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Laboratory Measurements of Asphalt-Rubber Concrete Mixtures

R.A. JIMENEZ

The objective of this study was to develop procedures for making and testing specimens made with asphalt-rubber and aggregates. The investigation was aimed at finding a method or methods for (a) mixing the high-viscosity asphalt-rubber with aggregates, (b) forming test specimens made with this resilient material, and (c) testing the compacted specimens for characterization by using some common procedures. The above factors are discussed along with results obtained for Hveem stability, cohesiometer value, axial tension, double-punch tension and dynamic modulus of elasticity, and resistance to debonding under a dynamic repeated pore-water pressure exposure. In general, it was found that good aggregate coating can be obtained with a common laboratory mixer at the usual mixing temperatures, that California-tamping-foot compaction was not possible and that vibratory compaction yielded higher densities than static compaction, that compacted specimens required a storage period of three days in the mold at room temperature, that testing for strength had to be performed at room temperature or lower, and that expected low strength and durability are attributed to high air-void content.

Asphalt-rubber (A-R) is a blend of asphalt and fine grindings from rubber tires. The amount of rubber in the blend has been a relatively high value, about 25 percent by weight, and the rubber has been either vulcanized or devulcanized. An A-R with vulcanized rubber was investigated by C.H. McDonald and a specific formulation was patented by him in the 1960s. A review of the development and use of A-R has been given both by Jimenez, Morris, and DaDeppo (1) and by Morris and McDonald (2).

In Arizona, the main use of A-R blends 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 this study was the use of a strain-attenuating layer (SAL) constructed by using a mixture of A-R and aggregate. With chip-seal construction, there are difficulties with uniformity of application and with provision of a consistently good performance. The use of kerosene in the vulcanized rubber and asphalt blends would seem to present additional problems in the A-R SAL construction. The solution to the construction problems of chip seals would appear to be its replacement with a hot-mix A-R concrete. This would control the proportioning of materials and construction.

The objective of this study was to develop procedures for making and testing A-R concrete specimens; these mixtures were then characterized by using common asphaltic concrete (AC) measurements.

MATERIALS

Asphalts

The majority of spray applications of vulcanized rubber and asphalt has used a soft asphalt of the AR-1000 grade that meets the specifications described by the Arizona Department of Transportation (3). The A-R blends containing devulcanized rubber generally use an AR-4000 asphalt and an extender oil. Both these asphalt grades were used in the work presented.

Rubbers

The two types of rubber granules that have been used in the construction of A-R were mixed with the above asphalts to make the A-R blends. The two types are vulcanized and devulcanized rubber. The vulcanized rubber granules came from the grinding of passenger tire treads. These are a styrene-butadiene rubber that is of one size passing a No. 16 sieve and being retained on the No. 25 sieve. The second type of rubber granules was a mixture of natural and devulcanized rubber. The particle sizes were graded from the No. 8 sieve to the No. 200 sieve.

Aggregates

Two aggregate gradations of 9.5-mm (3/8-in) maximum size were used for making the AC. Their gradations and other physical properties are listed in Table 1. The open gradation was chosen because of its possible use as a hot plant seal for replacing a chip seal. Also, it was anticipated that coating difficulties might be overcome by using an aggregate of low surface area. The maximum size of aggregate was limited to 9.5 mm since in its use as an SAL the thickness of the layer would not be greater than 12.7 mm (0.5 in).

A-R Blends

The A-R blends were made according to procedures described in a report by Jimenez (4). A brief description follows.

Table 1. Characteristics of aggregates.

Physical Characteristic	Dense Aggregate[a] (% passing) Original	Dense Aggregate[a] (% passing) Modified	Open Aggregate[a] (% passing)
Sieve size			
3/8-in	100	100	100
No. 4	87	92	55
No. 8	68	76	12
No. 16	49	56	4
No. 30	34	34	1
No. 50	21	16	1
No. 100	13	7	
No. 200	8	4	
Surface area (ft^2/lb)	42		2
Sand equivalent	28	82	
Centrifuge kerosene equivalent oil ratio (%)	4.3		2.6
Effective specific gravity	2.614		2.588

Note: 1 in = 25.4 mm; 1 ft^2/lb = 0.09 m^2/kg.
[a]Size: 3/8 in.

The batch size was held to about 1000 g (35 oz) [250 g (9 oz) of rubber and 750 g (26 oz) of AR-1000 asphalt]. The asphalt was brought to a temperature of 191°C (375°F) in a stainless-steel saucepan. The hot asphalt was stirred with an electric mixer that had a three-bladed propeller 76 mm (3 in) in diameter. The rubber grindings were added to the asphalt within a 5-min period and then the mixture was stirred and held to the 191°C temperature for 30 min. It was then ready to be added to the hot aggregate for mixing.

The blend containing the devulcanized rubber (AR-S) was made of 78.4 percent AR-4000, 1.6 percent extender oil, and 20.0 percent rubber granules. The reacting temperature of 204°C (400°F) was held for 1 h.

MIXING A-R AND AGGREGATE

In regular AC design it is customary to heat the aggregate and AC to specified temperatures prior to mixing and compacting. This is to provide good coating of the aggregate and compaction of the mixture. For example, test method T245-78 of the American Association of State Highway and Transportation Officials (AASHTO) (5) specifies that, for mixing, the asphalt temperature should correspond to that at which the asphalt has a viscosity of about 170 cSt and that, for compacting, the hot mixture should be at a temperature corresponding to that at which the asphalt has a viscosity of about 280 cSt. For most paving AC, the laboratory mixing temperature is usually less than 163°C (325°F) and the compaction temperature of the mixture is more than 110°C (230°).

Earlier work with making A-R blends showed that the mixture had high viscosity at a mixing temperature of 191°C. In the report by Jimenez, Morris, and DaDeppo (1), temperature-viscosity relationships were presented for an AR-1000 and an A-R blend that had a weight ratio of vulcanized rubber to AR-1000 asphalt of 25/75. These equations were as shown below:

$$\text{AR-1000} \quad \eta = 6.767 \times 10^{25} F^{-10.69} \quad (1)$$

$$\text{A-R blend} \quad \eta = 5.768 \times 10^{14} F^{-4.494} \quad (2)$$

where η is viscosity in poises at a shear rate of 0.05 sec^{-1} and F is temperature in degrees Fahrenheit.

Equation 1 indicates that at a temperature of 121°C (250°F) the viscosity of the asphalt would be 1.6 poises or approximately 180 cSt if it is assumed that the hot asphalt has a density of 0.9 g/cm^3 (0.03 oz/in^3). If one enters in the A-R equation with a value of 1.53 poises (170 cSt), one will obtain a temperature of 938°C (1721°F), which is certainly not a reasonable temperature for mixing with aggregates. It is not necessary to explain the discrepancies involved in obtaining the unreasonable mixing temperature for A-R mixtures; however, at the initiation of this study it was considered reasonable to assume that a relatively high mixing temperature and/or high shear rate (much greater than 0.05 sec^{-1}) would be necessary to coat an aggregate with the A-R blend.

The results of experimentation with variations in mixing temperature and compaction are given in a report by Jimenez (6). The outcome of that work led to the use of our standard mixing procedure, in which the aggregate was heated to 149° C (300°F), the A-R was at 121°C, and a 4000-g (140-oz) batch was mixed in an 11-L (10-qt) Hobart C-10 mixer by using a type-D wire whip and a speed setting of 2, which gave a maximum free tangential speed of 2.56 m/s (8.35 ft/s).

Mixing time was approximately 2 min or less if the aggregate appeared to be completely coated. After machine mixing, the material was transferred to a large hot metal pan to check for completeness of coating and to facilitate the scooping of individual test samples for weighing.

TEST SPECIMEN COMPACTION

The concept of a strain-attenuating layer for minimizing reflection cracking in an overlay is based on the fact that the layer has a relatively low resistance to elongation but also the elasticity to recover on the release of stress. The rubber granules in an A-R and aggregate mixture enhance the necessary functions of a strain-attenuating layer; however, these characteristics would work against compaction efforts expended for making test specimens of the mixture. In addition, because of the intermediate-to-high value of shear rate or strain rate during most standard compaction procedures, the A-R blend would have much higher viscosity than that of the asphalt to resist the compaction effort.

From the work described by Jimenez (6), the compaction temperature for the A-R and aggregate mixtures was set at 121°C even though there was no prior knowledge of probable density values achievable under construction of an SAL. Specimen size was to be standard--102 mm (4 in) in diameter by 63 mm (2.5 in) in height--and two compaction procedures were used.

Static Compaction

The Triaxial Institute (T.I.) compactor, also known as the California kneading compactor, is used for making specimens to be tested by the Hveem procedure [AASHTO T246-74 and T247-74 (5)]. After the effects of variations in compaction temperature, tamping pressure, and static loading had been determined, the following procedure was established for making specimens to be evaluated for Hveem stability and cohesiometer value.

The hot mixture was placed in a hot mold and rodded according to AASHTO T247, a double-plunger load of 178 kN (40 000 lbf) was applied, and then the specimen was left in the mold and stored at 25°C (77°F) for three days prior to being extruded. It had been noted that specimens extruded soon after compaction became swollen and cracked. For the specimens that did not crack, radial swelling was such that the specimens could not be placed inside the stabilometer shell.

The storing of a specimen in a mold for three days eliminated the radial swelling but not the swelling in the axial direction. It was noted by feel that the ends of a specimen were less dense than the middle portion was. No measurements were made to determine a density gradient along the length of a specimen.

Vibratory Kneading Compaction

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

A mold 102 mm (4 in) in diameter that contains the hot mixture is mounted on the compactor's turntable. The turntable can be tilted as well as rotated; the standard angle for compaction is 0.02 rad (1 degree) and the rotation is 25 rpm. A vibratory and impact loading is applied through a steel foot 102 mm (4 in) in diameter placed in the mold and at a frequency of 20 Hz. The impacting force is applied in a vertical direction while the tilted mold is rotating; the mold is free to slide along the surface of the turntable. The combined vertical and rotational displacements cause a kneading action during the compaction period. After the period of kneading action, the turntable is leveled and 30 s of vibratory loading are given while the mold is being rotated. This final period of vibratory loading is for the purpose of squaring the specimen.

The resilient nature of the A-R mixtures required that a modification be made to the standard VKC procedure. The modification consisted of an additional double-plunger load of 2.0 MPa (300 psi) immediately following vibratory compaction.

TESTS AND MEASUREMENTS OF COMPACTED SPECIMENS

The tests and measurements made were selected for ease of implementation and for characterization of the specimens by using recognizable units.

Density and Air-Void Content

After the three days of curing in the mold, a specimen was extruded and measured for both height and diameter. Then the specimen was weighed in air and submerged in water. The density of the open-graded specimens was determined by using the dry weight and the volume calculated from the dimensions of the specimen.

The density of the compacted dense-graded specimen was determined by using the air and the submerged weight. This procedure yields a higher density value than the one that obtains the specimen's volume from its height and diameter.

It was expected that these A-R mixtures would be used in layers not thicker than 12.7 mm (0.5 in), and, as such, density values would not have as much significance as air-void content. Air-void content value was calculated by using the effective specific gravity (ESG) of the aggregate. The ESG accounts for the asphalt absorbed by the aggregate and was calculated from the Rice specific gravity of mixtures at various binder contents and the specific gravity of the binder. For a completely coated aggregate the ESG is constant regardless of asphalt content.

Hveem Tests

The frictional and cohesive components of shear strength of the compacted mixtures were characterized with the Hveem stability and cohesiometer values. The tests for the value were performed at 25°C by using the basic procedures of test methods ARIZ 803 and 804 (8). The performance of the stability test had to be slightly modified since the initial confining pressure of 34.5 kPa (5 psi) could not be held without preloading the specimen. Modification of the test consisted of preloading the specimen in the stabilometer with 0.44 kN (100 lbf) and then obtaining the required confining pressure before the preload fell to 0.27 kN (60 lbf). Following the setting of the initial confining pressure, the specimen was loaded at the prescribed rate up to 26.7 kN (6000 lbf). The cohesiometer test was performed following that for stability, and the test temperature was also 25°C.

The double-punch test (9) is an indirect tensile test in which a specimen is loaded in compression by using an axial steel punch 25.4 mm (1 in) in diameter centered on each flat face. This test followed the cohesion test.

Tensile Strength and Elasticity

Tensile strength and elasticity were measured on specimens made with the 9.5-mm dense-graded aggregate and formed by VKC. The measurements were made under static axial tension and also under a new procedure in which a repeated load was applied to a specimen by using the double-punch concept.

Static Axial Tension

Specimens were formed by VKC to a height of 82.5 mm (3.25 in) so that 9.5 mm could be cut from each end. The ends of the specimens were glued to steel discs with Devcon plastic steel B and allowed to cure for one day.

The test setup was made of ball joints and chain so that an axial load was applied by using the testing machine. Tests were performed at temperatures of 4°C and 25°C (39.2°F and 77°F) and at a crosshead speed of 25.4 mm/min. A recorder drew a graph of load versus crosshead movement.

Dynamic Modulus of Elasticity

The dynamic modulus of elasticity (E_D) was obtained by using a repeated-load double-punch procedure (10), which has shown excellent correlation with resilient-modulus (M_R) values obtained by Chevron, U.S.A. (11). 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 2.1 rad (120 degrees) apart. For a standard-sized specimen the loading fluctuates sinusoidally to yield tensile stresses that range from 34.5 to 131.1 kPa (5-20 psi) at a frequency of 11.5 Hz. The low tensile strength of the A-R specimens required that the stress level be reduced and ranged from 20.0 to 82.8 kPa (2.9-12.0 psi).

Resistance to Debonding

The strength of a paving mixture is as important as its durability. A measure of this property is given by its resistance to debonding of the asphalt from the aggregate caused by the action of water and traffic on the pavement.

Our test procedure for evaluating a mixture's resistance to debonding was described by Jimenez (9). The test concept is similar to the AASHTO immersion-compression test T165-77 (5) in that a retained strength after exposure to a test environment is a measure of durability. In our debonding test, the exposure environment is a repeated pore-

Table 2. Effects of vulcanized rubber granules on physical characteristics of compacted AC specimens at 25°C.

Compaction and Binder	AC Content (%)	A-R Content (%)	Void Content (%)	CV[a] (%)	Hveem Stability (%)	CV (%)	Cohesiometer Value	CV (%)	Double-Punch Tension(psi)	CV (%)
Dense-Graded Aggregate										
Static										
AR-1000	6.0		11.0	3	39	1	340	13	51	8
	7.5		8.0	4	44	1	330	5	57	1
	9.0		5.5	6	49	4	370	3	58	5
A-R	6.0	8.0	23.0	9	19	8	160	19	11	18
	7.5	10.0	21.0	13	13	4	240	16	11	13
	9.0	12.0	21.0	14	9	13	290	7	14	19
Vibratory										
AR-1000	6.0		9.5	8	53	7	340	7	75	10
	7.5		4.0	9	49	7	360	8	87	2
	9.0		2.0	35	35	2	320	13	65	4
A-R	6.0	8.0	18.0	2	35	7	200	8	31	10
	7.5	10.0	15.0	8	23	6	220	13	33	9
	9.0	12.0	14.5	4	16	4	200	5	29	7
Open-Graded Aggregate										
Static										
AR-1000	6.0		17.5	3	23	3	230	11	22	9
	7.5		14.5	3	24	9	240	18	26	7
	9.0		12.0	9	24	7	250	11	28	4
A-R	6.0	8.0	16.5	4	22	6	170	17	10	10
	7.5	10.0	14.5	13	20	16	190	11	14	29
	9.0	12.0	11.5	14	15	13	190	8	17	6
Vibratory										
AR-1000	6.0		24.5	3	28	39	200	20	19	29
	7.5		19.5	1	33	6	240	9	25	11
	9.0		18.5	17	26	36	240	8	19	37
A-R	6.0	8.0	23.5	8	22	22	130	24	12	6
	7.5	10.0	19.0	4	25	7	160	16	14	5
	9.0	12.0	15.0	0	22	12	170	4	18	4

Note: 1 psi = 6.89 kPa.
[a]CV = coefficient of variation.

water pressure that fluctuates between 34.7 and 207.0 kPa (5-30 psi) for 10 min at a frequency of 9.7 Hz and at a temperature of 50°C (122°F). The strength value is from the double-punch test performed at 25°C.

TEST RESULTS AND DISCUSSION

Results of the tests performed are given in Tables 2-5. The reader is reminded that the mixtures under investigation are not intended to have strength properties comparable with those of standard AC that would impart structural strength to a pavement. The tests used and the values obtained serve to identify or characterize these materials, whose function would be to serve as strain attenuators to minimize reflection cracking.

Hveem and Double-Punch Tests

The results of the Hveem and double-punch tests are listed in Table 2 for the dense-graded and open-graded aggregates.

Dense Gradation

The values of test results listed in Table 2 show that the vibratory compaction was more effective than the static compaction in that all corresponding values were higher for the specimens formed by VKC. For both types of compaction the addition of vulcanized rubber reduced the strength values; apparently this was because of the reduced density caused by the rubber granules. The reduction in strength values due to the addition of rubber was less under vibratory compaction. The actual values of Hveem stability and cohesiometer should not be compared with standard results since these tests were performed at 25°C rather than at 60°C (140°F). It is significant to note that the void content of the A-R specimens was quite high--generally more than 15 percent--and that the variability of replicates was seemingly not affected by the addition of rubber.

Open Gradation

It is noted that the compaction method did not have so great an effect on density as it did for the dense-graded specimens. As noted earlier, density was calculated from linear measurements for determining volume and thus resulted in lower-than-actual density. The differences in density between the specimens of the two aggregates would not be so great as that indicated. The relatively small differences in void content indicated for the four types of specimens are attributed to the filling of voids in the open-graded aggregate by the binder and in this location its effects on compaction would be minimized. As expected, all strength values were lower than those for the dense-graded specimens. A visual summary of these data is shown in Figure 1.

Tensile Properties of Vulcanized- and Devulcanized-Rubber Mixtures

The results obtained from tensile testing of two types of rubber mixture are shown in Tables 3 and 4. Table 3 presents data for specimens tested under static and dynamic conditions. The specimens were made with the 9.5-mm dense gradation with vulcanized rubber and formed by using vibratory compaction. Table 4 presents the data obtained for specimens made with devulcanized rubber and the two aggregate blends.

Vulcanized-Rubber Mixtures

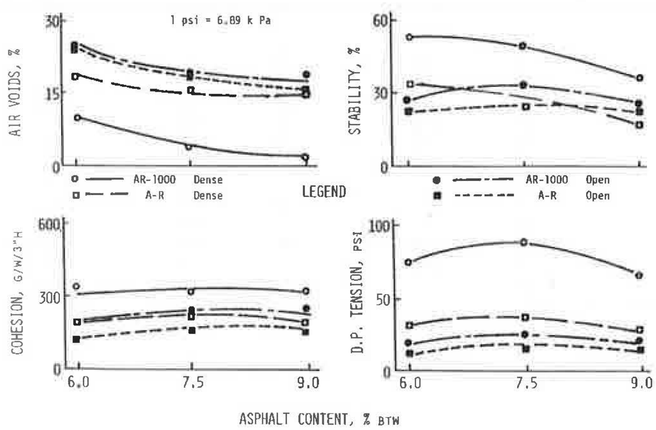
Table 3 presents data for comparing effects of temperature, method of testing, and rubber granules on tensile properties of the dense-graded aggregate. In general, the addition of rubber reduced the modulus of elasticity and tensile strength as compared with the soft (AR-1000) specimens. Under the static loading, the modulus of elasticity for the straight asphalt was 75.8 MPa (11 000 psi) at 4°C (39.2°F) and was reduced to about 51.7 MPa (7500 psi) for the rubberized mixture. Both mixtures were too soft to obtain a measure of modulus at 25°C.

Under dynamic loadings, the modulus of elasticity increased for both mixtures; however, the percentage increase was greater for the rubberized specimens. The asphalt specimens showed an increase by a factor of about 20 and the rubberized ones by a factor of about 26 to yield an E_D of about 1380 MPa (200 000 psi) at 4°C.

Although the effects of temperature on strength and modulus were greater for the rubberized mixtures, the absolute values for the A-R specimens were all less than those for the mixture containing the very soft AR-1000 asphalt.

The data in Table 3 are presented in Figure 2 for ease of comparison.

Figure 1. Effects of asphalt content and vulcanized rubber on Hveem specimens by using dense and open gradation by vibratory compaction.



Devulcanized-Rubber Mixtures

The data in Table 4 show that the static tension test was not used with these mixtures. However, the open-graded aggregate was included for these tensile measurements.

Air Voids

Examination of the air-void data shows that approximately equal density was obtained with the AR-4000 asphalt as was the case for the AR-1000 specimens compacted by VKC; this was so for both aggregates. However, it is noted that the density of the devulcanized-rubber (AR-S) specimens was much higher than that of the A-R specimens; again, this was so for both aggregates. Note that the void content for the dense-graded specimen was comparable with that of regular AC. The reader is reminded that the AR-S binder contains 1.6 percent of an extender oil, which would serve to reduce the viscosity of the AR-4000 asphalt.

Modulus of Elasticity

The dynamic modulus of elasticity (E_D) values

Table 3. Effects of vulcanized rubber granules on tensile characteristics of dense-graded AC specimens formed by using vibratory compaction.

Binder and Temperature	AC Content (%)	A-R Content (%)	Void Content (%)	CV[a] (%)	Static $E_D^b - 10^{-3}$ (psi)	CV (%)	Dynamic $E_D^b - 10^{-5}$ (psi)	CV (%)	Strength (psi)	CV (%)
Static Axial Tension										
AR-1000										
4°C	6.0		10.0	8	11.1	1			425	1
	7.5		5.0	5	11.3	7			483	3
	9.0		2.0	13	11.1	3			519	3
25°C	6.0		10.5	3	Too weak	Too weak			62	7
	7.5		5.0	12	Too weak	Too weak			92	8
	9.0		3.0	17	Too weak	Too weak			78	4
AR										
4°C	6.0	8.0	14.5	9	7.4	22			145	6
	7.5	10.0	15.5	13	7.9	6			126	3
	9.0	12.0	15.0	5	7.2	6			132	14
25°C	6.0	8.0	15.0	20	Too weak	Too weak			11	33
	7.5	10.0	14.5	3	Too weak	Too weak			11	20
	9.0	12.0	14.5	12	Too weak	Too weak			15	13
Dynamic Double-Punch Tension										
AR-1000										
4°C	6.0		12.0	0			2.3	10	296	2
	7.5		5.5	5			2.2	13	397	2
	9.0		4.0	8			1.5	12	300	4
25°C	6.0		12.5	7			2.1	20	79	20
	7.5		5.5	20			2.1	13	100	12
	9.0		4.0	27			1.6	14	93	20
A-R										
4°C	6.0	8.0	18.0	6			1.8	21	47	15
	7.5	10.0	15.0	2			2.9	15	69	4
	9.0	12.0	15.0	7			1.4	15	74	7
25°C	6.0	8.0	19.0	5			1.2	13	27	2
	7.5	10.0	15.0	8			1.1	23	25	16
	9.0	12.0	18.0	6			1.7	32	17	32

Note: 1 psi = 6.89 kPa; $t°C = (t°F - 32)/1.8$.

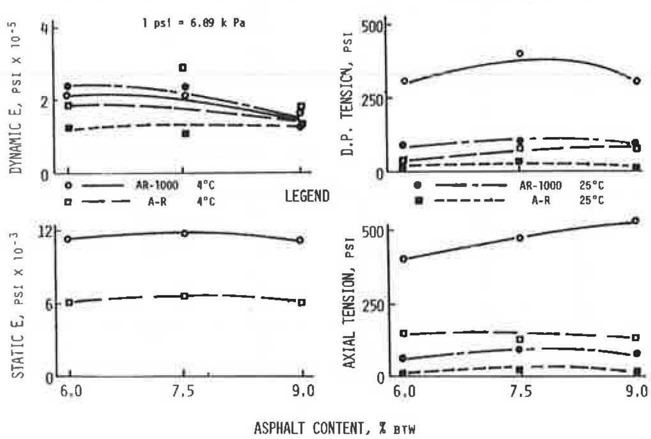
[a]CV = coefficient of variation. [b]E_D = modulus of elasticity.

Table 4. Effects of devulcanized rubber granules on tensile characteristics of vibratory compacted AC specimens.

Binder and Temperature	AC Content (%)	A-R Content (%)	Void Content (%)	CV[a] (%)	Dynamic $E_D^b - 10^{-5}$ (psi)	CV (%)	Strength (psi)	CV (%)
Dense-Graded Aggregate								
AR-4000								
4°C	6.3		13.0	42	1.7	43	344	11
	7.8		5.0	22	2.2	34	404	12
	9.4		2.5	20	2.1	16	409	3
25°C	6.3		9.5	6	0.6	10	157	10
	7.8		5.5	5	1.4	24	138	6
	9.4		2.5	35	1.8	31	119	9
AR-S								
4°C	6.3	8.0	8.0	10	1.2	38	317	0
	7.8	10.0	4.0	8	0.8	13	353	13
	9.4	12.0	1.0	0	1.3	16	367	6
25°C	6.3	8.0	8.0	6	0.5	47	129	23
	7.8	10.8	3.0	10	0.9	22	137	1
	9.4	12.0	1.0	0	0.8	20	89	10
Open-Graded Aggregate								
AR-4000								
4°C	6.3		25.0	8	2.3	29	97	21
	7.8		16.0	11	2.9	11	202	12
	9.4		12.5	39	2.2	14	216	25
25°C	6.3		24.0	21	1.4	46	50	18
	7.8		16.5	11	1.8	33	66	5
	9.4		16.5	26	1.3	26	48	45
AR-S								
4°C	6.3	8.0	18.5	5	1.8	18	155	4
	7.8	10.0	12.0	12	1.7	9	215	13
	9.4	12.0	11.5	4	2.3	4	191	14
25°C	6.3	8.0	16.0	3	1.5	10	53	8
	7.8	10.8	15.0	0	2.3	18	42	9
	9.4	12.0	10.5	24	1.0	13	51	9

Note: 1 psi = 6.89 kPa; $t°C = (t°F - 32)/1.8$.
[a]CV = coefficient of variation. [b]E_D = modulus of elasticity.

Figure 2. Effects of asphalt content, vulcanized rubber, and temperature on tensile properties of dense-graded specimens by vibratory compaction.



obtained for the AR-S specimens were lower than those for the A-R specimen. The values shown in Table 4 were obtained from a modification of our double-punch procedure. A study of our method for determining E_D showed the following relationship with values obtained by using the Chevron, U.S.A. (11) method for obtaining modulus of resiliency M_R:

$$M_R = 2.29E_D + 168(\text{ksi}) \quad (3)$$

By using Equation 3, E_D-values for the AR-S specimens are transformed to M_R-values that range from 1946 MPa (282 500 psi) at 25°C to 3209 MPa (465 700 psi) at 4°C for the dense-graded aggregate.

A close inspection of the E_D-values in Table 4 shows that the open-graded specimens with AR-S were stiffer than the dense-graded ones. This is an interesting finding, since one would expect a less-dense specimen to have a lower modulus. Perhaps this behavior can be attributed to the supposition that because of the larger air voids in the open-graded aggregate, the rubber particles filled air-void space and the aggregate particles were coated with asphalt only. It is noted that the modulus values for the asphalt-only, open-graded specimens were comparable with those for the AR-S specimens at 25°C.

Tensile Strength

The results of the double-punch tensile strength listed in Table 4 show that the AR-S specimens had fairly high values. For the dense-graded aggregate the strength ranged from 620 kPa (90 psi) at 25°C to 2480 kPa (360 psi) at 4°C. In comparison with these strengths, the A-R specimens had corresponding values of 117-510 kPa (17-74 psi), which were even lower than the strength obtained for the open-graded specimens made with AR-S.

The following listing serves to compare the elastic modulus of these rubberized materials with that of AC determined at 4°C (1 MPa = 145 psi):

Material	M_R (MPa)	E_D (MPa)
AC	5257	1791
Dense-graded 9.5-mm A-R	4313	1378
Dense-graded 9.5-mm AR-S	3209	896
Open-graded 9.5-mm AR-S	4786	1585

Some of the data in Tables 3 and 4 are summarized and presented graphically in Figure 3.

Resistance to Debonding of Vulcanized-Rubber Specimens

The results of the debonding test on both the dense-

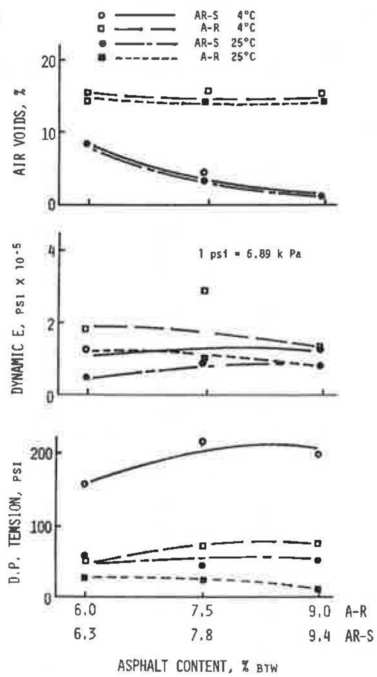


Figure 3. Effects of asphalt content, rubber type, and temperature on tensile properties of dense-graded specimens by vibratory compaction.

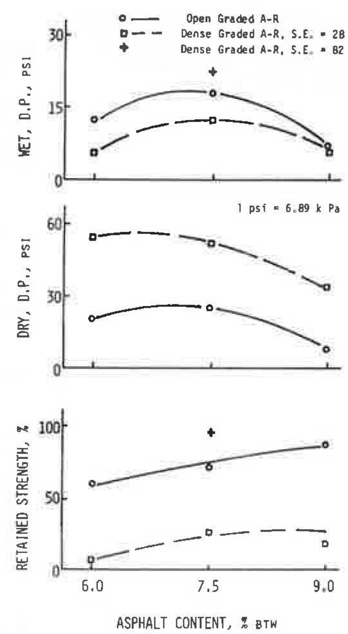


Figure 4. Effects of asphalt content on debonding test on dense- and open-graded A-R specimens by vibratory compaction.

Table 5. Effects of vulcanized rubber granules on resistance to debonding of vibratory compacted AC specimens.

Binder	AC Content (%)	A-R Content (%)	Void Content (%)	CV[a] (%)	Double-Punch Failure Stress Wet (psi)	CV (%)	Dry (psi)	CV (%)	Retained Strength (%)	Sand Equivalence Value
Open-Graded Aggregate										
AR-1000	6.0	-	25.5	7	21	15	28	7	75	
	7.5	-	20.0	6	23	4	33	12	70	
	9.0	-	25.5	7	8	22	6	0	100	
A-R	6.0	8.0	22.5	4	12	22	20	12	60	
	7.5	10.0	18.5	3	17	17	24	7	71	
	9.0	12.0	23.5	8	7	22	8	7	87	
AR-1000	7.5	-	-	-	-	-	-	-	-	
A-R	7.5	10.0	-	-	-	-	-	-	-	
Dense-Graded Aggregate										
AR-1000	6.0		10.0	16	3	19	73	9	4	28
	7.5		4.0	7	6	25	80	21	8	28
	9.0		2.0	14	31	5	49	10	63	28
A-R	6.0	8.0	15.5	9	5	11	54	9	9	28
	7.5	10.0	12.5	16	12	8	52	3	23	28
	9.0	12.0	11.0	30	6	33	32	17	19	28
AR-1000	7.5	-	5.5	9	51	6	66	5	17	82
A-R	7.5	10.0	14.0	11	22	11	24	11	96	82

Note: 1 psi = 6.89 kPa.
[a]CV = coefficient of variation.

and the open-graded specimens are shown in Table 5. It is quite apparent that high void content and low sand equivalent value resulted in very low retained strength for the dense-graded specimens. It appears that the relative lack of dirty fines in the open-graded specimens resulted in high values of retained strength, although the dry strengths were much lower than those for the comparable dense-graded specimens (Figure 4).

Table 5 also shows that when the dense-graded aggregate was modified to have less fines and a sand equivalent value of 82, the retained strength was increased tremendously (to 96 percent) for the A-R specimens. The dry strengths were reduced because the reduction in fines yielded higher air-void values; the wet strength increased because of the cleanness of the aggregate. The data indicate that because of the resulting high air-void content of A-R mixtures, the aggregates must be quite clean if the mixtures are to serve effectively as an SAL. It was noted that the 9.5-mm dense-graded specimens made with AR-S had a much lower air-void content than those made with A-R. As a consequence, we would expect the AR-S mixture to have better resistance to debonding than the A-R specimens.

CONCLUSIONS

The aim of the study was to make and test laboratory-prepared specimens in order to characterize A-R and aggregate mixtures by using results from standard test procedures. The A-R concrete is intended to be used as an SAL interlayer to minimize reflection cracking in an overlay and, as a consequence,

it was not expected to have strength values comparable with those of normal AC. Within the bounds of the experimentation and the materials used, the following conclusions are warranted for the making and testing of A-R concrete specimens:

1. Good coating of the 9.5-mm dense-graded and open-graded aggregates was obtained when the aggregate was at a temperature of 149°C (300°F) and the A-R was at 121°C. A Hobart C-10 food mixer was used with a type-D wire whip and medium speed. This type of mixer is commonly used in many laboratories.
2. Compaction of standard-sized specimens could not be effected by using the tamping-foot procedure of the California kneading compactor at a temperature of 121°C. Specimens could be formed by using static double-plunger compaction and also by using our VKC, which gave higher densities. The Marshall compaction procedure was not attempted.
3. It was necessary to leave the hot-compacted specimen in the mold for three days at ambient temperature prior to extrusion in order to eliminate swelling of the unconfined specimen that would cause cracking.
4. The air-void content for the 9.5-mm dense-graded specimens had a much higher value when the specimens were mixed with the vulcanized rubber than when they contained devulcanized rubber.
5. Specimens made by using both aggregates and the vulcanized rubber had Hveem stability values that ranged between 25 and 35 and cohesiometer values between 170 and 200 when tested at 25°C.
6. Dynamic modulus of elasticity values for both aggregates and both types of rubber were approximately 70 percent of that for regular AC. The lowest modulus at 4°C was 896 MPa (130 000 psi).
7. Due to the high void content of the 9.5-mm dense-graded specimen made with the vulcanized rubber, it will be necessary for the aggregate to be very clean in order to obtain good resistance to debonding from the action of water.

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Field Evaluation of Rubber-Modified Bituminous Concrete

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The flexibility and, as a result, the durability of bituminous concrete placed as an overlay over old pavement can be increased by the addition of reclaimed rubber. The conditions under which the modified characteristics are most beneficial have not been well defined. Within the maintenance program of the Connecticut Department of Transportation, reclaimed-rubber test sections were placed at nine locations. The locations were selected to include three levels of traffic from a low of 1300 average daily traffic (ADT) to a high of 10 400 ADT and three levels of pavement condition (low, medium, and high). At each location, mixes in which the rubber content was 0, 1, and 2 percent of the mix were placed. Comparisons were made of permeability, density, skid number, and crack development over three years.

The planning for this study was formally started by a group that consisted of the Office of Research of the Connecticut Department of Transportation (ConnDOT), the Civil Engineering Department of the University of Connecticut (UConn), the Solid Waste Section of the Department of Environmental Protection, and the Reclaiming Division of Uniroyal, Inc. ConnDOT, UConn, and the Rubber Reclaimers Association had carried out a laboratory study in which reclaimed rubber was added to asphalt paving mixes (1). The results from that work indicated that reclaimed rubber added to mixes in the laboratory significantly improved the properties of pavement