Mechanistic Evaluation of Asphalt Concrete Mixtures Containing Reclaimed Roofing Materials

N. ALI, JOSEPH S. S. CHAN, ALEX J. POTYONDY, ROBERT BUSHMAN, AND A. T. BERGAN

Recycling of waste construction materials has gained popularity owing to increasing demands on landfill sites. This is evident by the use of ground rubber tire, glass, fly ash, and slag in asphalt pavements by various highway agencies in North America and around the world. Waste roofing materials also pose a heavy burden on landfill sites. Using reclaimed roofing materials (RRM) in hot mix asphalt (HMA) concrete pavements can lessen the demand on landfills. A study was carried out to determine the feasibility of using RRM in HMA pavement. This paper presents the results of a mechanistic evaluation of three asphalt concrete mixes containing 0, 15, and 25 percent of RRM. By using laboratory prepared specimens of RRM mixes, mechanical properties such as resilient modulus, creep and permanent deformation, fatigue, and moisture sensitivity of these RRM mixes were determined. Performance of representative RRM pavements were modeled using the VESYS performance prediction model. Performance parameters, such as rut depths, cracking index, and the present serviceability index, were used to assess potential improvements of asphalt concrete mixes using RRM. The results indicated that the mix containing 25 percent of RRM exhibited significant improvements in greater pavement rutting resistance, longer fatigue life, and better overall pavement performance compared with a conventional asphalt mix.

Recycling has become increasingly popular due to a heightened awareness of the environmental impact of waste disposal. The disposal of waste roofing material is problematic because of its high asphalt content. Roofing material does not break down naturally; the degree of disintegration is insignificant even over long periods of time. The needs for new housing and replacement of aged asphalt roofing increase as society grows. The amount of waste roofing material produced will increase annually. Currently, it is estimated that the United States produces 12 million tons of waste asphalt roofing material each year. In Canada, more than 100,000 tons of waste roofing material is deposited into landfills annually.

Many landfills have imposed a fee for asphalt roofing waste or have banned it altogether. An alternative for disposing of waste asphalt roofing is needed. The high asphalt content and crushed stone aggregates in RRM suggest that it would be compatible with HMA. Studies have shown that it is feasible to recycle waste roofing materials in HMA pavements (*1–3*). In practice, however, the use of RRM in HMA pavements has been limited to test sections and laboratory evaluation and has yet to be used in large-scale production.

N. Ali, Department of Civil Engineering, Technical University of Nova Scotia, P.O. Box 1000, Halifax, Nova Scotia, Canada, B3J 2X4. J.S.S. Chan and R. Bushman, Transportation Centre, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, S7N 0W0. A.T. Bergan and A. J. Potyondy, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, S7N 0W0.

The objectives of this paper are

- To provide an overview of the availability and feasibility of using common residential and commercial RRM in HMA;
- To present the results of a mechanistic evaluation of three different asphalt concrete mixes containing 0, 15, and 25 percent of RRM, respectively;
- To evaluate potential improvements in mechanical properties of asphalt concrete mixes with the use of RRM; and
- To evaluate the effect of RRM to mitigate pavement distress and improve pavement performance.

BACKGROUND

Although a relatively new concept, recycling waste roofing materials for use in asphalt paving is a growing and promising practice. One roofing material recycler used the motto "Recycling your roof to repair your road" (*4*). A number of highway authorities have made extensive use of cold patch compounds containing RRM to repair potholes. These hybrid compounds, compared to conventional cold patch compounds, can be applied more quickly and easily, are less expensive, and stay in place longer (*4*).

The properties of the various components in RRM make it a satisfactory substitute for many commercial additives presently used in HMA. Table 1 lists components commonly found in recycled roofing asphalt and their commercial equivalents. Significant economic savings can be achieved if a single additive composed primarily of RRM replaces the numerous and more costly additives currently used.

IKO Industries Ltd., in conjunction with the City of Brampton, and DBA Engineering Ltd. of Markham, Ontario, initiated a test project in 1994 which uses waste roofing materials in HMA pavements.

ReACT's HMA™, a commercially available recycled roofing material, is produced by ReClaim Inc. of Tampa, Florida. Currently, this is the only commercially available RRM material on the market which is specifically produced for use in HMA pavements. Grzybowski, et al. (*1*) found that up to 50 percent net asphalt savings could be achieved by using ReACT's HMA™ as an additive in HMA pavements. They also recorded improvements in terms of high temperature susceptibility and rutting resistance.

Paulsen, et al. (*2*) carried out laboratory testing to determine the feasibility of incorporating waste roofing materials in HMA pavements. The scope of their work included carrying out material com-

TABLE 1 Composition of Roofing Asphalt Recycled

Component	Commercial/Functional Equivalent
Fibres	Minerals, Cellulose in SMA's, Polypropylene
Fillers	Carbon Black, Limestone, Hydrated, Lime, Diatomaceous Earth
Hard Asphalt	Gilsonite, Trinidad Lake Asphalt, Propane Precipitated Asphalts

* after (1)

position analysis of waste roofing materials and determining an optimum quantity that can be added to a hot mix design. Their results indicated that up to 20 percent of recycled roofing material by volume (10 to 12 percent by weight) could be added to HMA while still providing adequate performance properties. They also noted that current methods of extracting asphalt from recycled roofing materials produced unsatisfactory binder samples with inconsistent penetration and viscosity. They further suggested that the properties of shingle asphalt and the gradation of shingle aggregates should be considered when formulating HMA with RRM.

Newcomb, et al. (*3*) examined the use of roofing shingles in densely graded and stone mastic asphalt (SMA) mixes. They found that up to 7.5 percent of asphalt roofing waste can be incorporated in densely graded mixes, and up to 10 percent can be added to SMA mixes. They also found that the addition of roofing materials lowers the resilient modulus at low as well as at high temperatures and that, in general, the roofing waste mixtures exhibited less temperature susceptibility. The resilient modulus of SMA mixes tended to remain relatively constant despite variations in the amount of waste roofing incorporated. However, the tensile strength of SMA mixes examined were 10 percent lower than those of the control mix.

MATERIALS

Common RRM discarded by contractors at residential sites was used in this research project. Table 2 shows compositions for both residential and commercial RRM. The commercial RRM sample acquired contained numerous layers of felt, tar paper, organic fibre, wood pieces, nail, and metal flashing not found in residential RRM. The presence of a number of foreign materials in commercial RRM would make it difficult to maintain uniform composition in shredded commercial RRM. Furthermore, commercial RRM only constitutes up to 10 percent of total roofing waste deposited in landfills. Therefore, commercial RRM was not included in this study.

Abson Recovery Method (ASTM 2172) was used to extract asphalt cement from samples of RRM. A discussion of methods for extraction and separation of asphalt cement can be found in ASTM D1856. Table 3 shows physical properties of recovered asphalt cement from both commercial and residential RRM.

The viscosity of both residential and commercial RRM asphalt was much higher than that of a typical paving grade asphalt. This is due to the oxidation of RRM during the service life of roofing mate-

TABLE 2 Composition of Reclaimed Roofing Materials

Composition Breakdown (% by wt.)	Residential	Commercial
Asphalt Shingles	96	89
Metal Flashing	0.14	2.5
Nails	0.5	3.4
Plastic Strips	0.06	0.35
Felt Underlayment	3.3	4.75
Total	**100**	**100**

TABLE 3 Physical Properties of Recovered Asphalt Cement

	Commercial RRM	Residential RRM
Asphalt Cement Content (%)	83.9*	38.7*
Pene. at 25°C in 0.1 mm (ASTM D-5)	15.0	17.0
Kinematic Viscosity at 135°C in Cst. (ASTM D-2170)	28,200	54,000
Specific Gravity (ASTM D-3124)	1.032	1.000

* Following the removal of debris.

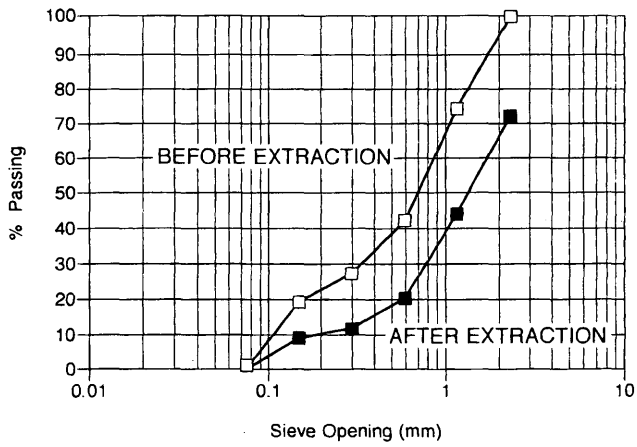

FIGURE 1 Typical grading curves of roofing waste before and after extraction.

rials. A comparison of asphalt cements extracted from residential and commercial RRM showed that while penetration values were comparable, the viscosity of residential RRM asphalt cement was almost twice that of commercial RRM asphalt cement. The high viscosity of asphalt cement from residential RRM compared to that of commercial RRM is likely due to the thick and dense consistency of commercial roofing materials. Figure 1 shows the gradation of RRM before and after the extraction process. Extraction of asphalt cement reduced the top size particles by approximately one sieve size. This is consistent with findings of Paulsen, et al. (2).

Materials used in the preparation of laboratory specimens were

- Crushed aggregates meeting the Nova Scotia Department of Transportation and Communication (NSDOT&C) standards for Type C aggregate. Aggregates were obtained from a quarry located in Bedford, Nova Scotia. Table 4 lists physical properties of aggregates used.
- ASTM designated 200 to 300 penetration grade asphalt cement supplied by the ESSO refinery in Dartmouth, Nova Scotia.
- Shredded residential RRM as described in previous sections.

MIX DESIGN

RRM Shredding

It was found that the best way to add RRM to HMA was in the form of a fine aggregate. Raw RRM must be shredded by some means. The most successful method for shredding RRM in the laboratory involved freezing raw RRM to approximately −10°C and then shredding it with a 10-in. circular carbide tipped blade on a chop saw. The particles produced passed No. 4 sieve size. Other methods tried, including a commercial tire shredder, produced enough heat to melt the asphalt cement in the RRM, resulting in "gumming up" the shredder, and producing a poor quality RRM additive.

Preliminary Investigation

In a preliminary investigation, the Marshall Method of Mix Design and the guidelines set forth by NSDOT&C for a Type C mix were used. The purpose of this phase of investigation was to establish satisfactory procedures for adding RRM to an HMA and to identify potential problems that may arise and affect the quality of Marshall briquette specimens. Further, percentages of RRM that can be added to the HMA had to be predetermined to avoid the needless testing of unlikely ratios.

TABLE 4 Physical Properties of Aggregates

Size Fraction	Bulk S. G.	Apparent S.G.	% Absorption
Coarse Aggregate (ASTM C127)	2.549	2.616	1.41
Fine Aggregate (ASTM C128)	2.579	2.660	1.21
Filler (ASTM D854)		2.651	
RRM (ASTM C128)		2.10	

Sieve Size	% Passing			Specification
	Mix A	Mix B	Mix C	
20.0 mm	100	100	100	100
14.0 mm	95	96	95	95-100
4.75 mm	50	47	55	45-70
2.36 mm	30	26	29	25-55
300 μm	13	12	13	5-20
75 μm	5	2	5	2-9

TABLE 5 Marshall Mix Criteria

	Mix Designations		
	A	**B**	**C**
% of RRM	25%	15%	0
(%) Opt. Asphalt Content	1.85	3.4	5.25
Bulk Specific Gravity	2.350	2.340	2.410
Max. Theo. Specific Gravity	2.420	2.440	2.490
(%) Void	3.25	3.95	3.5
Stability, kN	18	14	9.3
Flow, 0.25 mm	8.5	10.0	8.0
VMA (%)	14.0	14.0	15.0

Preliminary investigation showed that the addition of cold RRM to virgin aggregates followed by mixing and heating was not feasible. If heating was done after the addition of RRM, asphalt cement in the RRM would separate and bond the entire mix together. Once bonded, mixing was difficult.

The only satisfactory results achieved were accomplished by heating the virgin aggregates alone to the maximum allowed temperature (150°C) and then adding the RRM. When room temperature RRM was added to hot aggregates, the mixture could be blended thoroughly since the RRM did not have time to melt and consequently form clumps in the aggregate. Once the RRM was added to the aggregates, virgin asphalt cement could then be added.

During the preliminary investigation, neither the requisite amount of virgin asphalt cement nor the contribution made by the RRM was known. Consequently, virgin asphalt cement was added until a coating and mix consistency resembling that of the control mix, at optimum asphalt cement content, was achieved. A more accurate optimum virgin asphalt cement content was determined from a series of HMA test mixes containing varying percentages of RRM.

RRM was added at increments of 5 percent and ranged from 5 percent to 50 percent by weight of HMA mixes. The addition of 5 percent and 10 percent of RRM had little effect, in terms of Marshall flow and stability, on HMA briquettes produced. At more than 25 percent of RRM, briquettes produced were unsatisfactory and crumbled easily. Not surprisingly then, stability and flow values from these samples were unacceptable.

These results suggested that the optimum amount of RRM to be added ranged from 15 percent to 25 percent. Potentially, the addition of less than 15 percent RRM could produce satisfactory results, but because the addition of 10 percent or less of RRM had limited effects, the minimum RRM content was fixed at 15 percent.

Mix Design

Three mixes were prepared for engineering evaluation and performance analysis:

- Mix A: 25 percent RRM;
- Mix B: 15 percent RRM; and
- Mix C: Control mix (0 percent RRM).

Room temperature RRM was added to and mixed with aggregates, which were preheated to approximately 150°C. Virgin asphalt cement was then added to the mix and again blended thoroughly. Although the mixing time was increased, special attention was given to the mix temperature to prevent burning of the binder in the RRM. The hot mix was then compacted following the 75-blow Marshall procedure. Table 5 shows the Marshall mix parameters for the three mixes prepared. All three mixes satisfy the Marshall mix design criteria and the virgin asphalt cement content has been reduced from 5.25 percent for Mix C (control mix) to

TABLE 6 Resilient Modulus MPa (Ksi)

	Temperature					
	0°C		**20°C**		**40°C**	
	F1	**F2**	**F1**	**F2**	**F1**	**F2**
Mix A	18550	14800	7270	5400	3150	2350
Mix B	13400	11600	6350	3400	1200	780
Mix C	14700	12650	2300	1400	300	220

F1 = 1 Hz; F2 = 0.33 Hz

1.870 percent for Mix A (25 percent RRM), a reduction of almost 3 percent.

LABORATORY TESTING AND RESULTS

Resilient Modulus

The diametral resilient modulus (M_r) test method detailed in ASTM D4123 was used in this study. Repeated haversine loading was used in all resilient modulus testing to avoid impact loading to specimens. Three levels of temperature, 0°C, 20°C, and 40°C, and two load frequencies, 1 Hz (0.1 sec loading and 0.9 sec unloading) and 0.33 Hz (0.25 sec loading and 2.75 sec unloading) were used. Results of resilient modulus testing are summarized in Table 6.

Resilient modulus has a well-defined negative correlation with test temperature. M_r decreased from about 18,000 MPa at 0°C to about 3,000 MPa at 40°C for Mix A and from about 15,000 MPa to about 300 MPa for Mix C. The results indicate that the addition of RRM in mixes increased the stiffness of mixes. This is consistent with findings of previous research conducted on HMA mixtures, which indicated that M_r reflected the stiffness of the binder used.

Results in Table 6 also show that the addition of RRM improves M_r characteristics of a conventional mix, especially at an elevated temperature (40°C). M_r of 25-percent RRM mix (Mix A) was about 10 times that of the conventional mix (Mix C). It was evident that rutting resistance could be improved by the addition of RRM. On the other hand, at a low temperature (0°C) the M_r value of the 25-percent RRM mix was about 1.5 times that of the conventional mix. Therefore, low temperature cracking potential should not be adversely affected by the addition of RRM.

Creep and Permanent Deformation

Indirect tensile loading was used to determine the effect of RRM on the viscoelastic behavior of paving mixtures. This behavior is usually measured by the creep and the permanent deformation parameters. Creep and permanent deformation tests were conducted in accordance with procedures outlined in the VESYS manual (*5*). The objective of this test series was to obtain modeling parameters that would be used to predict the rutting performance of a pavement.

Specimens were tested under a constant stress of 20 psi at 0°C, 20°C, and 40°C. The permanent deformation characteristics of the three mixes are in Figure 2. As expected, permanent deformation increased exponentially to loading times in all temperatures ranges. Figure 2 also shows that the 25-percent RRM mix exhibited the lowest permanent deformation at all test temperatures owing to the stiffening effects of RRM. This inferred that the 25-percent RRM mix (Mix A) had the least rutting potential. The conventional mix, Mix C, did not survive testing at 40°C. Test results were used to calculate the permanent deformation modeling parameters, ALPHA and GNU, for the VESYS structural subsystem to evaluate rutting potential of representative pavement structures.

Data from the 1,000-sec loading creep test were used to generate creep characteristic curves (Figure 3). As expected, the creep moduli decreased with increased loading time and/or temperature. The results in Figure 3 indicated that the addition of RRM to the mixes increased the creep modulus values. Creep modulus values increased as RRM content increased. Results also showed that Mix A had the highest creep modulus values. This was consistent with permanent deformation test results.

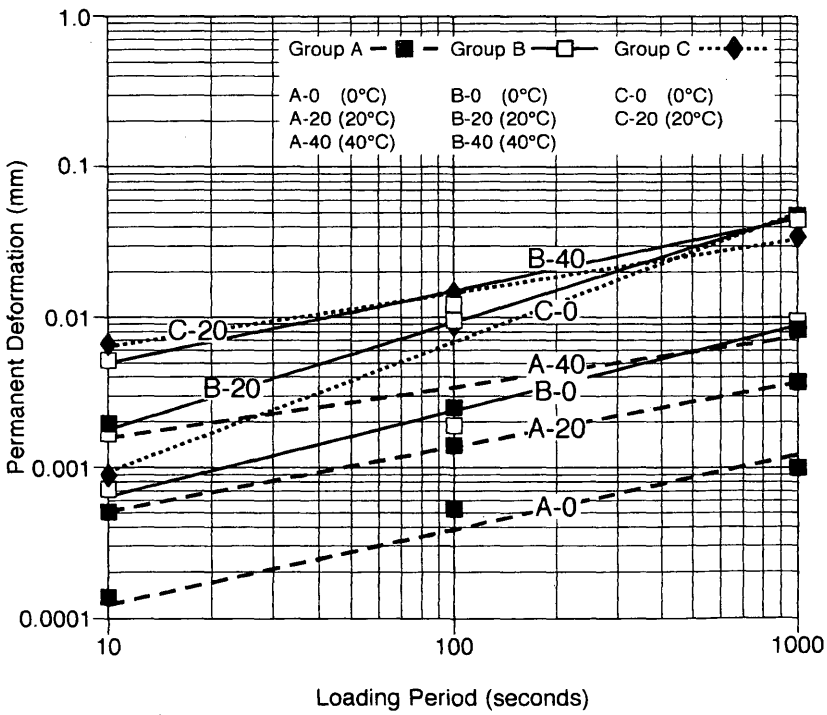

FIGURE 2 Permanent strain from incremental static loading test at 0°C, 20°C, and 40°C.

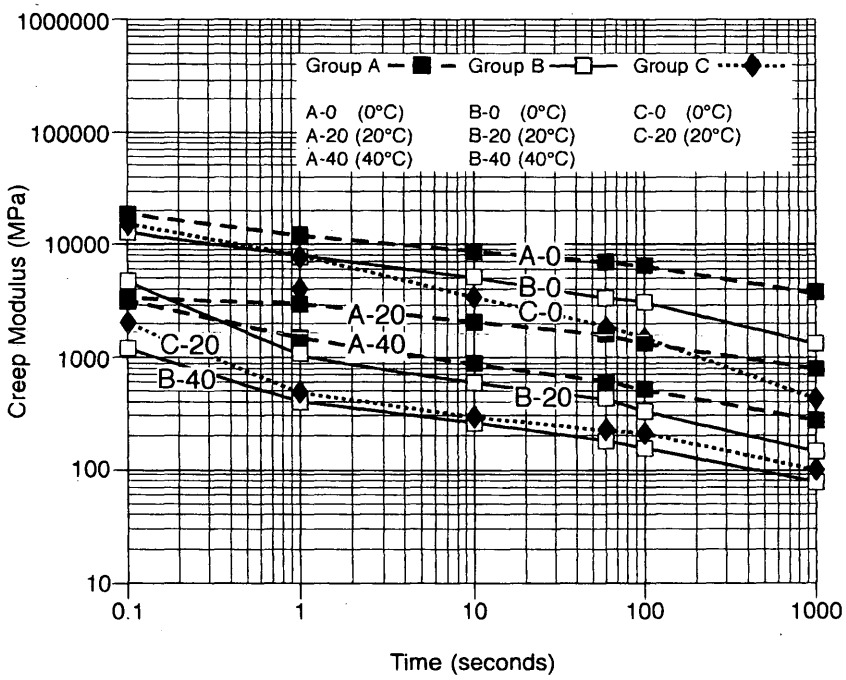

FIGURE 3 Creep modulus versus loading time at 0°C, 20°C, and 40°C.

Fatigue

Fatigue characteristics of the three mixes were measured using diametral indirect tensile tests in controlled stress mode. All tests were conducted at a temperature of 21°C. A load frequency of 1 Hz with 0.1 sec loading and 0.9 sec unloading was used. Indirect tensile stresses in the range of 4 to 50 kPa were used.

Fatigue analysis required an evaluation of both the induced tensile strain in the paving mixture and relation of this tensile strain to the allowable number of load applications. This analysis was performed by using the following equation:

$$N_f = K_1 \left(\frac{1}{\epsilon}\right)^{K_2} \tag{1}$$

where

N_f = the number of load applications to failure,
ϵ = the initial tensile strain, and
K_1, K_2 = the material constants which can be determined through regression.

Strain increased continually throughout the duration of the controlled stress test. The initial strains reported were indirect tensile strains obtained at mid-height of specimens after 200 load applications.

Fatigue characteristic curves for all mixes are shown in Figure 4. The fatigue parameters, K_1 and K_2, can be found in Table 7. Values of K_1 and K_2 can be used as indicators of how RRM content affects

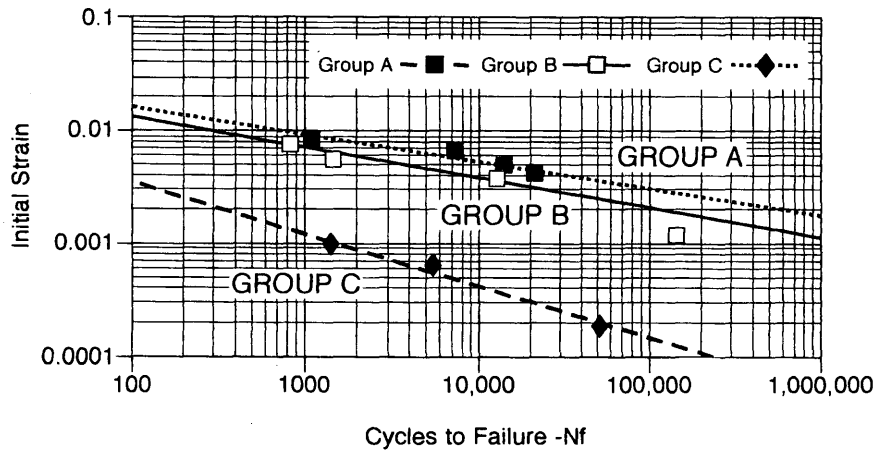

FIGURE 4 Fatigue characteristics.

TABLE 7 VESYS Modeling Parameters

	Season							
	Winter		Spring		Summer		Fall	
Resilient Modulus - MPa								
Mix A	18500		7270		3150		7270	
Mix B	13400		6350		1200		6350	
Mix C	14700		2300		300		2300	
Permanent Deformation Parameters								
	μ	α	μ	α	μ	α	μ	α
Mix A	0.14	0.8	0.67	0.79	0.53	0.79	0.67	0.79
Mix B	0.18	0.73	0.55	0.51	0.69	0.69	0.55	0.51
Mix C	0.4	0.59	0.65	0.84	0.71	0.19	0.65	0.84
Fatigue Coefficients								
	K_1				K_2			
Mix A	$1.4 * 10^{-7}$				4.81			
Mix B	$4.1 * 10^{-5}$				3.43			
Mix C	$2.6 * 10^{-4}$				2.28			

the fatigue mechanism of a paving mixture. The flatter the slope of the fatigue curve, the larger the value of K_2. If two materials have the same K_1 value, a large value of K_2 indicates a potential for longer fatigue life. On the other hand, a smaller K_1 value represents a lower fatigue life when fatigue curves are parallel (i.e., K_2 is constant). Two intersecting fatigue curves indicate that the magnitude of initial induced strain would determine which material would have a longer fatigue life.

Results in Figure 4 and Table 7 show an increase in K_2 and a decrease in K_1 as the RRM content increased. This indicates that the use of RRM increases fatigue properties of HMA mixes. To examine the combined effect of these parameters, K_1 and K_2 were used as input in the VESYS model to predict the fatigue distress (cracking index).

Moisture Damage

Moisture damage evaluation can be accomplished using a number of different methods. Procedures for evaluating the potential for long-term moisture damage as outlined in NCHRP 246 were used in this study. This method used either the ratio of the resilient modulus or the indirect tensile strengths of wet (moisture conditioned) and of dry (unconditioned) specimens as indicators of moisture damage susceptibility.

All three mixes were conditioned as prescribed. Diametral resilient modulus and indirect tensile tests were performed on conditioned and unconditioned specimens. Table 8 summarizes the results of moisture damage tests. Previous research indicates that moisture damage or stripping can occur in asphalt concrete pavements when the ratio of dry to conditioned test specimens is below 0.70 to 0.75 (*6*).

Results in Table 8 indicate that ratio values calculated for both M_r and tensile tests were above 0.9 which suggests that all mixes are not prone to stripping. The use of RRM had no adverse effects on the moisture damage resistance of asphalt concrete. Also noteworthy was that the tensile strength of mixes increased with an

TABLE 8 Moisture Damage Results

		Mix A	Mix B	Mix C
Resilient Modulus MPa	**Dry**	5120	4200	1900
	Wet	4850	4050	1810
	Ratio	0.94	0.96	0.95
Tensile Strength kPa	**Dry**	757	446	233
	Wet	734	407	217
	Ratio	0.97	0.92	0.93

increase in RRM content. Tensile strengths ranged from 233 kPa for the control mix to 757 kPa for a 25-percent RRM mix, which likely resulted from the reinforcing effect of fibres in RRM.

PERFORMANCE ANALYSIS

To assess the influence of RRM on pavement performance, three representative pavement sections were selected for analysis. Each section had a 150-mm (6-in.) asphalt concrete layer over a 300-mm (12-in.) base course layer. The difference between the three pavement sections was in the type of asphalt concrete mix used in the surface layer: two sections used RRM mixes (Mix A and Mix B), while the third had a crushed aggregate mix (Mix C). For the purpose of predicting pavement performance, the VESYS IIIA structural subsystem was used.

Performance can be expressed in terms of rutting, cracking, roughness, and present serviceability index (PSI). Full details of the VESYS model are described in the FHWA Report (*5*).

The mechanical properties of the asphalt concrete layers are summarized in Table 7. The properties of the granular base course and the subgrade layer were identical for all three structures. An analysis period of 20 years and an average traffic of 130 equivalent single axle load (ESAL) per day were used in the analysis. A summary of the VESYS model results are shown in Table 9.

Rut depth, a measure of permanent deformation in the wheel path, is a function of permanent deformation parameters, stiffness of the materials, and traffic volume. As shown in Table 9, pavement sections constructed with Mix C (0 percent RRM) and Mix B (15 percent RRM) will have 12.5 mm (0.5 in.) of rutting during service lives of 5 to 7 years, respectively. The pavement constructed with Mix A (25% RRM) will take 12.5 years to reach rut depth of 12.5 mm (0.5 in.).

The fatigue cracking index, a dimensionless parameter, is a function of fatigue parameters (K_1 and K_2), traffic loading, and layer thickness. It provides an indication of the amount of fatigue cracking over the service life of the pavement. Light cracking will occur between values 1.0 to 1.5; moderate cracking at 1.5 to 2.5; and severe surface cracking at 2.5 to 3.5. Results in Table 9 indicate that pavement constructed with Mix C (0 percent RRM) will experience severe cracking in 5 years of service, whereas pavement constructed with Mix B (15 percent RRM) will experience severe cracking in 9.5 years of service. On the other hand, pavement constructed with Mix A (25 percent RRM) had the lowest cracking index and will experience only moderate cracking over 17 years of service.

The present serviceability index (PSI) provides an indication of rideability of the pavement structure. As shown in Table 9, PSI values for pavement constructed with Mix C will reach the terminal serviceability index of 2.5 in 7 to 8 years of service. Pavement constructed with Mix B (15 percent RRM) will reach a PSI of 2.5 in 11 to 12 years of service. Pavement constructed with Mix A (25 percent RRM) will reach a PSI value of 2.5 after 16.5 years in service.

COMMERCIAL FEASIBILITY

For RRM to be commercially feasible on a large scale, certain criteria have to be met:

1. Satisfactory performance: as shown above, the addition of RRM to HMA can produce a mix that meets or exceeds perfor-

TABLE 9 Performance Modeling Results

	Time (years)				
	1	**5**	**10**	**15**	**20**
	Traffic $ESAL_{18}$ (x 1000)				
	48	240	480	720	960
Fatigue Cracking Index					
Mix A	0.11	0.69	1.38	2.37	3.17
Mix B	0.53	1.11	2.54	4.61	6.12
Mix C	0.54	2.97	6.55	10.03	13.01
Rut Depth, mm					
Mix A	4.10	8.10	11.90	14.90	18.08
Mix B	5.60	12.70	17.80	23.10	26.10
Mix C	7.60	15.50	22.90	28.70	36.09
Present Serviceability Index (PSI)					
Mix A	4.15	3.67	3.17	2.61	2.12
Mix B	4.01	3.29	2.76	2.01	1.69
Mix C	3.92	3.11	2.12	1.26	0.99

mance parameters set forth by the NSDOT&C. Mixes containing 15 percent and 25 percent of RRM will have performance properties superior to that of a comparable mix containing no RRM.

2. Economic considerations: in any commercial application, the cost of using RRM in HMA pavements should be comparable to that of conventional pavements. Extra costs should be offset by performance benefits of the new product. According to the results of other studies carried out, it is estimated that an initial set-up cost of $500,000 is required to produce large quantities of shredded RRM (*4*). Production costs of shredded RRM are estimated at approximately $8 to $19 per ton (*4*). However, in batch mix operation, which resembles laboratory mixing of RRM mixes, the extra costs can be offset by savings in virgin asphalt cement of up to 50 percent. Extra costs can also be offset by a superior HMA pavement, which translates into lower maintenance costs in the long term.

3. Environmental impact: the use of RRM in a large-scale HMA pavement will have a positive impact on the environment. Recycling waste roofing material will ease the burden of disposing nonbiodegradable roofing waste in landfills. Savings of up to 50 percent in virgin asphalt will reduce the demand on depleting resources of the petroleum industries. These advantages will, in part, offset the initial start-up and production costs mentioned above.

CONCLUSIONS

On the basis of the results of advanced testing and modeling of RRM mixes, the following conclusions can be made:

- Acceptable asphalt mixes containing up to 25 percent of RRM by weight can be produced at savings of approximately 3 percent asphalt cement compared to conventional HMA mixes.
- Permanent deformation and rut depth predication results strongly suggest that an increase in RRM content (up to 25 percent) reduces the rutting potential in pavements.
- The use of RRM in asphalt mixes improves fatigue lives of HMA pavements, especially at 25-percent RRM content.
- Although field verification is required, preliminary analysis using the VESYS model predicts that Mix A (25 percent RRM) will outperform the other two mixes, resulting in smaller rut depth, and less fatigue cracking. This in turn gives an improved serviceability index.
- Recycling waste roofing material in hot mix asphalt pavement is commercially feasible with existing technology. However, expensive start-up costs encountered in large-scale production may limit its usefulness.

REFERENCES

1. Grzybowski, K. Recycled Roofing Materials: A Multi-Functional Hot-Mix Asphalt Pavement Additive/Modifier—Low Cost SMA's, *Use of Waste Materials In Hot-Mix Asphalt, ASTM STP 1193* (H. Fred Waller, ed.), ASTM, Philadelphia, Pa., 1992.
2. Paulsen, G., M. Stroup-Gardiner, and Jon Epps. Recycling waste Roofing material in Asphalt Paving mixtures. In *Transportation Research Record 1115*, TRB, National Research Council, Washington, D.C., 1987, pp. 171,182.
3. Newcomb, D., M. Stroup-Gardiner, B. Weikle, and A. Drescher. Properties of Dense-graded and Stone-Mastic Asphalt Mixtures Containing Roofing Shingles. *Use of Waste Materials In Hot-Mix Asphalt, ASTM STP 1193* (H. Fred Waller, ed), ASTM, Philadelphia, Pa., 1992.
4. Flynn, L., Roofing Materials Hold Promise for pavements. *Roads and Bridges*, April 1993, pp. 26–29.
5. *Predictive Design Procedures, VESYS User Manual.* Report FHWA-RD-77-154, FHWA, U.S. Department of Transportation, 1978.
6. Stuart, K. D. *Evaluation of Procedures Used to Predict Moisture Damage in Asphalt Mixtures.* Report FHWA-RD-86-090. FHWA, U.S. Department of Transportation, 1986.

Publication of this paper sponsored by Committee on Characteristics of Nonbituminous Components of Bituminous Paving Mixtures.