	19.0	15.0	18.0
$\%C_v$	9	13	5	20	3	12	6	2	7	5	8	6
Modulus of Elasticity, psi	7.7	8.2	6.8				1.5	2.7	1.2	2.2	2.0	1.3
10^{-3}--static	5.6	7.3	7.6				1.6	3.4	1.5	2.2	2.0	1.6
10^{-5}--D.P.	8.8	8.1	7.1				2.2	2.6	1.6	2.6	2.5	1.6
$\overline{X}$	7.4	7.9	7.2				1.8	2.9	1.4	2.3	2.2	1.5
$\%C_v$	22	6	6				21	15	15	10	13	12
Strength, psi	150	129	120	15	9	17	51	71	69	27	24	22
	136	122	154	8	13	15	39	66	74	26	27	17
	145	126	123	11	12	13	51	69	80	27	21	11
$\overline{X}$	145	126	132	11	11	15	47	69	74	27	25	17
$\%C_v$	6	3	14	33	20	13	15	4	7	2	16	32
Strain at Max. Stress, %				2.0	2.0	2.0						
				2.0	2.0	2.0						
				1.5	3.0	2.0						
$\overline{X}$				2.0	2.5	2.0						
$\%C_v$				16	25	0						

1 psi = 6.89 k Pa

TABLE 9 - TENSILE CHARACTERISTICS OF RUBBER AS AGGREGATE, DENSE GRADED SPECIMENS FORMED BY VIBRATORY KNEADING COMPACTION

TENSILE TEST	Static - Axial						Repeated Double Punch					
Test Temp. °F (°C)	39.2 (4)			77 (25)			39.2 (4)			77 (25)		
A.C. Content, %	6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0
Void Content, %	15.0	16.0	13.5	15.5	13.5	13.0	17.5	14.5	14.5	17.5	14.0	13.5
	15.0	15.5	16.0	16.5	13.5	11.5	17.0	16.0	13.0	17.5	15.5	14.5
	17.0	16.0	13.5	15.5	14.5	11.5	18.0	16.0	14.0	17.5	14.5	13.5
$\overline{X}$	15.5	16.0	14.5	16.0	14.0	12.0	17.5	15.5	14.0	17.5	14.5	14.0
$\%C_v$	7	2	10	4	4	7	3	6	6	0	5	4
Modulus of Elasticity, psi	3.3	2.6	--				4.4	3.4	3.0	3.7	3.0	2.1
10^{-3}--static	2.2	3.8	--				3.0	2.1	1.9	2.7	3.0	1.9
10^{-5}--D.P.	3.7	2.8	3.8				1.8	2.0	2.4	2.8	3.1	2.9
$\overline{X}$	3.1	3.1	3.8				3.1	2.5	2.4	3.1	3.0	2.3
$\%C_v$	25	21	0				42	31	23	18	2	23
Strength, psi	51	80	73	30	16	21	106	114	105	24	28	31
	53	84	72	25	19	24	113	106	118	27	25	24
	76	78	75	30	20	18	101	105	118	23	21	32
$\overline{X}$	60	81	73	27	18	21	106	108	114	25	25	29
$\%C_v$	23	4	2	22	11	14	5	4	6	8	13	15
Strain at Max. Stress, %				2.0	2.0	3.0						
				2.0	2.0	2.5						
				2.0	3.0	2.5						
$\overline{X}$				2.0	2.5	2.5						
$\%C_v$				0	2.5	11						

1 psi = 6.89 k Pa

TABLE 10 - EFFECTS OF RUBBER GRANULES ON RESISTANCE TO DEBONDING OF DENSE GRADED SPECIMENS FORMED BY VIBRATORY KNEADING COMPACTION

BINDER	AC-1000 No Rubber			A-R Immediate			AC-1000 + Rubber Aggregate		
A.C. Content, %	6.0	7.5	9.0	6.0	7.5	9.0	6.0	7.5	9.0
Void Content, %	11.0	3.5	2.0	16.5	11.5	14.5	17.5	20.0	8.5
	10.5	4.0	2.5	14.0	11.5	8.5	17.0	17.5	11.0
	8.0	4.0	2.0	16.0	15.0	10.5	17.0	14.0	11.5
$\overline{X}$	10.0	4.0	2.0	15.5	12.5	11.0	17.0	17.0	10.5
$\%C_v$	16	7	14	9	16	30	2	18	15
Failure Stress D.P., psi									
Wet	3	5	31	4	13	4	4	4	6
	3	6	33	5	11	8	4	4	6
	4	8	30	5	12	6	5	6	7
$\overline{X}$	3	6	31	5	12	6	4	5	6
$\%C_v$	19	25	5	11	8	33	14	23	10
Dry	80	89	51	59	51	27	33	17	18
	68	91	44	50	51	32	24	22	16
	70	61	53	52	54	38	32	19	19
$\overline{X}$	73	80	49	54	52	32	30	19	18
$\%C_v$	9	21	10	9	3	17	16	13	8
Retained Strength, %	4	8	63	9	23	19	13	26	33

TABLE 11 - EFFECTS OF RUBBER GRANULES ON RESISTANCE TO DEBONDING OF OPEN GRADED SPECIMENS FORMED BY VIBRATORY KNEADING COMPACTION

BINDER	AC-1000 No Rubber			A-R Immediate		
A.C. Content, %	6.0	7.5	9.0	6.0	7.5	9.0
Void Content, %	24.0	18.5	23.5	23.0	19.0	25.5
	22.0	21.0	27.0	23.0	18.5	22.0
	21.0	20.0	26.5	21.5	18.0	22.5
$\overline{X}$	22.5	20.0	25.5	22.5	18.5	23.5
$\%C_v$	7	6	7	4	3	8
Failure Stress D.P., psi						
Wet	17	23	9	13	15	5
	23	22	6	9	19	7
	22	24	9	14	16	8
$\overline{X}$	21	23	8	12	17	7
$\%C_v$	15	4	22	22	17	22
Dry	26	37	6	20	25	8
	30	29	6	23	25	9
	28	33	6	18	22	8
$\overline{X}$	28	33	6	20	24	8
$\%C_v$	7	12	0	12	7	7
Retained Strength, %	75	70	100	60	71	87

Figure 1. Particle Size Distribution of Aggregates and Rubber

Figure 2. Effects of Asphalt Content and Rubber on Hveem Specimens Using Static Compaction on 3/8-Inch Dense Gradation

Figure 3. Effects of Asphalt Content and Rubber on Hveem Specimens Using Vibratory Compaction on 3/8-Inch Dense Gradation

Figure 4. Effects of Asphalt Content and Rubber on Hveem Specimens Using Static Compaction on 3/8-Inch Open Gradation

Figure 5. Effects of Asphalt Content and Rubber on Hveem Specimens Using Vibratory Compaction on 3/8-Inch Open Gradation

Figure 6. Effects of Asphalt Content and "Fines" Rubber on Hveem Specimens Using Vibratory Compaction on 3/8-Inch Dense Gradation

Figure 7. Effects of Asphalt Content and Rubber on 4°C Tensile Characteristics of Specimens Using Vibratory Compaction on 3/8-Inch Dense Gradation

Figure 8. Effects of Asphalt Content and Rubber on 25°C Tensile Characteristics of Specimens Using Vibratory Compaction on 3/8-Inch Dense Gradation

Figure 9. Effects of Asphalt Content and Rubber on Debonding Test on Specimens Using Vibratory Compaction on 3/8-Inch Dense Gradation

Figure 10. Effects of Asphalt Content and Rubber on Debonding Test on Specimens Using Vibratory Compaction on 3/8-Inch Open Gradation

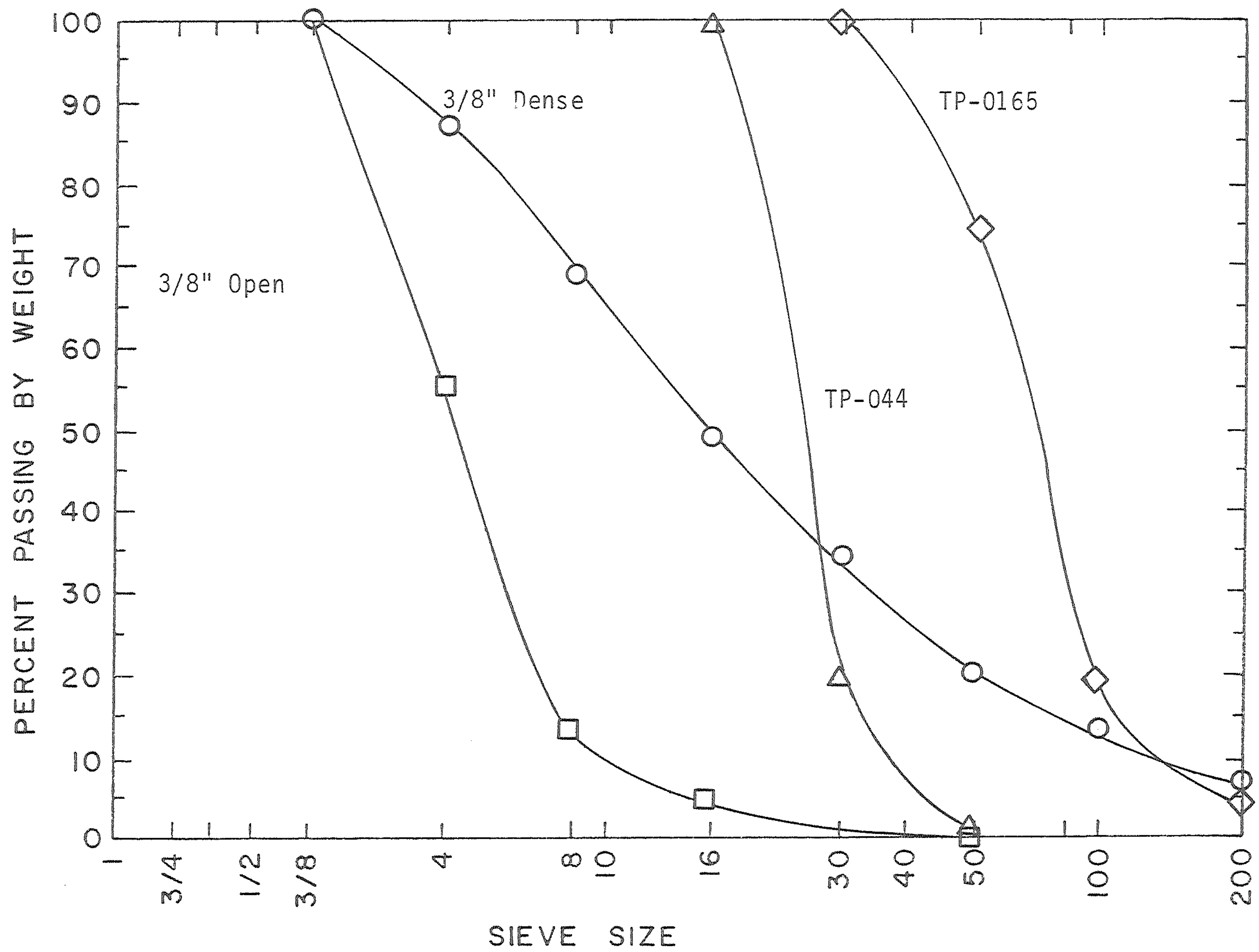

Figure 1. Particle size distribution of aggregates and rubber.

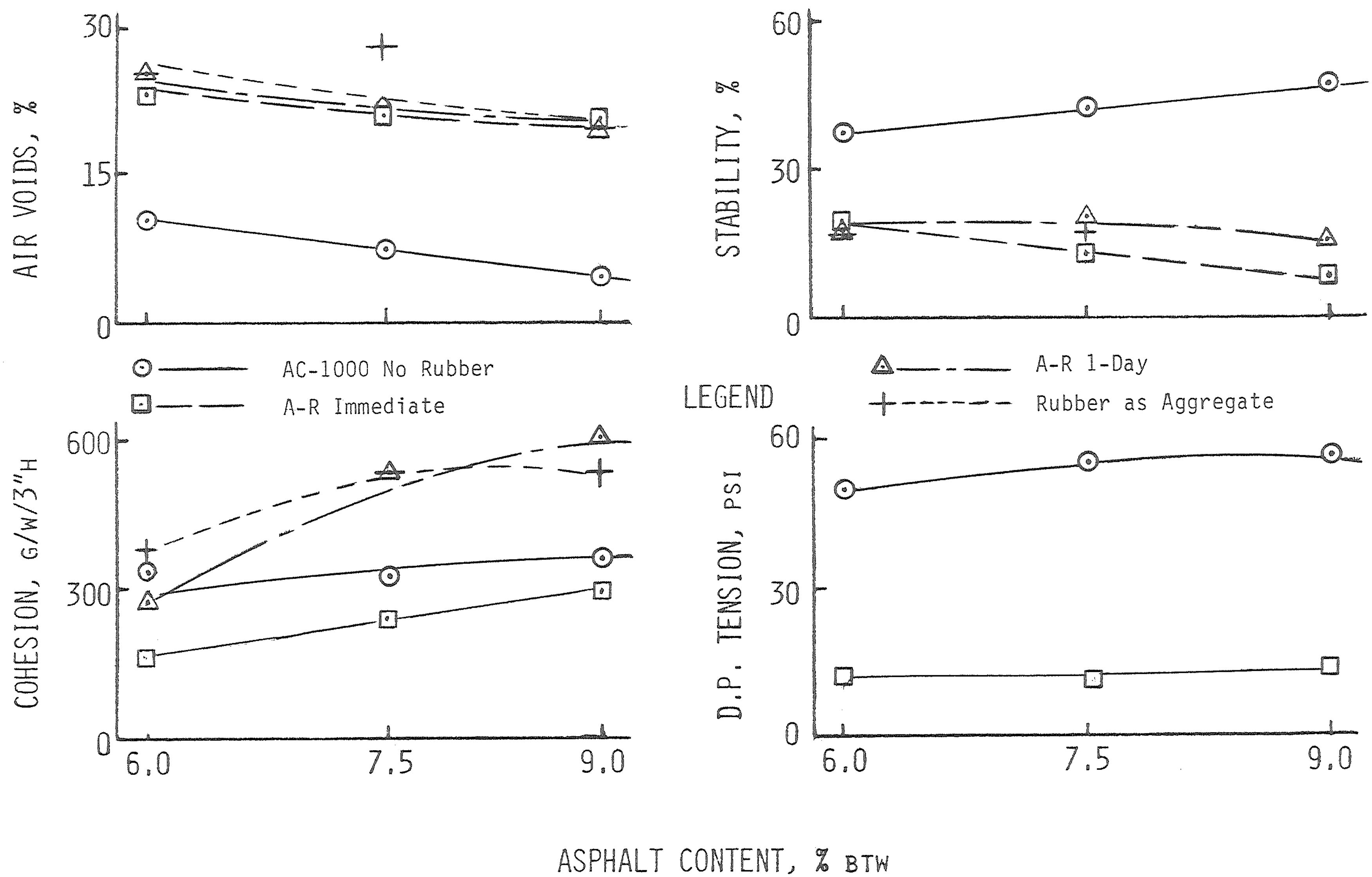

Figure 2. Effects of asphalt content and rubber on Hveem specimens using static compaction on 3/8-inch dense gradation.

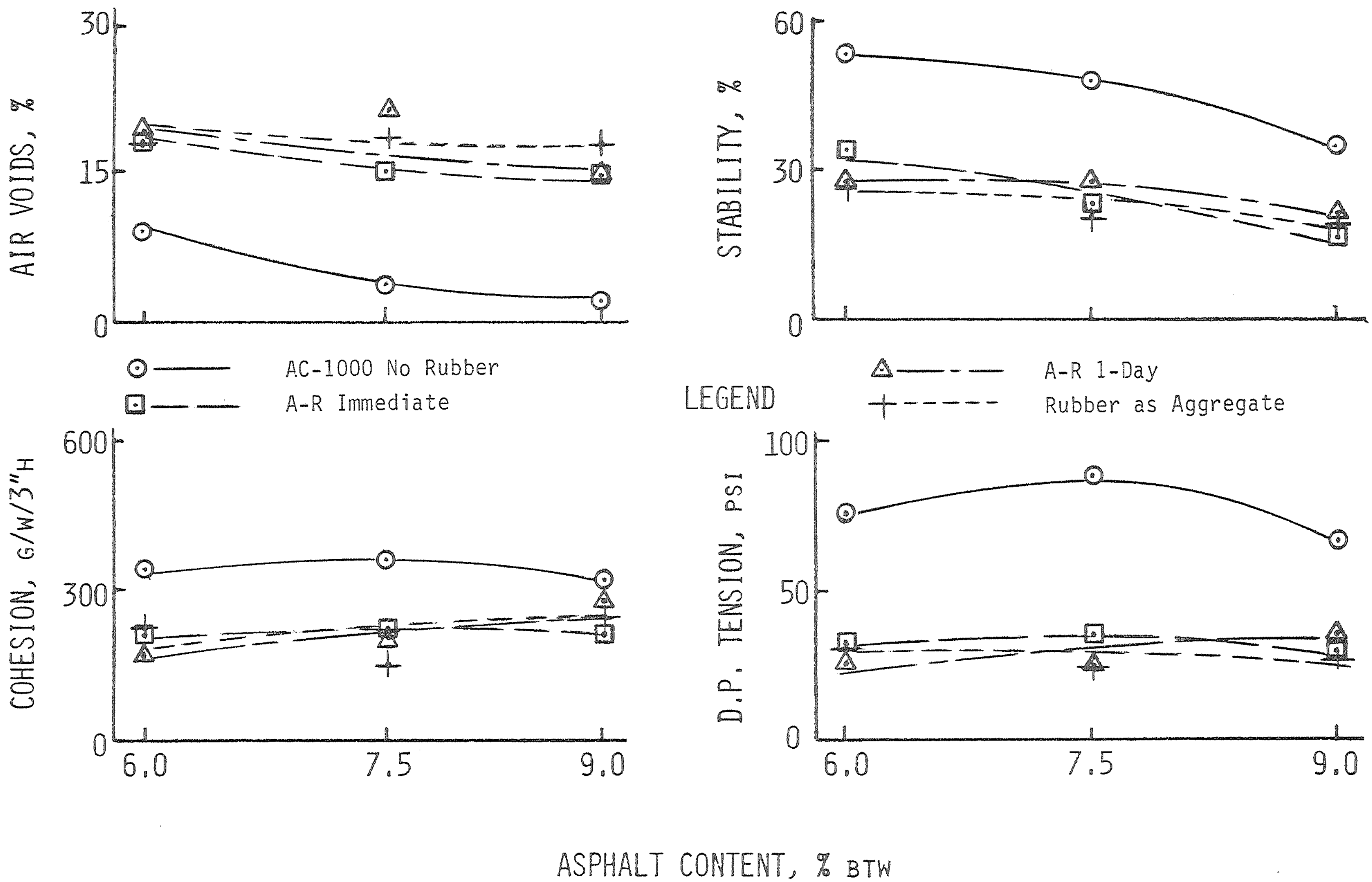

Figure 3. Effects of asphalt content and rubber on Hveem specimens using vibratory compaction on 3/8-inch dense gradation.

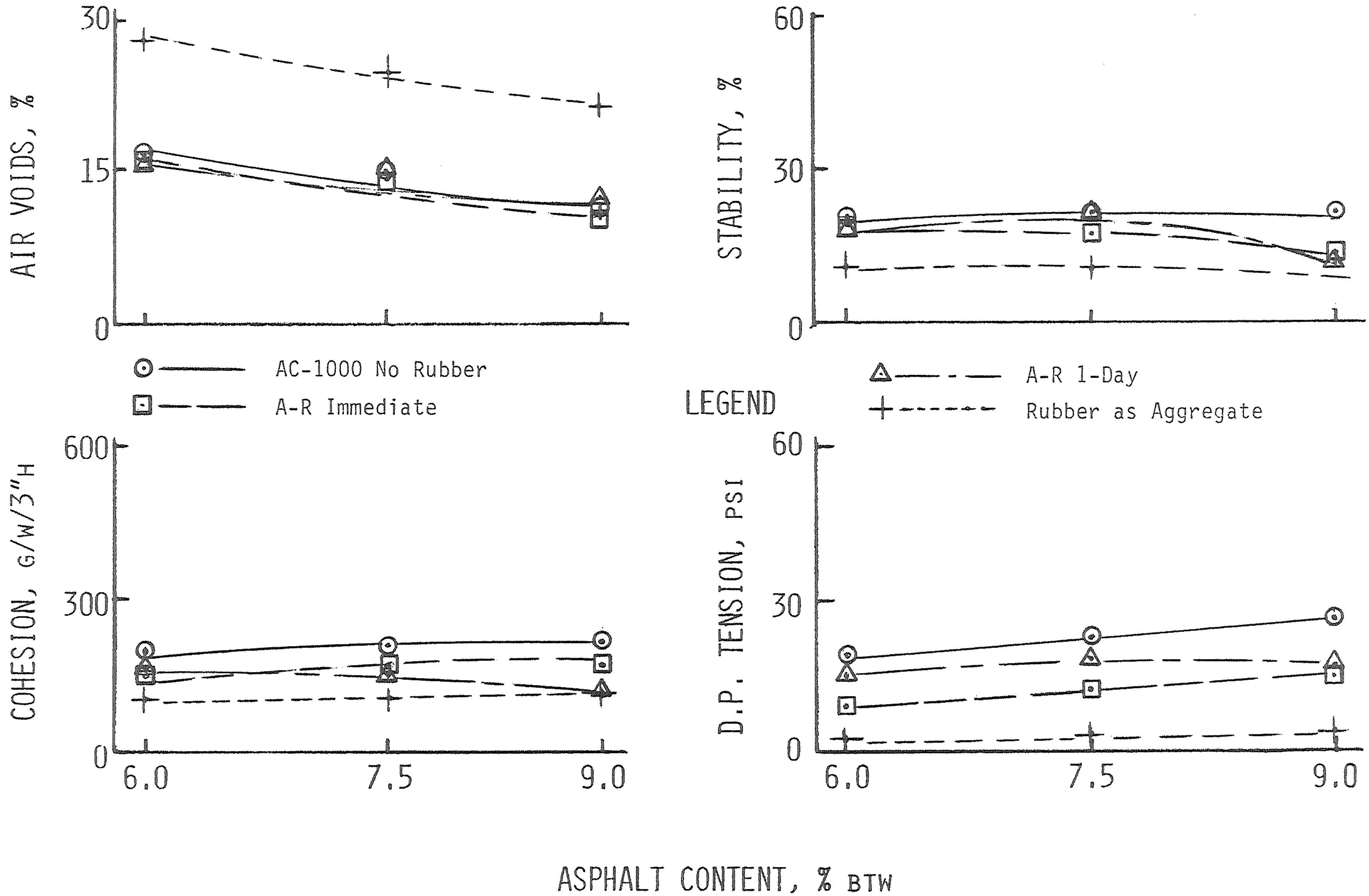

Figure 4. Effects of asphalt content and rubber on Hveem specimens using static compaction on 3/8-inch open gradation.

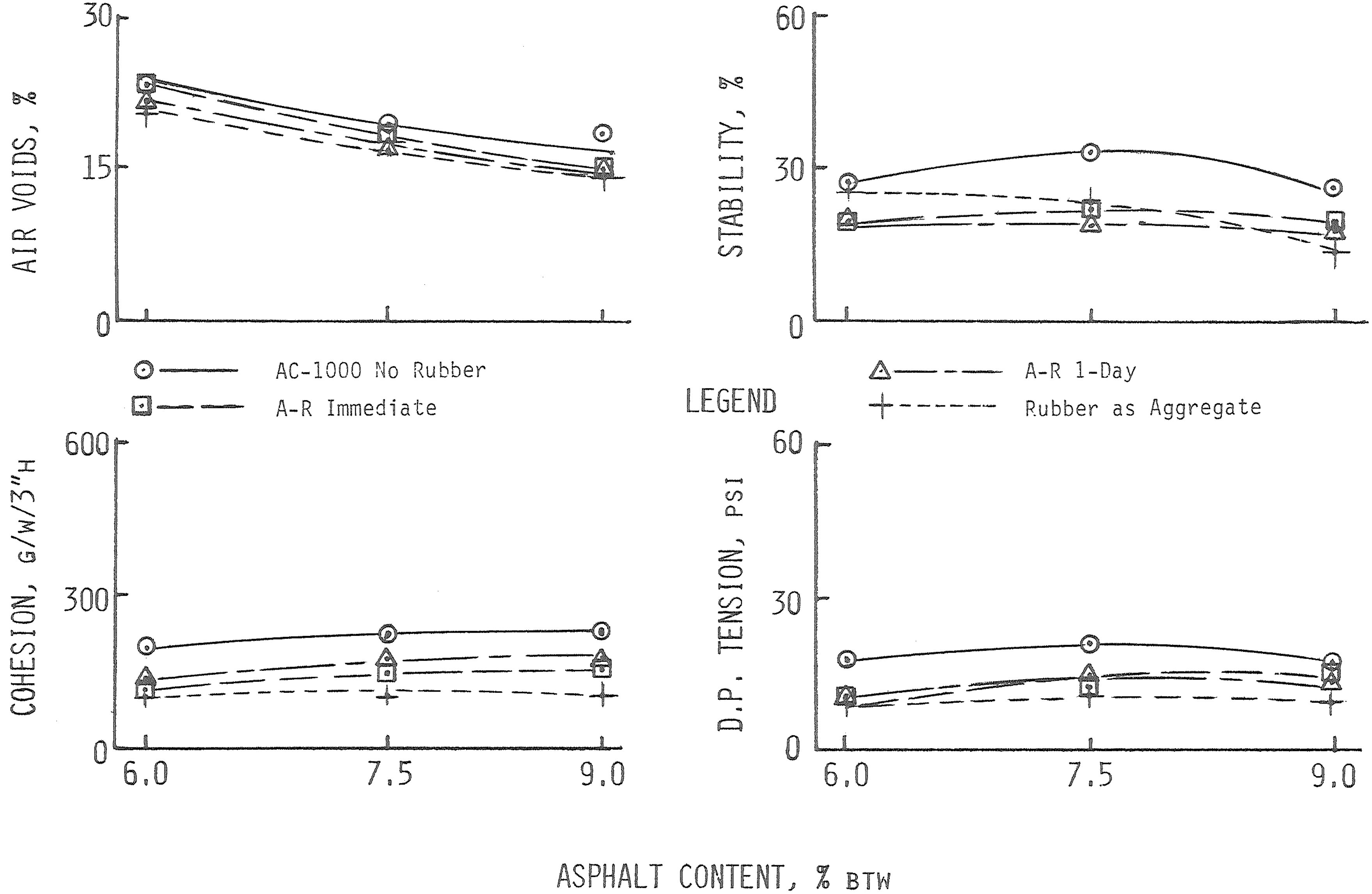

Figure 5. Effects of asphalt content and rubber on Hveem specimens using vibratory compaction on 3/8-inch open gradation.

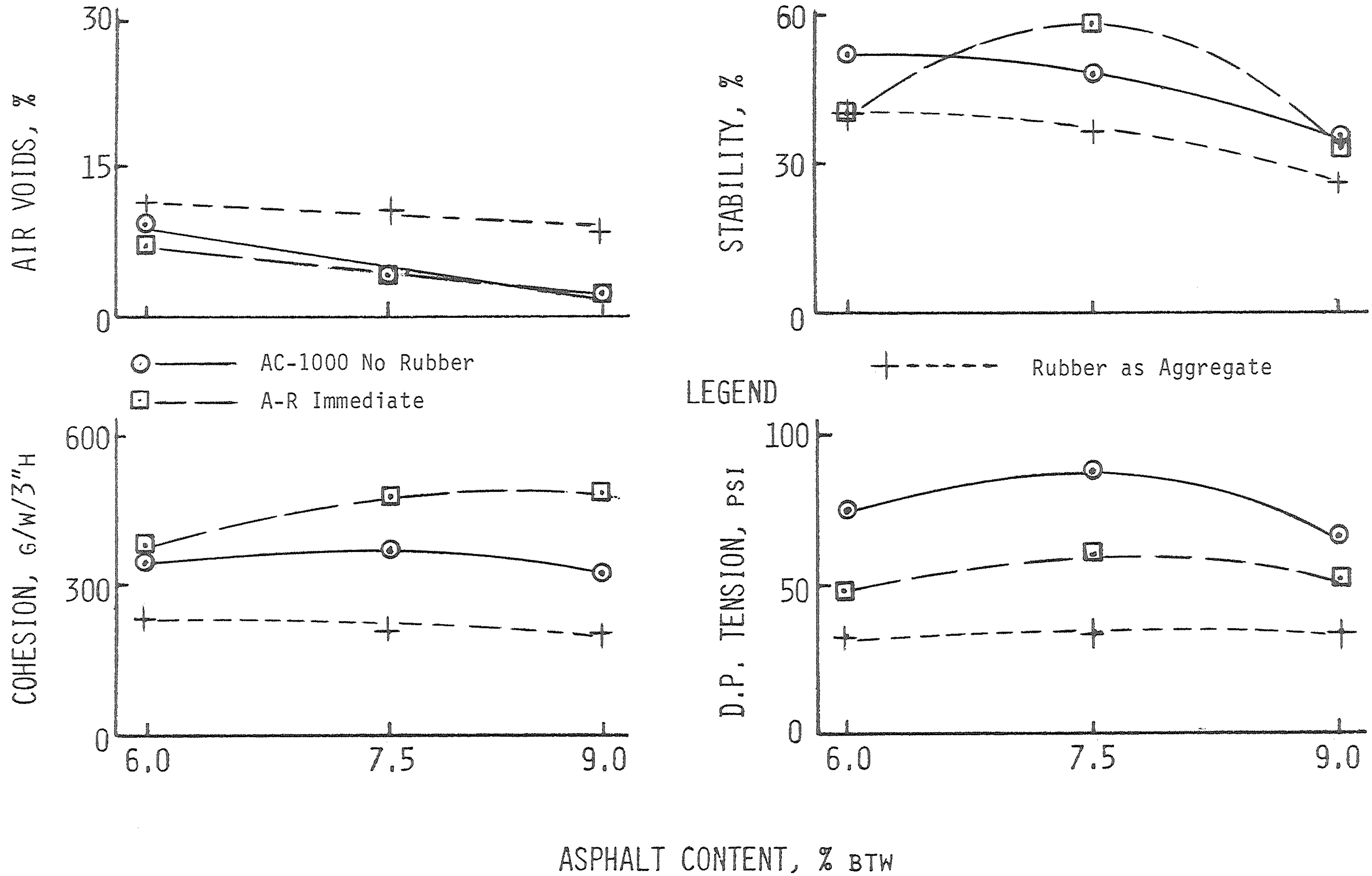

Figure 6. Effects of asphalt content and "finer" rubber on Hveem specimens using vibratory compaction on 3/8-inch dense gradation.

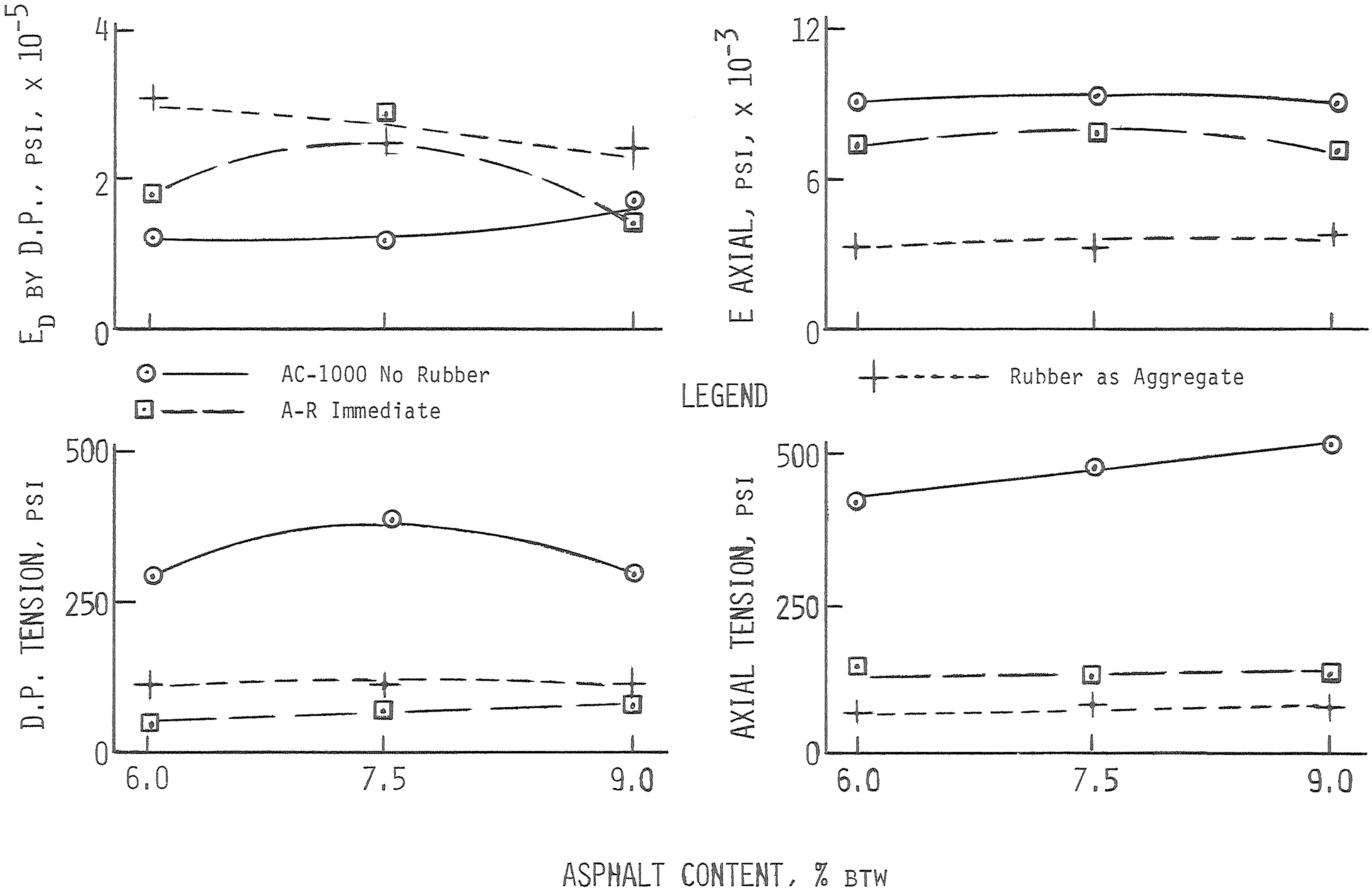

Figure 7. Effects of asphalt content and rubber on 4°C tensile characteristics of specimens using vibratory compaction on 3/8-inch dense gradation.

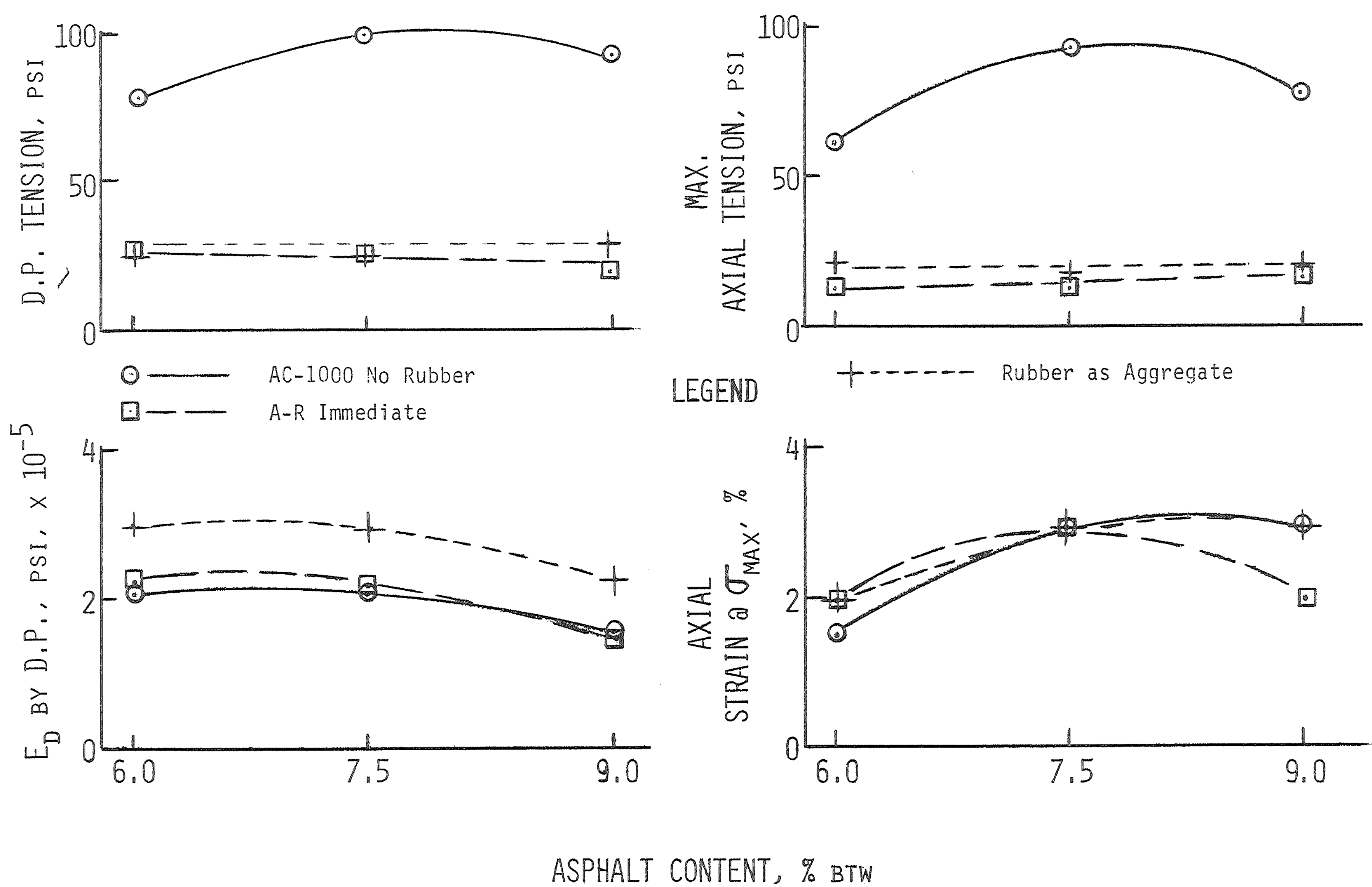

Figure 8. Effects of asphalt content and rubber on 25°C tensile characteristics of specimens using vibratory compaction on 3/8-inch dense gradation.

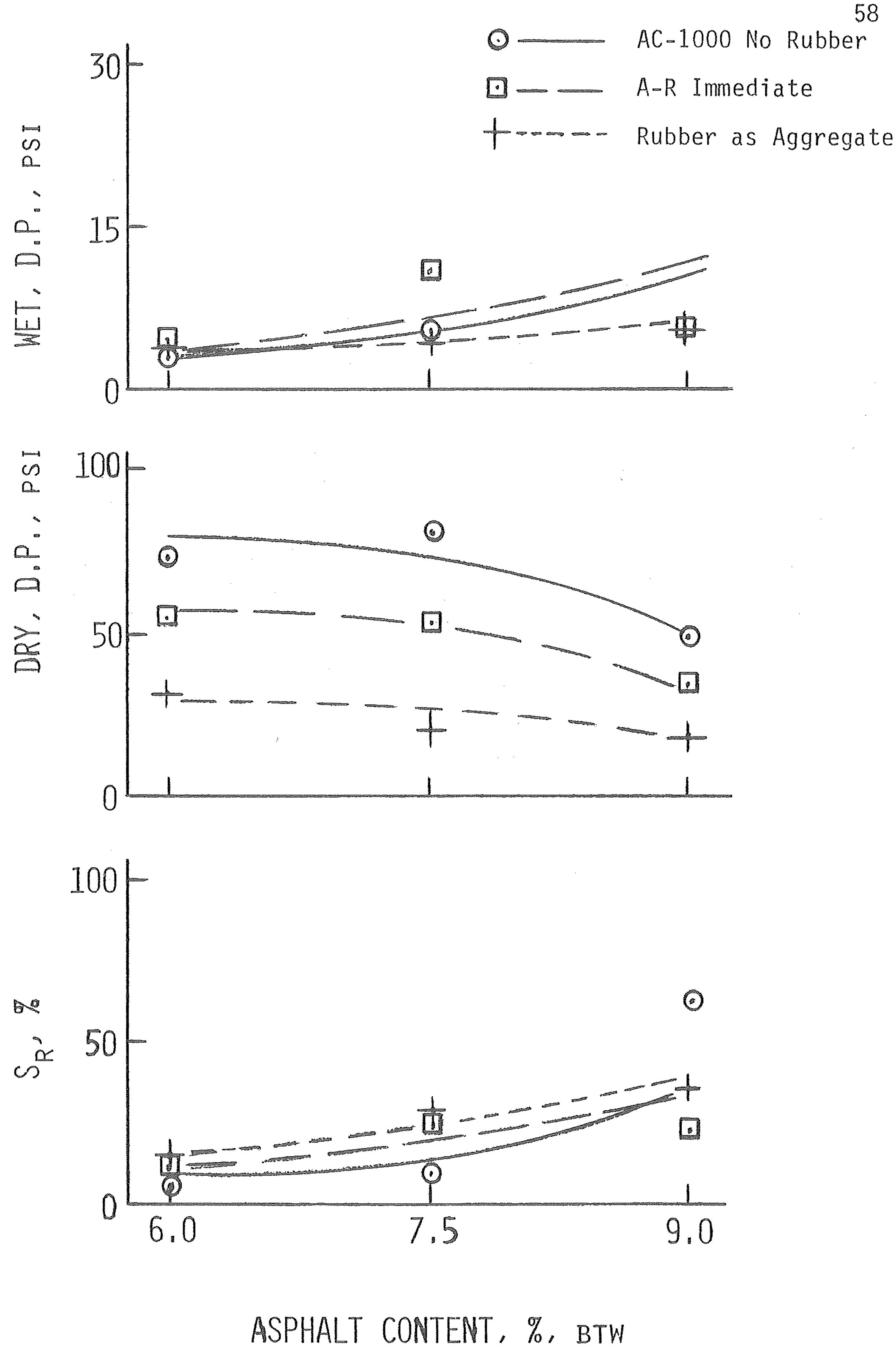

Figure 9. Effects of asphalt content and rubber on debonding test on specimens using vibratory compaction on 3/8-inch dense gradation.

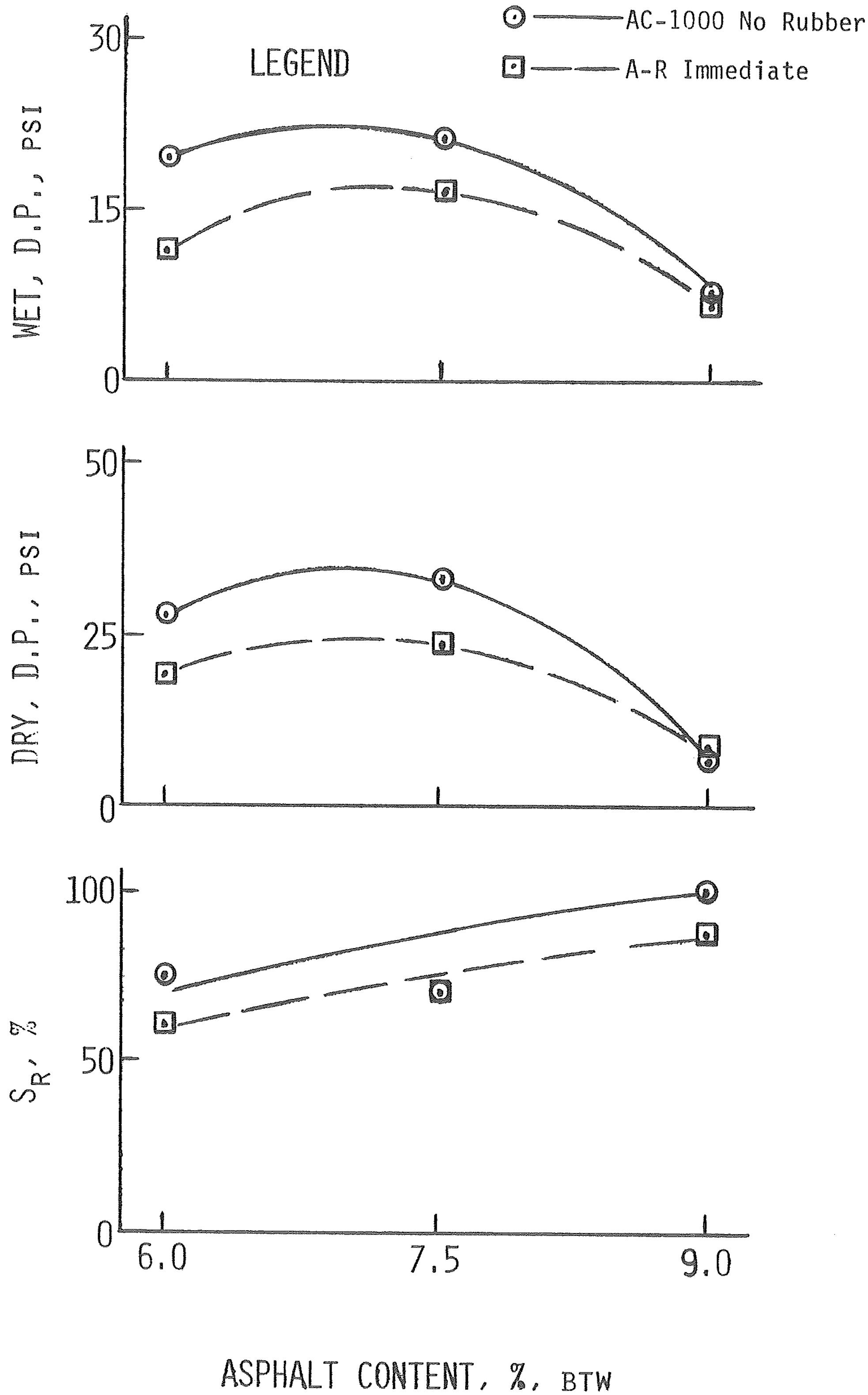

Figure 10. Effects of asphalt content and rubber on debonding test on specimens using vibratory compaction on 3/8-inch open gradation.

APPENDIX B

Addendum

This section contains data and discussion of work performed beyond the scope of the original proposal and mainly during the review period of the original draft.

APPENDUM

This section contains discussions of work performed beyond the scope of the original proposal. The major portion of this discussion is related to the testing of aggregate mixtures made with a different blend of asphalt and rubber granules. Also included in this section are the results obtained in testing the A-R system for debonding in a clean 3/8-inch dense graded aggregate.

A-R Resistance to Debonding

As indicated in the front portion of this text, the poor resistance to debonding of the 3/8-inch dense graded mixture was attributed to the aggregate's low sand equivalent value of 28. Table 12 at the end of this section shows the gradation of the original aggregate and also after cleansing the aggregate and adding three percent portland cement.

Results of the debonding tests of specimens containing 7.5 percent asphalt are shown as Table 13 for both aggregates. The data in this table show that void content and "dry" strength for the clean aggregate are higher and lower respectively and probably due to the lower fines content. However, the "wet" strengths are considerably higher for the clean aggregate which raise significantly the retained strength values to over 75 percent.

Testing of the Different Rubber-Asphalt Blend

The different rubber-asphalt blend is called Arm-R-Shield and in this report it will be identified as AR-S. The blend was composed of asphalt AR-4000, 78.4 percent; extender oil, 1.6 percent; and G-274 rubber, 20.0 percent; all by total weight proportions.

In order to be consistent with the making of the A-R material, the AR-S blends were made in 1,000-gram batches and using the same equipment; however, the holding temperature of 400°F (204°C) for one hour was used as prescribed by the supplier.

Ductility Test

The ductility test was performed on the base asphalt and also on the AR-S blend at temperatures of 39.2 and 77°F (4 and 25°C). Table 14 presents the results of these tests and also ductility values obtained for the A-R material. The data shown indicate that the AR-S had better low temperature ductility value than did the AC-4000; however, the AR-S had greater temperature susceptibility than did the A-R blend.

Tensile Characteristics of An AR-S Mixture

The double punch procedure was used to determine the dynamic modulus of elasticity and also the indirect tensile strength of mixtures made from 3/8-inch open and also dense graded aggregates. The dense graded aggregate was identical to the one used with the A-R mixture. However, the 3/8-inch open gradation, although the same as for the A-R specimens, was made with slightly different stone chips. All specimens were compacted with the vibratory kneading procedure.

Tables 15 and 16 show the results obtained on specimens containing AC-4000 or AR-S, 3/8-inch open or dense graded aggregate, at temperatures of 39.2°F (4°C) or 77°F (25°C) when tested for double punch modulus and strength. Although the asphalt contents are higher than those used for A-R mixtures, the A-R and AR-S contents are the same.

Comparisons between these two tables show the following:

1. For the open graded mixtures:
   a. The AR-S specimens had lower air voids than did the AC-4000 ones.
   b. The AR-S specimens had lower 77°F (25°C) modulus but higher 39.2°F (4°C) modulus than did the AC-4000 specimens.
   c. The AR-S and AC-4000 specimens had comparable tensile strength values at both temperatures.

2. For the dense graded mixtures:
   a. The two sets of specimens had comparable air voids content.
   b. The AR-S specimens had the lower dynamic modulus at both temperatures and these values were also less than for the open graded mixtures.
   c. The AR-S specimens had the slightly lower tensile strength value and these were significantly higher than for the open graded mixtures.

A study of AR-S and the A-R tensile characteristics (Tables 8 and 16) shows that the 3/8-inch dense gradation of the A-R specimens had higher void content, higher dynamic modulus, and lower tensile strength. These differences are difficult to explain because of the interactions or effects caused by differences in asphalt content and viscosity and also the use of the extender oil. Again, it is seen that differences in the strain levels used for the determinations of modulus and strength emphasize temperature and binder effects on these two properties.

Conclusions and Comments

Based on the project's objectives stated earlier, most of the conclusions reached from the work with the A-R material are applicable for the AR-S. Without being too repetitious, some of these are included below:

1. The improvement in resistance to debonding by increasing the sand equivalent of the 3/8-inch dense graded aggregate from 28 to 82 was significant; S_R values went from 8 to 27 and 23 to 96 for the AC-1000 and A-R mixtures respectively.
2. Specimens could be made with the aggregates used in the same fashion as described for the A-R blend.
3. This work did not investigate the possibility of using T.I. compaction with the 500 psi (3.4 M Pa) nor the possibility of eliminating the three-day curing period following compaction.
4. In comparing results of the AC-4000 and AR-S mixtures with the 3/8-inch dense gradation, the AR-S specimen had lower and improved dynamic modulus values ranging from 5,000 to 130,000 psi (350 - 900 M Pa) and slightly lower tensile strength values.
5. Comparing the AC with the AR-S specimen of the 3/8-inch open gradation show small differences in the strength characteristics. Approximate values for modulus and strength at 39.2°F (4°C) are 200,000 psi (1,400 M Pa) and 50 psi (344 k Pa).
6. The AR-S mixtures with the dense gradation had lower dynamic modulus values but higher tensile strength values than the specimens with the open gradation.

7. The differences in dynamic modulus and tensile strength between the A-R and AR-S specimens cannot be directly explained due to interactions or effects caused by differences in asphalt content and viscosity, and also the use of the extender oil.
8. Since the AR-S specimens had higher asphalt content and lower air voids than comparable A-R specimens, it would be anticipated that they would have better resistance to debonding.

TABLE 12 - GRADATIONS OF THE ORIGINAL 3/8-INCH DENSE GRADED AGGREGATE AND AFTER CLEANSING PLUS 3% PORTLAND CEMENT

Sieve Size	3/8"	#4	#8	#16	#30	#50	#100	#200	S.E.
Percent Passing									
Original	100	87	68	49	34	21	13	8	28
Cleansed	100	92	76	56	34	16	7	4	82

TABLE 13 - EFFECTS OF SAND EQUIVALENT VALUE ON RESISTANCE TO DEBONDING OF DENSE GRADED SPECIMENS WITH 7.5% ASPHALT

Binder	AC-1000		A-R	
Sand Equivalent	28*	82	28*	82
Void Content, %				
$\overline{X}$	4.0	5.5	12.5	14.0
$\%C_v$	7	9	16	11
Failure Stress D.P., psi				
Wet, $\overline{X}$	6	51	12	22
$\%C_v$	25	6	8	11
Dry, $\overline{X}$	80	66	52	24
$\%C_v$	21	5	3	11
Retained Strength, %	8	77	23	96

* Table 10

1 psi = 6.89 k Pa

TABLE 14 - DUCTILITY TEST VALUES FOR THE BASE ASPHALTS, A-R, AND AR-S

Test Temperature °F (°C)	33(0.5)	39.2 (4)	77 (25)
AC-1000*	0		150+
A-R*	22		22
AC-4000		0	150+
AR-S		16	38

* Reference 1

TABLE 15 -- TENSILE CHARACTERISTICS OF AC-4000 NO RUBBER ON SPECIMENS FORMED BY VIBRATORY KNEADING COMPACTION AND DOUBLE PUNCH TEST

Aggregate		3/8" Open Graded						3/8" Dense Graded					
Test Temp °F (°C)		39.2 (4)			77 (25)			39.2 (4)			77 (25)		
A.C. Content, %		6.3	7.8	9.4	6.3	7.8	9.4	6.3	7.8	9.4	6.3	7.8	9.4
Void Content, %		25.0	17.0	8.0	22.5	14.5	19.0	19.0	4.5	2.5	9.0	5.0	3.0
		23.0	17.0	11.5	29.5	16.5	19.0	10.0	4.5	2.0	10.0	5.5	1.5
		27.0	14.0	17.3	20.0	18.0	11.5	9.5	6.5	3.0	10.0	5.5	3.0
	$\overline{X}$	25.0	16.0	12.5	24.0	16.5	16.5	13.0	5.0	2.5	9.5	5.5	2.5
	$\%C_v$	8	11	39	21	11	26	42	22	20	6	5	35
Modulus of Elasticity, psi 10^{-5}		2.1	1.3	1.7	2.9	3.3	2.2	0.6	1.6	1.3	1.3	1.4	1.8
		1.0	2.5	1.3	2.3	2.7	2.5	0.5	1.5	2.4	2.5	2.4	2.1
		2.0	1.7	1.0	1.6	2.8	1.9	0.6	1.0	1.7	1.2	2.9	2.5
	$\overline{X}$	1.4	1.8	1.3	2.3	2.9	2.2	0.6	1.4	1.8	1.7	2.2	2.1
	$\%C_v$	46	33	26	29	11	14	10	24	31	43	34	16
Strength, psi		109	189	262	41	66	33	380	437	396	175	129	106
		108	186	229	50	70	38	347	428	418	151	139	125
		74	231	156	59	63	72	305	347	412	146	145	125
	$\overline{X}$	97	202	216	50	66	48	344	404	409	157	138	119
	$\%C_v$	21	12	25	18	5	45	11	12	3	10	6	9

1 psi = 6.89 k Pa

TABLE 16 - TENSILE CHARACTERISTICS OF AR-S ON SPECIMENS FORMED BY VIBRATORY KNEADING COMPACTION AND DOUBLE PUNCH TEST

Aggregate	3/8" Open Graded						3/8" Dense Graded					
Test Temp °F (°C)	39.2 (4)			77 (25)			39.2 (4)			77 (25)		
A.C. Content, %	6.3	7.8	9.4	6.3	7.8	9.4	6.3	7.8	9.4	6.3	7.8	9.4
Void Content, %	17.5	13.0	12.0	16.0	15.0	10.0	8.5	4.0	1.0	7.5	3.0	1.0
	19.5	10.5	11.0	16.5	15.0	8.5	7.0	4.0	1.0	8.0	3.0	1.0
	18.5	13.0	11.5	15.5	15.0	13.5	8.0	3.5	1.0	8.5	2.5	1.0
$\overline{X}$	18.5	12.0	11.5	16.0	15.0	10.5	8.0	4.0	1.0	8.0	3.0	1.0
$\%C_v$	5	12	4	3	0	24	10	8	0	6	10	0
Modulus of Elasticity, psi 10^{-5}	2.2	1.6	2.3	1.5	2.7	2.3	0.8	0.7	0.9	0.8	0.7	1.5
	1.7	1.9	2.4	1.7	2.2	1.9	0.5	0.9	0.6	1.7	0.8	1.2
	1.6	1.7	2.2	1.4	1.9	1.8	0.3	1.1	0.8	1.1	0.9	1.1
$\overline{X}$	1.8	1.7	2.3	1.5	2.3	1.0	0.5	0.9	0.8	1.2	0.8	1.3
$\%C_v$	18	9	4	10	18	13	47	22	20	38	13	16
Strength, psi	157	209	184	58	45	54	318	327	350	163	136	97
	149	244	222	50	38	54	317	327	390	105	139	89
	160	191	170	52	44	46	315	406	360	120	136	80
$\overline{X}$	155	215	192	53	42	51	317	353	367	129	137	89
$\%C_v$	4	13	14	8	9	9	0	13	6	23	1	10

1 psi = 6.89 k Pa