Laboratory Evaluation of Recycled Asphalt Pavement Using Nondestructive Tests

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Many tests have been devised for measuring the characteristics of bituminous materials. These tests can be divided into four categories: (a) destructive tests that are associated with fundamental elastic and viscoplastic behavior such as the indirect tensile tests; (b) destructive tests that are arbitrary (in the sense that their usefulness lies in the correlation of their results with field performance), such as the Marshall and Hveem stability tests; (c) nondestructive tests that are associated with fundamental elastic and viscoplastic behavior such as the resilient modulus test; and (d) nondestructive tests that are arbitrary, such as the sonic pulse velocity test. The nondestructive resilient modulus and sonic pulse velocity tests were used for characterization of hot-mix recycled asphalt paving mixtures. Asphalt specimens were tested for pulse velocity, resilient modulus, and Marshall stability. Analysis and evaluation of the test data indicated sensitivity of the resilient modulus to mix design parameters. The test was identified as an additional criterion for design and evaluation of hot-mix recycled asphalt pavement. Pulse velocity data were not sensitive to the mix design used. However, the modulus of elasticity estimated from the test indicated low statistical variations, suggesting the use of test values as input for pavement thickness design related to layered theory solutions. Stiffness and strength characteristics of the recycled mixtures were comparable to those of a companion virgin bituminous mix, with no recycled materials.

Hot-mix bituminous pavement recycling is a process in which reclaimed bituminous pavement materials, reclaimed aggregate materials, or both, are combined with new bitumen, rejuvenating agents, or virgin aggregate, as necessary, to produce hot-mix paving mixtures that meet standard materials specifications and construction requirements for the type of mixture being produced.

The increase in recycling operations has resulted in an increased awareness that the recycled materials must be properly characterized to ensure a high-quality pavement. The cost and energy savings obtained during construction may be lost through excessive maintenance if the recycled pavements undergo severe deterioration. Initial indications are that a high-quality recycled pavement is being constructed using conventional design methods. However, there are several fundamental questions still unanswered in the area of hot-mix recycling that require research. These include its homogeneity, compatibility, and rate of hardening of a recycled mix when compared to a virgin mix. In addition, assurance is needed that weathering actions, long-term behavior, mechanical properties of compacted recycled mixtures, and the effect of repeated loads on recycled pavements are not problems.

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A laboratory investigation was performed to characterize the performance of the hot-mix recycled asphalt pavement in comparison with a virgin mix. A virgin mixture and three recycled mixtures were evaluated. Marshall size specimens were prepared and evaluated using the pulse velocity, resilient modulus, and Marshall stability tests. Subjective conclusions were established for the performance of recycled mixtures under various conditions.

Study results will provide the highway engineer with a better understanding of the effect of different factors on the resilient characteristics of hot-mix recycled bituminous paving mixtures.

SAMPLING PLAN AND MATERIALS

Recycled Asphalt Pavement

A stockpile of representative salvaged asphalt pavement was obtained for laboratory evaluation. The material used was milled from US-52, a highway south of Indianapolis, Indiana, that was randomly selected and was under the supervision of the Indiana Department of Highways personnel for the purpose of this study. Sampling of the laboratory-created stockpile was also randomly selected to obtain statistically representative asphalt materials for the study.

Samples of the Recycled Asphalt Pavement (RAP) were randomly chosen, reduced in size, and characterized. Asphalt extraction and recovery was conducted using ASTM D2172 method A and the Abson method, ASTM D1856. The salvaged binder was characterized by means of penetration, softening point, and viscosity tests. Amount of asphalt present was determined, and the salvaged aggregate obtained from extraction was characterized by sieve analysis.

Tables 1 and 2 present the characteristics of the extracted hard asphalt and the gradation of salvaged aggregate, respectively. The Indiana State Highway *Standard Specifications* (*1*) for No. 12 surface were also included in Table 2 for comparison purposes and for future determination of the feasibility of the salvaged aggregate for use as a high-quality hot surface mix. The recovered aggregate consisted mainly of crushed limestone as coarse aggregate (material retained on No. 4 sieve) and crushed sand as fine aggregate (material passing No. 4 sieve). The sieve analysis of the salvaged aggregate indicated a gradation that is within the specification for No. 12 surface.

Recycling Agents (Rejuvenators)

Three types of recycling agents were selected for use in combination with the age-hardened salvaged asphalt binder. The

TABLE 1 CHARACTERISTICS OF EXTRACTED HARD ASPHALT

Test	Value
Penetration, 77°F, 100 gm, 5 sec.	28
Viscosity, 140°F, Poises	20,888
Kinematic visc., 275°F, c. st.	726
Softening Point, °F	137
Asphalt Content (Total Wt.)	6%

selections were based on their previous usage in other recycling techniques, wide variation between their natures, and knowledge of their physical and chemical properties. The following recycling agents were used:

- AC-2.5, ASTM designation, produced by Amoco Oil Company.
- AE-150, Indiana-designated high-float, medium-setting-type asphalt emulsion, supplied by McConnaughy, Inc.
- Mobilsol-30, ASTM-designated Type 101 oil, produced by McConnaughy, Inc.

Tables 3–5 present the characteristics of AC-2.5, AE-150, and Mobilsol-30.

Virgin AC-20

The three recycling agents were to be used to restore the old binder present in the RAP to the AC-20, ASTM designation, classification range. A virgin AC-20 was obtained from Amoco Oil Company to use in comparing virgin and recycled hot mixes. Virgin AC-20 was not used in any combination with recycled mixtures. Table 6 gives the characteristics of AC-20. The choice of AC-20 was based on its usage in Indiana to produce hot-mix asphalt pavements.

Virgin Aggregate

Crushed limestone and crushed sand were selected to represent the coarse and fine aggregate material for the virgin aggregate, the same as for recovered salvaged aggregate.

TABLE 3 CHARACTERISTICS OF AC-2.5

Test	Value
Penetration, 100 gm, 77°F, 5 sec., 0.1 mm	200
Absolute viscosity, 140°F, Poise	292
Specific Gravity, 77°F	1.024
Ductility, 77°F, 5 cm/min., cm.	150+

TABLE 4 CHARACTERISTICS OF AE-150

Test	Value
Residue by Distillation	68%
Penetration of Residue	
100 gm, 5 sec, 787°F, 0.1 mm	200
Specific Gravity of Residue, 77°F	1.01
Float, 1140°F, sec.	1200+
Absolute Viscosity of Residue,	
140°F, Poise	270

DETERMINATION OF THE AMOUNT OF REJUVENATOR

The Asphalt Institute curves (*2*) were used to determine an initial value for the percentage of rejuvenator (AC-2.5 and AE-150) to be added to the old binder to restore the properties to AC-20 range of classification. The AC-20 classification range was a target for its wide usage in producing high-quality hot-mix paving mixtures in Indiana. The curves suggest the rejuvenator percentage on the basis of its viscosity at 140°F, the old binder viscosity at 140°F, and the required viscosity for the new rejuvenated binder at 140°F. The initial value for the percentage of Mobilsol-30 was chosen on the basis of previous recycling projects (*3,4*).

A series of extraction and recovery tests were conducted to justify these initial values. Table 7 shows the characteristics

TABLE 2 GRADATION OF SALVAGED AGGREGATE

Sieve Size	3/8	#4	#8	#16	#30	#50	#100	#200
% Passing	98	74	62	44	28	15	7.5	5
IND. spec for								
#12 Surface	96-100	70-80	36-66	19-50	10-38	5-26	2-17	0-8

TABLE 5 CHARACTERISTICS OF MOBILSOL-30

Percent Asphaltenes*	0
Percent Polar Compounds*	8
Percent Aromatics*	79
Percent Saturates*	13
Percent Residue in Emulsified Form	66.7
Flash Point*, °F	505
Kinematic Viscosity* at 140°F, c.st.	164
Specific Gravity*	0.974

*Properties of Residue

Note: Constituents were obtained using Clay-Gel Analysis (ASTM D2007-75)

TABLE 6 CHARACTERISTICS OF AC-20

Test	Value
Penetration, 100 gm, 5 sec., 77°F, 0.1 mm	65
Absolute Viscosity, 140°F, Poise	1890
Softening Point, °F	122
Ductility, 77°F, 5 cm/min., Cm	150+

of salvaged asphalt, the rejuvenators, and the three rejuvenated binders, together with the amount of rejuvenator being used.

TESTING PROGRAM TO EVALUATE COMPACTED HOT-MIX RECYCLED ASPHALT PAVEMENT

Virgin mixtures containing virgin AC-20 and No. 12 surface virgin aggregate were compared with three other recycled mixtures. Salvaged binders present in recycled mixtures were restored to AC-20 range of classification by using (60 percent AC-2.5 + 40 percent old asphalt), (55 percent AE-150 + 45 percent old asphalt), and (85 percent Mobilsol-30 + 15 percent old asphalt). Salvaged and virgin aggregate combinations in recycled mixtures were adjusted to have the gradation of No. 12 surface. This adjustment was not complicated because the gradation of the salvaged aggregate was within No. 12 surface specification limits, and the virgin aggregate gradation was selected to be the specification midpoint of No. 12 surface.

The four mixes prepared were designated as $(AC)_0$, $(AC\text{-}20)_1$, $(AC\text{-}20)_2$, and $(AC\text{-}20)_3$. All mixtures had the same aggregate gradation (No. 12 surface) and binders satisfying AC-20 specifications. The only difference was that the first was a completely virgin mix and the other three were recycled mixtures with AC-2.5, AE-150, and Mobilsol-30, respectively, as rejuvenating agents.

Three asphalt contents were used in mix preparations: 5.5 percent, 6 percent (original asphalt content present in RAP), and 6.5 percent by total weight of mixture. The mixtures were compacted using the kneading compactor and evaluated using the pulse velocity, resilient modulus, and Marshall stability tests.

TABLE 7 CHARACTERISTICS OF SALVAGED ASPHALT REJUVENATORS AND REJUVENATED BINDERS

Binder	Penetration	Vis. 140°F, Poises
Old Asphalt	28	20,888
AC-2.5	200	292
AE-150 Residue	200	270
40% Old Asphalt + 60% AC-2.5	62	2112
45% Old Asphalt + 55% AE-150 Residue	68	1994
85% Old Asphalt + 15% Mobilsol-30 Residue	69	1974
AC-20 spec.	60+	1600-2400

Note: Mobilsol-30 characteristics are given in Table 5.

Preparation of Specimens

Samples of the recycled asphalt pavement (RAP), virgin aggregate, and virgin AC-20 were heated in an oven at 240°F for 1 hr. The rejuvenators AC-2.5, AE-150, and Mobilsol-30 were heated in an oven at 180°F. The RAP, virgin aggregate, and one rejuvenator were mechanically hot-mixed for 2 min. Absolute virgin mixtures containing AC-20 and virgin aggregate were hot-mixed similarly.

The loose samples containing 5.5, 6, and 6.5 percent asphalt binder for $(AC\text{-}20)_0$ and $(AC\text{-}20)_1$, $(AC\text{-}20)_2$, and $(AC\text{-}20)_3$ specimens were stored in an oven at 140°F for 15 hr. The mixtures were then reheated to 240°F and compacted using the standard California kneading compactor, ASTM D1561, to form specimens of 4-in. diameter and approximately 2.5-in. height.

Tests on Compacted Specimens

The merit in using conventional design indices such as the Marshall or the Hveem stabilities exists in the need for similarity of design procedures for the recycled mix and conventional mixtures.

Pieces of equipment used were the pulse velocity, resilient modulus, and Marshall testing equipment.

Pulse Velocity Test

Pulse velocity tests have been used since the 1940s for evaluating the elastic properties of solid composite materials such as rocks and concrete blocks (*5*). Sonic testing has been used for studying the elastic constants of bituminous mixtures over a wide range of temperature (*6*). The pulse velocity procedure has not been widely used for evaluating conventional bituminous mixtures and investigators have not reported its use for characterizing recycled mixtures. Some studies, however, show that this procedure may be suitable for studying changes taking place in asphalt mixtures with time (*7*).

The pulse velocity determination consists of measuring the rate of propagation of sound waves in a test specimen. The sound wave velocity for elastic materials is a function of elastic modulus, Poisson ratio, and density (*5,7*) and can be determined from the following equation:

$$E = v^2 d/c \tag{1}$$

where

E = material elastic modulus,
d = material density,
v = pulse velocity,
$c = 1/(3 - 6\mu) + 2/(3 + 3\mu)$, and
μ = Poisson ratio.

The material modulus can be estimated using this relationship, the pulse velocity measurements, and a proper measurement or assumption of the Poisson ratio. Correlations have been found between the concrete modulus estimated by the pulse velocity measures and from the flexural strength test (*5*).

Bituminous materials are viscoelastic and experience variations in their modulus and Poisson ratio with time and temperature. However, the change in Poisson ratio is not so great, relatively, as is the change in the modulus. A single value can be assumed for the ratio so that the modulus estimation can be used to obtain comparative values between different bituminous mixtures although no exact value can be determined. In addition, pulse velocity may be used directly as the criterion for evaluating asphalt mixtures and thus need not be converted to a modulus value (*7*).

The pulse velocity test is independent of the size and shape of the specimen being tested (*5*). Thus, the procedure is potentially adequate for both laboratory and field testing applications. The test is simple, inexpensive, and more important, nondestructive. Additional testing can be conducted on the same sample in the laboratory.

The pulse velocity test equipment used in this study is the same as that required in the standard test on rocks, ASTM D2845. The equipment briefly consists of a sample holder (a Marshall-type specimen can be used), two transducers, and a pulse generator with a timing unit. The sample height divided by the time measured is the pulse velocity.

The transducers are to be connected to the transmitter and receiver nodes of the pulse generator. The pulse generator is allowed to send mechanical pulses through the transducer connected to the transmitter node. These pulses pass through the compacted specimen and are received by the transducer connected to the receiver. The time taken by this pulse is displayed on the timing unit screen, read, and recorded.

The test was conducted at room temperature, 72°F. A sample holder was used to maintain contact between the transducers and the specimen. In addition, a thin coating of starch gel enhanced the contact between the sample and transducers. For pulse velocity computations, sample height was measured to the nearest 0.1 mm. Specimen weight and height were used to estimate the unit weight of the compacted mixtures.

The following parameters (response variables) were used to characterize the compacted mixtures:

$$V = 32.81\ H/t \tag{2}$$

where

V = pulse velocity (ft/sec/1,000),
H = specimen height (cm),
t = time displayed on screen (μsec), and
32.81 = constant for units adjustment.

$$E = V^2 d/C \tag{3}$$

where

E = instantaneous elastic modulus,
V = pulse velocity,
d = density,
$C = 1/(3-6\mu) + 2/(3+3\mu)$, and
μ = Poisson ratio.

To estimate the instantaneous elastic modulus a value for μ was assumed. The theoretical value ranges between 0 and 0.5 and depends on the materials property. Asphalt mixtures are believed to have values in the range 0.25 to 0.45. Schmidt (*8*) used a value of 0.35 at ambient temperature in the computations of the diametral resilient modulus. Mamlouk (*9*) indicated difficulties in laboratory determination of the Poisson

ratio value; instead, he assumed values for μ of 0.3, 0.35, and 0.4 at 50°F, 75°F, and 100°F, respectively.

The estimation of E from pulse velocity test results of this study was based on assuming a Poisson ratio of 0.35 for a test temperature of 72°F. Using this assumption and adjusting the units, Equation 3 can be expressed as

$$E = V^2 d/7{,}442 \quad \text{at } 72°\text{F} \tag{4}$$

Resilient Modulus Test

The resilient modulus, the modulus of elasticity when the theory of elasticity is applied to bituminous mixtures to analyze the stress-strain relationship, is the ratio of the applied stress to the recoverable strain when a dynamic load is applied.

The resilient modulus for an asphalt mix can be determined in the laboratory using the diametral compression mode in which Marshall-sized specimens can be used. The test method is based on the fact that when a viscoelastic material is loaded for a short duration of time, its response is mainly elastic.

Schmidt (*8*) developed a procedure in which a pulsating load is applied across the vertical diameter of a Marshall specimen every 3 sec with 0.1-sec duration and the corresponding horizontal deformation is recorded. The fact that the test is not only sensitive, but also rapid and nondestructive makes it an excellent tool for design and characterization of hot-mix recycled asphalt pavement.

The resilient modulus test equipment used in this study consists mainly of a load cell, specimen restraint, diaphragm air cylinder, source of compressed air, solenoid valve system, two transducers, and a control panel. The compressed air source is connected to the diaphragm air cylinder through the solenoid valve system. The solenoid valve is electrically activated and turned on for a duration of 0.1 sec every 3 sec, causing a pulse of compressed air to pass through the air cylinder and to create a pulse load along the vertical diameter of the test specimen.

The magnitude of the pulse load is controlled through adjustment of the compressed air. The horizontal deformation of the specimen is measured by the two transducers that are adjusted to lie on opposite sides of the horizontal diameter of the specimen. The magnitude of the load and resultant deformation are displayed on a detector on the electronic control panel. They can be read easily and recorded.

The horizontal transducers were moved until they just contacted the properly aligned specimen. The load was applied across the vertical diameter of the specimen using two curved loading strips of 0.5-in. width and 2-in. radius (same as the specimen). The magnitude of the applied load was controlled by adjusting the pressure regulator for the compressed air to 35 and 50 lb. Horizontal deformations corresponding to each of the applied loads were displayed on the recorder screen and recorded.

Resilient modulus MR values corresponding to each load magnitude and resulting deformation were computed using the following equation:

$$\text{MR} = \frac{P(\mu + 0.2734)}{hD} \tag{5}$$

where

P = compressed air pressure (lb),
MR = resilient modulus (psi),
h = specimen height (in.),
D = deformation (in.), and
μ = Poisson ratio, assumed to be 0.35 at a test temperature of 72°F.

Marshall Stability Test

The autographic Marshall testing apparatus was used to conduct the Marshall stability tests on the recycled mixtures. The recorder provides a continuous load-deformation plot as a specimen is being loaded to failure. Load at failure is the specimen stability, while total deformation at failure is its flow in units of 0.01 in.

The Marshall stability test was conducted on $(AC\text{-}20)_0$, $(AC\text{-}20)_1$, $(AC\text{-}20)_2$, and $(AC\text{-}20)_3$ specimens previously tested by the nondestructive pulse velocity and resilient modulus tests.

CHARACTERISTICS OF COMPACTED SPECIMENS

Pulse Velocity Test

Pulse Velocity

Table 8 presents pulse velocity values for different compacted mixtures at different asphalt contents. The analysis of variance (ANOVA) results suggested that there were no significant differences between the pulse velocity values caused by change of asphalt content. However, the mean value at 6.5 percent was slightly lower than those values at 5.5 and 6.0 percent. Pulse velocity values of compacted recycled mixtures $(AC\text{-}20)_2$ with AE-150 as a recycling agent were slightly lower than those values for absolute virgin mix $(AC\text{-}20)_0$. Other recycled mixtures, $(AC\text{-}20)_1$ and $(AC\text{-}20)_3$, did not demonstrate significant differences in the pulse velocity values compared to the $(AC\text{-}20)_0$ mix.

Density

Table 9 presents density values for the different compacted specimens at asphalt contents of 5.5, 6.0, and 6.5 percent. Analysis of variance indicated no significant difference between density values at the three asphalt contents. The density was determined by measuring the specimen weight and average specimen height. The limited accuracy of this method in determining density could be a factor in the lack of variation in density with change in asphalt content. In addition, the three asphalt contents (5.5, 6.0, and 6.5 percent) may be at or around the optimum content for maximum density, explaining the resulting insignificant differences. The statistical analysis also indicated a slight difference between density values of the virgin and two recycled mixtures. This difference might indicate better compactibility of recycled mixtures prepared using AE-150 and Mobilsol-30 as recycling agents.

TABLE 8 PULSE VELOCITY (× 1,000 ft/sec) AT 72°F FOR COMPACTED MIXTURES AT DIFFERENT ASPHALT CONTENTS

	Mixture Types				
%A.C.	$(AC\text{-}20)_0$	$(AC\text{-}20)_1$	$(AC\text{-}20)_2$	$(AC\text{-}20)_3$	Mean
	11.14	10.66	11.25	10.69	
5.5%	11.55	11.24	10.49	10.65	10.99
	11.16	10.99	11.10	11.00	
	11.09	10.86	10.71	11.19	
6.0%	11.27	11.23	10.63	11.28	11.04
	10.74	11.36	10.87	11.28	
	10.84	10.53	10.52	10.90	
6.5%	11.21	10.79	10.98	10.51	10.80
	11.19	11.11	10.37	10.62	
Mean	11.13	10.97	10.77	10.90	

TABLE 9 DENSITY (g/cm³) FOR COMPACTED MIXTURES OF DIFFERENT ASPHALT CONTENTS

	Mixture Types				
%A.C.	$(AC\text{-}20)_0$	$(AC\text{-}20)_1$	$(AC\text{-}20)_2$	$(AC\text{-}20)_3$	Mean
	2.33	2.35	2.39	2.40	
5.5%	2.39	2.37	2.39	2.41	2.38
	2.35	2.35	2.39	2.41	
	2.37	2.34	2.36	2.40	
6.0%	2.36	2.37	2.39	2.40	2.37
	2.35	2.34	2.37	2.39	
	2.36	2.32	2.36	2.40	
6.5%	2.37	2.38	2.38	2.40	2.37
	2.35	2.37	2.37	2.38	
Mean	2.36	2.36	2.38	2.40	

Note: (1) Density values were rounded to two decimal places.

(2) Statistical Analyses were based on non-rounded data.

Modulus of Elasticity

Table 10 presents the estimated modulus of elasticity values for the absolute virgin mixture $(AC\text{-}20)_0$ and the recycled mixtures $(AC\text{-}20)_1$, $(AC\text{-}20)_2$, and $(AC\text{-}20)_3$ at 5.5, 6.0, and 6.5 percent binder contents. The ANOVA suggests that the modulus of elasticity estimation by pulse velocity is neither sensitive to the binder type nor to the change in asphalt content. No significant differences were detected at $\alpha = 0.05$. However, recycled mixtures, especially those modified by AE-150, provided slightly lower modulus values than those of virgin mixtures. In addition, mixtures containing 6.5 percent binder content also provided slightly lower modulus values than those containing 5.5 and 6.0 percent.

Resilient Modulus Test

The diametral resilient modulus test was conducted on the same specimens tested by the nondestructive pulse velocity test. Table 11 presents the modulus values corresponding to 5.5, 6.0, and 6.5 percent binder contents and the various mixture types. The test was sensitive both to binder content and to binder type present in the virgin and recycled mixtures (unlike the pulse velocity test), and significant differences were detected. Asphalt content of 5.5 percent appears to be the optimum content for maximum modulus values. The increase in asphalt content from 5.5 to 6.0 percent resulted in a significant decrease in the modulus value. Resilient modulus values at 6.5 percent asphalt content were also slightly lower than those values at 6.0 percent, but significantly lower than the modulus values at 5.5 percent.

Virgin mixture $(AC\text{-}20)_0$ showed higher modulus values over recycled mixtures, as indicated in Table 11. Virgin mixture $(AC\text{-}20)_0$ provided the highest modulus values, followed by recycled mixture with Mobilsol-30 as rejuvenator; $(AC\text{-}20)_3$; and the recycled mixtures containing AC-2.5 and AE-150, with $(AC\text{-}20)_1$ and $(AC\text{-}20)_2$, respectively, as modifiers. $(AC\text{-}20)_2$ mixtures provided the lowest modulus values. The trend is identical to that obtained for pulse velocity and modulus of elasticity estimated from pulse velocity tests. However, the statistical significance was detected herein, whereas it was not detected from pulse velocity test results.

Marshall Stability Test

Specimens tested by the nondestructive pulse velocity and resilient modulus tests were loaded to failure by the Marshall loading mechanism, after placing them in an oven at 140°F for 2 hr.

Table 12 presents the Marshall stability values for virgin and recycled mixtures. Marshall stability values were sensitive to binder type in the various mixtures as well as the asphalt content, and significant differences were detected by ANOVA results. Virgin mixtures $(AC\text{-}20)_0$ provided the highest Marshall stability values, followed by RAP modified by Mobilsol-30, RAP modified by AC-2.5, and RAP modified by AE-150. Flow values, which were almost identical for all mixtures, ranged between 11.0 and 14.0 (in 0.01 in.).

DISCUSSION OF RESULTS

Some empirical values are presented that can give a general idea about the characteristics of asphalt paving mixtures. The usual judgment of a highway engineer is that for two asphaltic mixtures having Marshall stabilities of 700 and 2,000 lb to be

TABLE 10 MODULUS OF ELASTICITY ($\times 10^6$ psi) AT 72°F FOR COMPACTED MIXTURES AT DIFFERENT ASPHALT CONTENTS

	Mixture Types				
%A.C.	$(AC\text{-}20)_0$	$(AC\text{-}20)_1$	$(AC\text{-}20)_2$	$(AC\text{-}20)_3$	Mean
	2.421	2.234	2.531	2.302	
5.5%	2.672	2.505	2.205	2.290	2.408
	2.452	2.375	2.469	2.439	
	2.447	2.316	2.274	2.515	
6.0%	2.513	2.502	2.262	2.555	2.423
	2.268	2.532	2.346	2.546	
	2.326	2.159	2.191	2.387	
6.5%	2.499	2.318	2.404	2.224	2.317
	2.462	2.454	2.133	2.250	
Mean	2.451	2.377	2.313	2.390	

TABLE 11 DIAMETRAL RESILIENT MODULUS ($\times 10^6$) AT 72°F FOR COMPACTED MIXTURES AT DIFFERENT ASPHALT CONTENTS

	Mixture Types				
%A.C.	$(AC\text{-}20)_0$	$(AC\text{-}20)_1$	$(AC\text{-}20)_2$	$(AC\text{-}20)_3$	Mean
	0.755	0.653	0.675	0.671	
5.5%	0.936	0.648	0.706	0.697	0.717
	0.717	0.659	0.736	0.752	
	0.690	0.440	0.466	0.610	
6.0%	0.689	0.510	0.404	0.645	0.590
	0.738	0.596	0.556	0.739	
	0.726	0.434	0.353	0.635	
6.5%	0.615	0.594	0.462	0.466	0.543
	0.642	0.593	0.336	0.658	
Mean	0.723	0.570	0.522	0.653	

NOTES: Least significant difference between means, mixture type = 0.07 * 10^6 psi.
Least significant difference between means, %AC = 0.06 * 10^6 psi.
$\alpha = 0.05$.

TABLE 12 MARSHALL STABILITY AT 140°F FOR DIFFERENT COMPACTED MIXTURES

	Mixture Types				
%A.C.	$(AC\text{-}20)_0$	$(AC\text{-}20)_1$	$(AC\text{-}20)_2$	$(AC\text{-}20)_3$	Mean
	2450	2050	1850	2150	
5.5%	2500	2150	1900	2350	2138
	2550	1950	1750	2000	
	2250	1850	1700	1900	
6.0%	2200	1750	1600	1800	1929
	2300	1950	1750	2100	
	2000	1650	1500	1900	
6.5%	1950	1750	1550	1700	1721
	2050	1600	1400	1600	
Mean	2250	1856	1667	1944	

Notes:

*L.S.D., Mix Type = 91 pounds
*L.S.D., % AC = 79 pounds

used in pavement construction, the first is generally a poor mixture and the second is generally a good mixture. However, familiarity with other mechanical property values is not the same as for the better-known Marshall stability values. The following empirical values, the overall means of the various response variables obtained in this study, can give a rough idea about other mechanical property values. Asphalt mixtures with a Marshall stability value in the range of 1,400 to 2,550 lb and 1,930 lb average value, have roughly the following empirical values at ambient temperature (72°F):

- Pulse velocity through compacted specimens is in the range 10,500 to 11,500 ft/sec with an average value of 11,000 ft/sec. This value for structural concrete is roughly 15,000 ft/sec. Sonic pulse velocities are approximately 1,100 and 17,000 ft/sec in air and steel, respectively.
- Modulus of elasticity in the range 2.1 to 2.7 $\times$ 10^6 psi with an average of 2.4 $\times$ 10^6 psi.
- Resilient modulus in the range of 340 to 940 ksi with an average of 620 ksi.

The total variation from the mean was approximately ± 4.5 percent for pulse measurements, ± 12.5 percent for modulus of elasticity computations, ± 30 percent for Marshall stability measurements, and ± 47 percent for resilient modulus measurements. That the compacted specimens were identical in gradation and binder consistency characteristics implied that the resilient modulus test was the most sensitive to binder type (virgin or recycled). However, the sensitivity of the Marshall stability test was also good enough to identify mixtures with higher strength (stability).

Lower variation in sonic pulse velocity and modulus of elasticity values—estimated from pulse velocity measurement—suggest them as better candidates for pavement thickness design. Both measurements are closer to the elastic range of bituminous materials than is the resilient modulus and therefore they may be more appropriate for the application of elastic layered theory solutions for pavement thickness.

SUMMARY OF RESULTS

Three hot-recycled bituminous mixtures in the compacted state were characterized using the pulse velocity, resilient modulus, and Marshall stability tests. The recycled mixtures contained binders with the same consistency as AC-20 and the aggregate gradation of No. 12 surface. The three recycling agents used in the mixtures were AC-2.5, AE-150, and Mobilsol-30. Every recycled mixture contained old asphalt, salvage aggregate, virgin aggregate, and only one of these recycling agents. A virgin mixture containing virgin aggregate and virgin AC-20 was characterized by the same tests for comparative purposes. Binder contents in the mixtures were 5.5, 6.0, and 6.5 percent by total weight of the mix. The main findings are summarized as follows:

- Virgin mixture stiffness (resilient modulus) and strength values (Marshall stability) were in general higher than those of recycled mixtures.
- The stiffness and strength values of the recycled mixture with AE-150 as a rejuvenator were remarkably low. AE-150 may be a poor choice of rejuvenator for hot-mix recycling.
- Pulse velocity test parameters were neither sensitive to binder content nor to the binder type present in the mixtures. This result could be attributed to the similarity between all mixtures in the elastic range caused by the high rate of application of pulses.
- Resilient modulus test results were sensitive to both binder content and type. The test can be used for the design of asphalt mixture (virgin or recycled) and the evaluation of recycling agent used.
- The conventional Marshall stability test was appropriate enough to identify binders (virgin or recycled) with potential to produce mixtures with higher strength (stability).
- Low statistical variations obtained from pulse velocity and modulus of elasticity measurements may suggest their use for pavement thickness design on the basis of layered elastic theory solutions.

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