Evaluation and Characterization of a Rubber-Modified Hot Mix Asphalt Pavement

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The Intermodal Surface Transportation Efficiency Act of 1991 placed a minimum utilization requirement for recycled rubber in hot mix asphalt (HMA) on the state departments of transportation (DOTs). Each state DOT is required to use a minimum percentage of recycled rubber each year starting in FY 1994. As state DOTs gear toward incorporating recycled rubber materials, there is a need to evaluate the effect of the recycled rubber materials on the performance of asphalt pavement. In 1991 Mississippi placed a conventional HMA (control) along with a rubber-modified HMA (RMHMA) test section. Crumb rubber was incorporated into the pavement using a recent wet process technology known as the continuous process developed by Rouse Rubber Industries. This process blends the fine powdered crumb rubber, which passes a 236-μm (No. 80 sieve) screen and has a 75-μm (No. 200 sieve) mean particle size, with asphalt cement. The laboratory properties of the control HMA and the RMHMA were evaluated at various times for the first 2 years of the pavement's life. At the same time, the in-place performance of the two sections was also observed. The control HMA and RMHMA were subjected to a testing program that included tests to evaluate permanent deformation, indirect tensile strength, resilient modulus, gyratory properties, voids in total mix, and bulk densities. Laboratory test results indicated that the RMHMA mix has lower water susceptibility and higher tensile strength and resilient modulus. The gyratory properties and creep/permanent deformation tests indicate that the RMHMA mix should be more resistant to rutting. In-place performance was evaluated by visual observation of surface cracking and rut measurement for the first 2 years of the pavement's life. There was no cracking in either the control or the RMHMA test section. The amount of rutting was insignificant and was likely caused by densification of the mixes.

Recycling waste materials serves a much needed purpose of eliminating an expensive and environmentally unacceptable disposal problem for those products. One waste product showing promise in asphalt mixtures is processed rubber that has been retrieved from the recycling of waste passenger car and truck tires.

The environmental risks associated with land-filling tires and the possibility of incorporation of recycled rubber into asphalt pavements have brought about action at the state and national levels. By 1992, 44 states had drafted, introduced, or enacted laws or regulations to address the scrap tire problem (*1*). Section 1038 of the Intermodal Surface Transportation Efficiency Act of 1991 placed a minimum utilization requirement by stating the following:

> The minimum utilization requirement for asphalt pavement containing recycled rubber as a percentage of the total tons of asphalt laid in such State and financed in whole or part by any assistance pursuant to title 23, United States Code, shall be (*a*) 5 percent for the year 1994; (*b*) 10 percent for the year 1995; (*c*) 15 percent for the year 1996; and (*d*) 20 percent for the year 1997 and each year thereafter.

In June 1993 the Department of Transportation and the Environmental Protection Agency delivered to the Congress their report (*2*) containing guidelines on the use of rubber in hot mix asphalt (HMA). As state departments of transportation incorporate recycled rubber materials, there is a need to evaluate the laboratory properties and performance of rubber-modified HMA (RMHMA) mixes.

The primary objectives of this study were (*a*) to evaluate the properties of a control (conventional) HMA and an RMHMA immediately after construction and at various times during the first 2 years of the pavement's life and (*b*) to compare these laboratory properties with observed in-place performance.

In September 1991 a section of conventional HMA along with a section of RMHMA were placed on US-82 east of Columbus, Mississippi. At the time of construction, materials (aggregate, asphalt cement, and modified binder) were obtained for preparing laboratory specimens. Field cores were taken from the control and RMHMA pavement sections before opening to traffic and 3, 6, 9, 12, and 24 months after opening. Rutting was measured at each sampling interval. The laboratory specimens and field cores were tested to determine properties including permanent deformation, indirect tensile strength, resilient modulus, gyratory stability index (GSI), gyratory elastoplastic index (GEPI), gyratory shear (S_G), and physical properties such as voids in total mix and bulk densities.

The recycled rubber materials (CRM) were mixed with the asphalt cement using the continuous wet process developed by Rouse Rubber Industries. The CRM is finely powdered and passes a 236-μm (No. 80 sieve) screen and has a 75-μm (No. 200 sieve) mean particle size with a high surface morphology (pamphlets distributed by Rouse Rubber Industries, Inc., Vicksburg, Mississippi). Five percent of CRM by weight of asphalt cement was continuously blended with an AC-30 to produce the rubber-modified binder.

The rubber-modified binder may improve the binder and mix properties of the RMHMA mix, which should lead to better field performance. However, relationships between laboratory test results and field performance may not be accurate, especially for RMHMA, where little experience is available in correlating laboratory properties with field performance and there are many variables in the incorporation of the CRM into the asphalt.

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LITERATURE REVIEW

Binder Properties

When CRM is reacted with asphalt cement, a thick, elastic, viscous, and adhesive material called rubber-modified binder is formed. The elastic quality is caused by the mechanical action of the unreacted rubber particles performing as elastic aggregate (pamphlets distributed by Rouse Rubber Industries, Inc., Vicksburg, Mississippi). The absorbing of aromatic oil from the asphalt cement into the polymer chain of the CRM increases the viscosity of rubber-modified binder, resulting in lower penetration values and higher absolute and kinematic viscosity. The rubber-modified binder produced by the traditional McDonald process also has a higher softening point and lower temperature susceptibility (*3–7*). The swelling of the CRM (when aromatic oil is absorbed) increases the adhesive property of the rubber-modified binder. Bissada and Anani (*4*) studied the adhesion properties of a rubber-modified binder on one type of aggregate using the boiling test and adding a 12-hr dynamic immersion test to intensify the moisture effect. Visual examination of the percentage stripping of the coated aggregate particles indicated that aggregates coated with rubber-modified binder retained 80 percent of their coating. Aggregates coated with asphalt cement retained only 20 percent of their coating.

Mix Properties

Marshall Design Mix Properties

The optimum binder content for an RMHMA will generally be higher than that for a conventional HMA. This is because the rubber-modified binder is more viscous, the film coating on aggregate is thicker, and the rubber-modified binder contains some unreacted solid rubber particles, which increases the binder volume. The optimum binder content of an RMHMA mixture increases with the CRM/asphalt ratio in the binder. The increase is proportional to the amount of CRM in the binder. As the CRM/asphalt cement ratio increases in the binder, the bulk densities of mixture at optimum binder content increase to a maximum and then decrease (*4*).

In general, an RMHMA has a lower Marshall stability and a higher Marshall flow than a conventional HMA (*8,9*). The Marshall stability of RMHMA mix has been shown to decrease by as much as 60 percent and the Marshall flow of RMHMA mix has been shown to increase by as much as 4.2 times the control mix. The gradation of CRM used in the rubber-modified binder also has an influence on mix stability and flow. RMHMA modified with coarse rubber particles has lower stability and higher flow than RMHMA modified with fine rubber particles. A mix modified with a coarse rubber gradation has been shown to have 49 percent lower Marshall stability and 50 percent higher Marshall flow than a mix modified with fine rubber gradation (*8*).

Fatigue Resistance

On the basis of laboratory tests, the fatigue resistance of RMHMA is better than conventional HMA. Piggott and Woodhams (*9*) concluded that adding 5 percent CRM to HMA will probably increase the fatigue resistance of a pavement to twice that of a conventional asphalt mix. Vallerga et al. (*10*) studied the fatigue resistance of one type of rubber-modified binder (77 percent asphalt cement, 3 percent oil extender, and 20 percent rubber). Specimens were fabricated at different rubber-modified binder contents: ARC-Low (4.23 percent binder), ARC-Medium (4.73 percent binder), and ARC-High (5.23 percent binder). The control specimens had 4.8 percent asphalt content. These specimens were tested at temperatures ranging from 34°F to 104°F. The researchers found that the fatigue performance of RMHMA mixes was improved at higher rubber-modified binder contents. They compared the fatigue performance of RMHMA mixes with that of the control mix and found that, at temperatures less then 60°F, all RMHMA mixes except the mix with the lowest binder content (ARC-Low with 4.23 percent binder) performed better than the control mix. At temperatures greater than 60°F, all RMHMA mixes performed better than the control mix.

Resilient Modulus

Jimenez (*11*) showed that the resilient modulus of RMHMA mixes is about 75 percent of the control mixes. Vallerga et al. (*10*) showed that the resilient modulus of RMHMA mixes is lower than that of conventional mixes but only at low temperatures (below 75°F). At temperatures higher than 75°F, the resilient modulus of RMHMA mixes is higher than that of conventional mixes.

Vallerga et al. (*10*) found that RMHMA mixes with fine CRM have higher resilient modulus values than mixes modified with coarse CRM. RMHMA mixes with higher CRM content have lower resilient modulus values (*11–13*). For the 2 percent CRM content, the resilient modulus values increased as the CRM became finer, but for the 3 percent CRM content, the resilient modulus values reached maximum at the medium CRM content. This indicates that at a low CRM content, the fine CRM may have a more significant effect on the resilient modulus of the mixes.

Jimenez (*11*) studied the effect of adding an extra 2 percent fine CRM to three RMHMA mixes whose CRM contents were 2.5, 3, and 3.5 percent. The resilient modulus of all three RMHMA mixes were increased when an extra 2 percent fine CRM was added. The greatest improvement occurred at 3.5 percent CRM content, which showed an increase of about 60 percent.

Creep and Permanent Deformation

The work by Stephens (*12*) indicates that the RMHMA mixes investigated have lower static creep resistance than conventional asphalt mixes. This difference is more pronounced at higher test temperatures. Stephens also found that mixes with fine CRM gradation have better creep resistance than mixes with a coarse CRM gradation. However, test results from dynamic creep testing indicate that RMHMA mixes have higher resistance to permanent deformation than conventional HMA mixes (*10,12*). These studies showed that under constant load the RMHMA mix deforms more than the control mix, whereas under repeated load the RMHMA mix deforms less than the control mix.

TEST PLAN

A control HMA along with an RMHMA was placed on US-82 east of Columbus, Mississippi, in September 1991. This study was conducted to evaluate the properties of the control and RMHMA mixture during the first 2 years of traffic and compare those laboratory properties with observed in-place performance. The following test plan was established for this study.

Loose samples of materials used during the construction of the control HMA and RMHMA on US-82 east of Columbus, Mississippi, were obtained. A laboratory testing program was carried out to evaluate the materials (Figure 1).

Samples of the in-place pavement (cores) were taken at various times after construction: 0, 3, 6, 9, 12, and 24 months. The 9-month cores were taken to monitor the density of the control and RMHMA pavement sections. Only permanent deformation and gyratory recompaction testing was conducted on the 9-month cores. At the discretion of the sponsoring agency, only a limited number of 24-month cores (7 control cores and 13 RMHMA cores) were taken. Therefore, the gyratory recompaction test was not performed, and only a limited number of bulk density, indirect tensile, rice density, resilient modulus, and creep tests were conducted. In addition, the amount of rutting in the control and RMHMA pavement sections was measured at each time interval when field cores were taken.

TEST RESULTS OF LABORATORY-PREPARED SAMPLES

Mix Design Information

The mix designs for the control and the RMHMA pavement sections in Columbus, Mississippi, were performed by the Mississippi State Highway Department (MSHD). The control and RMHMA pavement sections have the same aggregate type and gradation (Table 1). Using the 4 percent air voids criteria, the optimum binder content of the control section (6.6 percent) would be higher than the optimum binder content (6.3 percent) of the RMHMA section. No reason was given for the higher optimum asphalt content for the RMHMA mix. However, MSHD indicated that both the control and RMHMA section were constructed at 6.3 percent binder content.

Loose samples of construction materials (aggregate, asphalt cement, and preblended rubber-modified binder) were obtained. The aggregate was batched according to the job mix formula (Table 1) to prepare 14 samples (7 control and 7 RMHMA samples). The

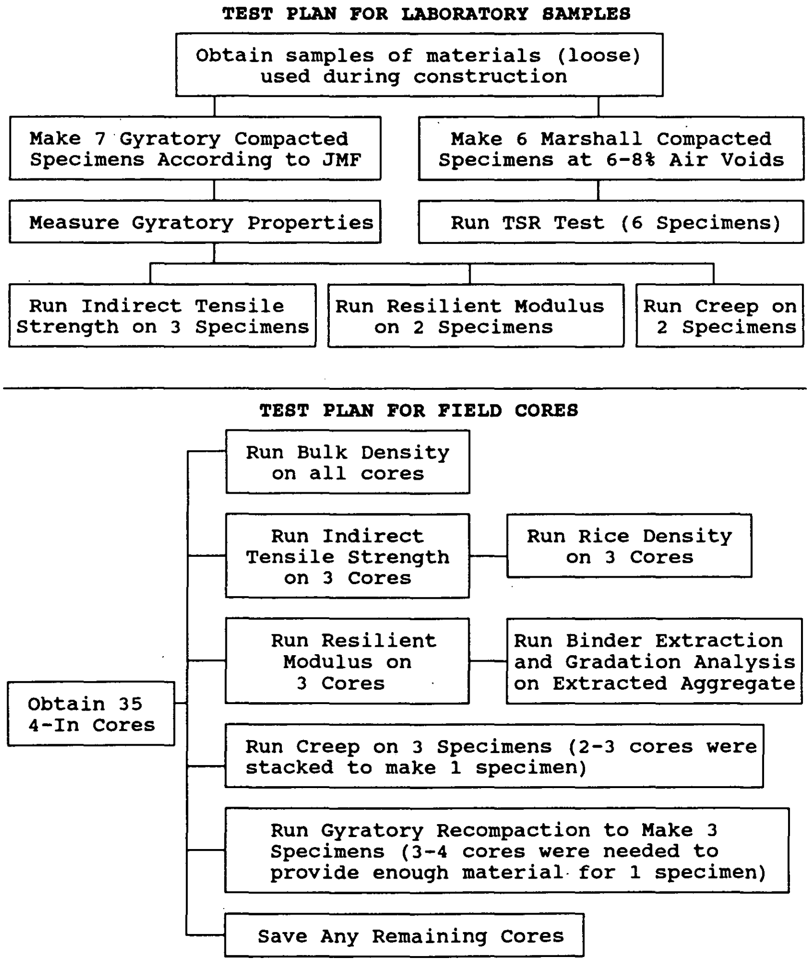

FIGURE 1 Test plan for laboratory and field (0-, 3-, 6-, 9-, 12-, and 24-month) cores.

asphalt cement and the preblended rubber-modified binder (obtained during construction) were mixed with the batched aggregate to fabricate the control and RMHMA samples, respectively. Both the control and RMHMA samples were prepared at 6.3 percent binder content because MSHD has reported that the control and RMHMA section were constructed at 6.3 percent binder content.

Gyratory Properties, VTM, and Bulk Density

The Corps of Engineers gyratory compactor, set at 1-degree angle, 120-psi normal pressure, and 300 revolutions, was used to compact the HMA specimens. The gyratory properties (S_G, GSI, and GEPI) were measured, and the compacted samples were tested for air voids and bulk density. S_G measures the shear stress required to produce a 1-degree angle during compaction. GSI is the ratio of maximum gyratory angle to the minimum gyratory angle. Asphalt mixtures with GSI values more than 1.1 have been shown to be susceptible to rutting in service, and mixtures with GSI values more than 1.3 have been shown to rut severely (*14,15*). GEPI is a reflection of the shear strain experienced by the specimen. It also reflects the internal friction in the specimen. The higher the internal friction, the lower the GEPI. The VTM and bulk density of samples compacted in the gyratory machine should reflect the in-place pavement air voids and density after traffic. HMA with voids in compacted samples below 3 percent tends to rut prematurely (*15*).

Table 2 gives the gyratory properties, VTM, and bulk density of the laboratory-fabricated samples. The gyratory properties of the control and RMHMA mix were similar. The GSI values for both mixes were less than 1.1, indicating a high probability that both mixes are not susceptible to rutting. However, the averaged laboratory compacted air voids of the control mix was 2.08 percent, whereas that of the RMHMA mix was 2.93 percent. The difference in the averaged air voids is statistically significant ($\alpha = 0.05$). According to Brown and Cross (*15*), the laboratory recompacted air voids indicated that the RMHMA mix should be more rut resistant than the control mix.

Indirect Tensile Strength and Resilient Modulus

Six of the 14 gyratory compacted samples (3 control and 3 RMHMA samples) were tested for indirect tensile strength. Table 3 shows that the RMHMA mix has a slightly higher tensile strength than the control mix, but the difference is not statistically significant ($\alpha = 0.05$).

Four of the gyratory compacted samples (two control and two RMHMA samples) were allocated for resilient modulus testing. The resilient modulus tests were not conducted for this series because of equipment problems. These four samples were kept and later tested for permanent deformation (not scheduled in the test plan).

Creep and Permanent Deformation

Four of the gyratory compacted samples (two control and two RMHMA samples) were tested for creep deformation. Creep samples were confined with 20-psi confining pressure and loaded with 120-psi total pressure for 1 hr and unloaded for 1 hr to measure creep deformation and rebound. The four samples allocated for resilient modulus test (not tested because of equipment problems) were tested for permanent deformation. The permanent deformation test results served to compare creep test results. In the permanent deformation test, samples were confined with 20-psi confining pressure and dynamically loaded with 120-psi total pressure. Dynamic loading was achieved with a cyclic rectangular

TABLE 1 Gradation Analysis of Extracted Aggregate

SIEVE SIZE	PERCENT PASSING					
	SPEC	JMF	CONTROL MIX (Averaged of two tests)		RMHMA MIX (Averaged of two tests)	
			0 Month	3 Month	0 Month	3 Month
3/4 "	100	100	100	100	100	100
1/2 "	100	100	100	99.9	99.6	99.9
3/8 "	87-100	94	91.8	94.7	92.4	94.4
No 4	53-80	61	59.7	64.2	63.2	64.4
No 8	32-63	43	40.9	43.6	42.5	42.8
No 16	-	-	30.3	31.8	31.4	31.2
No 30	12-33	22	23.3	24.6	23.7	23.1
No 50	6-20	12	15.3	14.3	13.7	12.4
No 100	-	-	8.0	7.6	7.1	5.8
No 200	2-10	4.8	6.5	5.9	4.7	3.3

Note: Gradation analysis was not conducted at 6, 9, 12, and 24 months because these tests would not yield extra information

TABLE 2 Gyratory Properties of Laboratory Specimens

	CONTROL MIX					RMHMA MIX				
	S_G (PSI)	GSI	GEPI	VTM (%)	$\gamma_b^{\#}$ (PCF)	S_G (PSI)	GSI	GEPI	VTM (%)	$\gamma_b^{\#\#}$ (PCF)
1	36.02	1.00	1.20	2.45	141.7	37.07	1.00	1.20	3.45	141.7
2	34.91	1.04	1.20	1.33	143.7	30.79	1.04	1.20	3.10	142.2
3	35.67	1.00	1.20	1.85	142.5	36.68	1.04	1.20	2.64	142.8
4	30.00	1.04	1.15	2.24	142.0	31.79	0.96	1.20	3.53	141.5
5	32.68	1.04	1.15	2.41	141.7	30.38	1.08	1.20	2.55	143.0
6	34.86	1.04	1.20	1.25	143.4	30.64*	1.50*	0.80*	0.02*	146.0*
7	31.80	1.00	1.10	3.05	141.0	35.38	1.08	1.20	2.30	143.3
AVE	33.71	1.02	1.17	2.08	142.2	33.68	1.03	1.20	2.93	142.4

*** - data was discarded because it is inconsistent, probably had error in batching materials**
 # - Maximum theoretical density (Control) = 145.22 pcf
- Maximum theoretical density (RMHMA) = 142.70 pcf

Statistical Test (F Test)

H_0	Mean Control voids = Mean RMHMA voids
F value for H_0	6.68
Pr > F	0.0254
Conclusion	Reject H_0: The two means are different at $\alpha = 0.05$

TABLE 3 Indirect Tensile Strength of Laboratory Samples

SAMPLE	INDIRECT TENSILE STRENGTH (PSI)	
	CONTROL MIX	RMHMA MIX
1	191.0	187.8
2	188.4	198.9
3	178.9	205.3
AVERAGE	186.1	197.4

Statistical Test (F Test)

H_0	Mean Control tensile strength = Mean RMHMA tensile strength
F value for H_0	3.18
Pr > F	0.149
Conclusion	Accept H_0: The two means are equal at $\alpha = 0.05$

load pulse. The loading period was 0.1 sec with a rest period of 0.9 sec. Permanent deformation samples were tested for 1 hr, and no rebound was measured since experience has shown that samples do not rebound in this test.

Like gyratory properties, creep and permanent deformation are believed to provide insight into the rut resistance of HMA mixes (*16,17*). Table 4 indicates that the averaged creep strain of the RMHMA mix (0.0067 in./in.) is higher than that of the control mix (0.0036 in./in.) and averaged permanent deformation of the RMHMA mix (0.0405 in./in.) is also higher than that of the control mix (0.0216). Although these differences appear numerically large, they are statistically insignificant ($\alpha = 0.05$) because of the small sample size ($n = 2$).

Tensile Strength Ratio

Six control and six RMHMA samples were prepared in the laboratory at approximately 7 percent voids total mix. Since there was no more preblended rubber-modified binder (obtained during construction) to prepare the six RMHMA samples, a decision was made to blend the rubber-modified binder in the laboratory. The CRM and asphalt cement were obtained from MSHD. Five percent of CRM (by weight) was added to the asphalt cement (heated in an oven to 310°F). The CRM-asphalt cement blend was kept in the oven maintained at 310°F for 45 min and stirred every 10 min.

The samples were compacted using a Marshall hammer. These samples were then conditioned using the Root-Tunnicliff procedure. Table 5 indicates that the RMHMA mix had a higher strength than the control mix before conditioning, and the difference is statistically significant ($\alpha = 0.05$). The tensile strength of the control and RMHMA mix after conditioning does not show any statistical difference ($\alpha = 0.05$). Table 5 also indicates that the RMHMA has a tensile strength ratio of 0.50 versus 0.38 for the control.

Pavement Density, Air Voids, and Rut Depth Measurements

Theoretical maximum density and bulk density tests were performed on the field cores. Average initial density for both the control and RMHMA pavement sections was approximately 90

TABLE 4 Creep and Permanent Deformation of Laboratory Samples

MIX DESCRIPTION	CREEP (IN/IN)		PERMANENT DEFORMATION (IN/IN)	
CONTROL MIX	TEST 1	0.0016	TEST 1	0.0140
	TEST 2	0.0055	TEST 2	0.0292
	AVERAGE	0.0036	AVERAGE	0.0216
RMHMA MIX	TEST 1	0.0056	TEST 1	0.0359
	TEST 2	0.0078	TEST 2	0.0450
	AVERAGE	0.0067	AVERAGE	0.0405

Statistical Test (F Test)

H_0	Mean Control creep = Mean RMHMA creep
F value for H_0	1.98
Pr > F	0.2947
Conclusion	Accept H_0: The two means are equal at $\alpha = 0.05$

Statistical Test (F Test)

H_0	Mean Control permanent deformation = Mean RMHMA permanent deformation
F value for H_0	4.53
Pr > F	0.1671
Conclusion	Accept H_0: The two means are equal at $\alpha = 0.05$

percent of maximum density (10 percent air voids) with a standard deviation of about 1.5. Table 6 gives the rut depth measurements made during the sampling of field cores and the core air voids at each sampling interval. It can be seen that the control mix is densifying faster than the rubber-modified mix and has therefore resulted in a little more "rutting" (densification). Neither of these mixes was rutting significantly after 2 years.

Extraction and Gradation

Bitumen extraction (ASTM D2172, Method A) and gradation analysis (ASTM C117 and ASTM C136) were performed on the 0- and 3-month cores only. Extraction and gradation analysis on the 6-, 9-, 12-, and 24-month cores were not conducted since these tests would not yield extra information. The average extracted binder contents for the control pavement was 5.9 percent (5.8 percent for 0-month cores and 6.0 percent for 3-month cores). The extracted asphalt content was lower than the targeted asphalt content (6.6 percent) by 0.7 percent. An increase in theoretical maximum density over time can be explained by asphalt absorption. An examination of the theoretical maximum density indicated that it remains relatively constant with time (2.352 at 0 months, 2.353 at 3 months, 2.352 at 6 months, and 2.361 at 12 months). The discrepancy between the targeted and extracted binder content was not pursued in this study because of the apparent inability to determine the binder content of the RMHMA section and, therefore, to compare the two sections. The average extracted binder content for the RMHMA pavement was 5.6 percent (5.7 percent for 0-month cores and 5.3 percent for 3-month cores). The extracted binder content was lower than the targeted binder content (6.3 percent) by 0.8 percent. The actual binder content was greater than 5.6 percent because rubber-modified binder contains solid rubber particles that are insoluble in trichloroethane. This is confirmed by visual observations of the extraction process indicating that rubber particles were contained in the aggregate mass after completion of the extraction process.

Table 1 gives the extracted aggregate gradations for the control and RMHMA pavement sections. The extracted aggregate gradations of both the control and CRM pavement sections are in close agreement with the JMF gradation.

Indirect Tensile Strength and Resilient Modulus

Table 7 gives the averaged tensile strength values of the control and RMHMA mixes. There is no significant difference between

TABLE 5 Water Susceptibility of Laboratory Compacted Samples (Measured by Tensile Strength)

SAMPLE	CONTROL MIX		RMHMA MIX LAB BLENDED BINDER	
	CONDITIONED SAMPLES (LBS)	UNCONDITIONED SAMPLES (LBS)	CONDITIONED SAMPLES (LBS)	UNCONDITIONED SAMPLES (LBS)
1	750	1950	700	2075
2	660	1875	1000	1975
3	740	1875	1425	2175
AVERAGE	717	1900	1042	2075
	TSR = 0.38		TSR = 0.50	

Statistical Test (F Test)

H_0	UNCONDITIONED Mean Control tensile strength = Mean RMHMA tensile strength
F value for H_0	7.74
Pr > |T|	0.0497
Conclusion	Reject H_0: The two means are different at $\alpha = 0.05$

Statistical Test (F Test)

H_0	CONDITIONED Mean Control tensile strength = Mean RMHMA tensile strength
F value for H_0	2.34
Pr > F	0.2005
Conclusion	Accept H_0: The two means are equal at $\alpha = 0.05$

TABLE 6 In-Place Air Voids and Rut Depth Measurements

TIME	CONTROL PAVEMENT SECTION		RMHMA PAVEMENT SECTION	
	VTM	RUT DEPTH (in)	VTM	RUT DEPTH (in)
0 MONTHS	10.3 %	0	9.6 %	0
3 MONTHS	9.0 %	0	8.0 %	0
6 MONTHS	6.5 %	0.128	7.9 %	0.080
9 MONTHS	6.5 %	0.133	8.0 %	0.084
12 MONTHS	6.2 %	0.142	8.0 %	0.084
24 MONTHS	6.3 %	0.136	8.3 %	0.086

TABLE 7 Indirect Tensile Strength and Resilient Modulus of Field Cores

TIME	CONTROL MIX				RMHMA MIX			
	Tensile Strength (psi)	M_r @ 40°F (ksi)	M_r @ 77°F (ksi)	M_r @ 104°F (ksi)	Tensile Strength (psi)	M_r @ 40°F (ksi)	M_r @ 77°F (ksi)	M_r @ 104°F (ksi)
0 MONTH	148.6	1125	243	94	196.5	1268	421	165
3 MONTH	153.9	1145	395	160	134.6	1394	553	252
6 MONTH	145.3	1792	891	*	162.3	2170	1086	*
12 MONTH	101.2	1327	461	161	114.5	1350	550	158.3
24 MONTH	185.3	1814	693	188	152.5	1781	860	275

Note: 9 month cores were not tested (see test plan) and * indicates sample failed during testing

the two mixes. No general trend between tensile strength and time can be established for either of the mixes. However, the tensile strength at 12 months appears to be significantly lower than the other time intervals. The reason is not known. This decrease was not observed in the resilient modulus test. Table 7 also indicates that the control mix has lower resilient modulus than the RMHMA mix. The 6-month test results were suspect and were discarded because test specimens should not be damaged during testing. Resilient modulus measured at 40°F, 77°F, and 104°F increased with time. This increase appeared to be similar for both the control and RMHMA mixes. The resilient modulus (measured at 40°F) of the control and RMHMA mixes are not significantly different. Resilient modulus (measured at 77°F and 104°F) of the control mix is significantly lower than that of the RMHMA mix. Temperature susceptibility (rate of change in M_r with temperature) for both control and RMHMA mixes were similar.

Creep and Permanent Deformation

Initially, creep tests were performed on the 0- and 3-month cores. After the 0- and 3-month tests, experience from other projects had shown that the permanent deformation test was preferred. As a result, creep tests were replaced by permanent deformation tests on and after the 3-month cores. Creep results and permanent deformation results are given in Table 8.

At 0 months, the creep deformation of the control mix is significantly greater than that of the RMHMA mix. There is no difference in creep deformation between the control and RMHMA at 3 months. Table 8 indicates that the permanent deformation of the control mix is significantly higher than that of the RMHMA mix. The permanent deformation of both the control and RMHMA mixes remains relatively constant with time. The creep and permanent deformation tests indicate that the control mix is more likely to have more rutting than the RMHMA mix.

Gyratory Recompaction

Field cores were recompacted, and the gyratory properties are given in Table 9. The S_G and GEPI values for the control mix were lower than those of the RMHMA mix at each time interval. At each time interval, the GSI values for the control mix were higher than those for the RMHMA mix. The recompacted air voids for the control mix were lower than those for the RMHMA mix. These data suggest that the RMHMA mix is more resistant to rutting than the control mix.

At 0, 3, and 12 months, the GSI values for the control mix were greater than 1.1, and the recompacted air voids were signif-

TABLE 8 Creep and Permanent Deformation of Field Cores

TIME IN MONTHS	CONTROL MIX		RMHMA MIX	
	CREEP (IN/IN)	P. DEFORMATION (IN/IN)	CREEP (IN/IN)	P.DEFORMATION (IN/IN)
0	0.0249	-	0.0110	-
3	0.0110	0.04925	0.0123	0.02995
6	-	0.04075	-	0.02824
9	-	0.03776	-	0.03128
12	-	0.03776	-	0.03128
24	-	0.04055	-	0.02731

TABLE 9 Gyratory Properties for Recompacted Field Cores

TIME IN MONTHS	CONTROL MIX					RMHMA MIX				
	S_G (PSI)	GSI	GEPI	VTM (%)	γ_b (PCF)	S_G (PSI)	GSI	GEPI	VTM (%)	γ_b (PCF)
0	22.5	1.18	1.12	2.17	143.6	28.8	1.00	1.13	3.36	142.4
3	24.9	1.31	1.20	1.64	144.7	33.4	1.09	1.13	3.21	143.0
6	27.3	1.05	1.20	2.91	142.5	34.0	1.00	1.13	5.63	139.5
9	36.6	1.03	1.13	3.77	141.4	36.5	1.03	1.10	6.03	138.8
12	25.9	1.17	1.20	1.95	143.9	32.2	1.00	1.13	5.28	140.5

Note: Gyratory properties at 24 months were not measured due to insufficient cores

icantly lower than 3 percent. These values indicate that the control mix is rut susceptible. However, the data for 6 and 9 months do not show this. The GSI values (less than 1.1) and the recompacted air voids (greater than 3 percent) for the RMHMA mix at all time intervals suggest that the RMHMA mix is not susceptible to rutting.

CONCLUSIONS

The following conclusions are obtained on the basis of the reported test results:

1. Tests on laboratory-prepared specimens indicated that the RMHMA mix has lower water susceptibility (tensile strength ratio) than the control mix.
2. The indirect tensile strength test on both laboratory samples and field cores indicated that the control and RMHMA mixes have comparable tensile strength.
3. The RMHMA field cores did not show the expected improvement in the M_r temperature susceptibility. The slopes of the M_r temperature curves for both control and RMHMA field cores were about the same. However, the curve for the RMHMA field cores was higher than (above) the control field cores. The resilient modulus of both control and RMHMA mixes increases with time.
4. In the permanent deformation test of field cores, the control mix deformed more than the RMHMA mix. Permanent deformation tests on laboratory-prepared samples indicate that there is no difference between the RMHMA and control samples, statistically.
5. The recompacted voids of the laboratory-prepared specimens suggested that the RMHMA mix is less likely to rut than the RMHMA mix. The gyratory properties of the recompacted RMHMA field cores at each sampling interval are consistently better than the control field cores. On the basis of these test results, the RMHMA mix evaluated appears to be more resistant to rutting than the control mix.
6. After 24 months of traffic, the amount of rutting in both sections is insignificant. The measured amount of rutting in the control and RMHMA pavement sections was likely due to densification of the mixes.

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