Evaluation of Rubber Modified Asphalt Demonstration Projects

JOHN EMERY

Eleven Ontario rubber modified asphalt demonstration projects were evaluated in terms of pavement performance and environmental impacts, including recyclability. On the basis of generally poor short-term performance of eight dry process (rubber modified asphalt concrete) projects, it appears that this method of crumb rubber modifier use should not be pursued unless there is considerable care in materials selection, mix design, and mix production and placement. The wet process (asphalt rubber) shows promise because it appears that asphalt rubber can enhance the durability of these asphalt mixes. Use of crumb rubber modifier in cold in-place recycling was not a technical success. A project with recycling of rubber modified asphalt concrete indicates no technical problems with recyclability. The economics (life-cycle cost) of the dry process are not favorable. If the incorporation of asphalt rubber does decrease maintenance costs or extend service life, there is a potential for savings through the wet process. Available asphalt technology, whether conventional or rubber modified, is capable of meeting environmental regulatory criteria. It is recognized that some technical issues require resolution to optimize rubber modified asphalt technology, and further work must be undertaken in such areas as long-term performance.

Eleven Ontario rubber modified asphalt demonstration projects were funded through the Ministry of Environment and Energy (MOEE) Tire Recycling Program or were completed by the Ministry of Transportation (MTO), between 1990 and 1992. An independent, comprehensive study of these demonstration projects was completed in 1993 (*1*). This study involved evaluation of the demonstration projects in terms of materials and pavements factors and environmental impacts, including recyclability; comparison of the findings to those of other jurisdictions, with identification of technical solutions to any issues; preparation of a summary of technically and cost-effective approaches to foster the use of rubber modified asphalt; and identification of policy and program impediments, with options for resolution. The materials and pavements factors and the economic analysis aspects of the study will be described in some detail, with an indication of the environmental impacts findings.

The 11 demonstration projects included 8 rubber modified asphalt concrete (RUMAC) projects in which the 1 to 3 percent recycled rubber from scrap tires, or crumb rubber modifier (CRM), which was introduced at the batch or drum plant (dry process), behaves essentially as rubber aggregate with some modification of the asphalt cement; 1 project with recycling of RUMAC placed the previous year (RRUMAC); 2 rubber modified cold in-place recycling (RUMCIP) projects in which the 3 percent CRM acts as unbound aggregate; and 1 rubber modified asphalt cement project in which the 0.5 percent fine CRM (7 percent CRM blended into asphalt cement, wet process) results in an asphalt rubber (AR) binder with reduced temperature susceptibility. The locations of these demonstration projects in southern Ontario are shown in Figure 1 (*1*).

John Emery Geotechnical Engineering Limited, Etobicoke, Toronto, Ontario, Canada, M9W 6Y1.

It should be noted that there were Ontario AR trial sections (typically fine CRM dry process) placed as early as 1976 (*2,3*). Those sections placed by the Municipality of Metropolitan Toronto Transportation Department between 1977 and 1980 on major urban routes appear to be performing equivalent to, or somewhat better than, the overall pavement system (*4*).

RUBBER-MODIFIED ASPHALT TECHNOLOGY

Various proprietary and generic technologies have evolved for the use of CRM in asphalt rubber (AR) binder and rubber modified asphalt concrete (RUMAC). From the late 1980s, the emphasis for this wet and dry process technology has been on its potential as a solution to the solid waste management problems of scrap tires. The material, process, technology, and product schematic for CRM use in AR and RUMAC is shown in Figure 2 (*5*).

There is some dry process interaction to modify the binder, as indicated by the dotted arrow lines, particularly for finer CRM or elevated mixing temperatures. The Ontario demonstration projects have mainly involved dry process generic RUMAC.

While the focus on CRM use in asphalt is currently RUMAC and AR, there is a wide range of other asphalt applications for recycled rubber from scrap tires, including hot-poured rubberized asphalt joint sealing compound, hot applied rubberized asphalt waterproofing membrane, hot applied rubberized mastic waterproofing membrane; protection board, paving "bricks," and recreational asphalt surfaces (running tracks, for instance) (*6*). Rubberized (CRM) asphalt joint sealant and waterproofing membrane are established and preferred materials technology in Ontario.

PERFORMANCE OF RUBBER-MODIFIED ASPHALT

Review of Available Information

In order to review the performance of AR and RUMAC pavements determined by various highway agencies, with emphasis on RUMAC, the available information was checked through DIALOG^R (TRIS, EICOMPENDIX*PLUS, MATERIAL, and RAPRA), requests for information to major agencies and their contacts, in-house technical files, MTO technical files, and direct experience and contacts. This provided an excellent information base to consider along with the Ontario rubber modified asphalt demonstration projects.

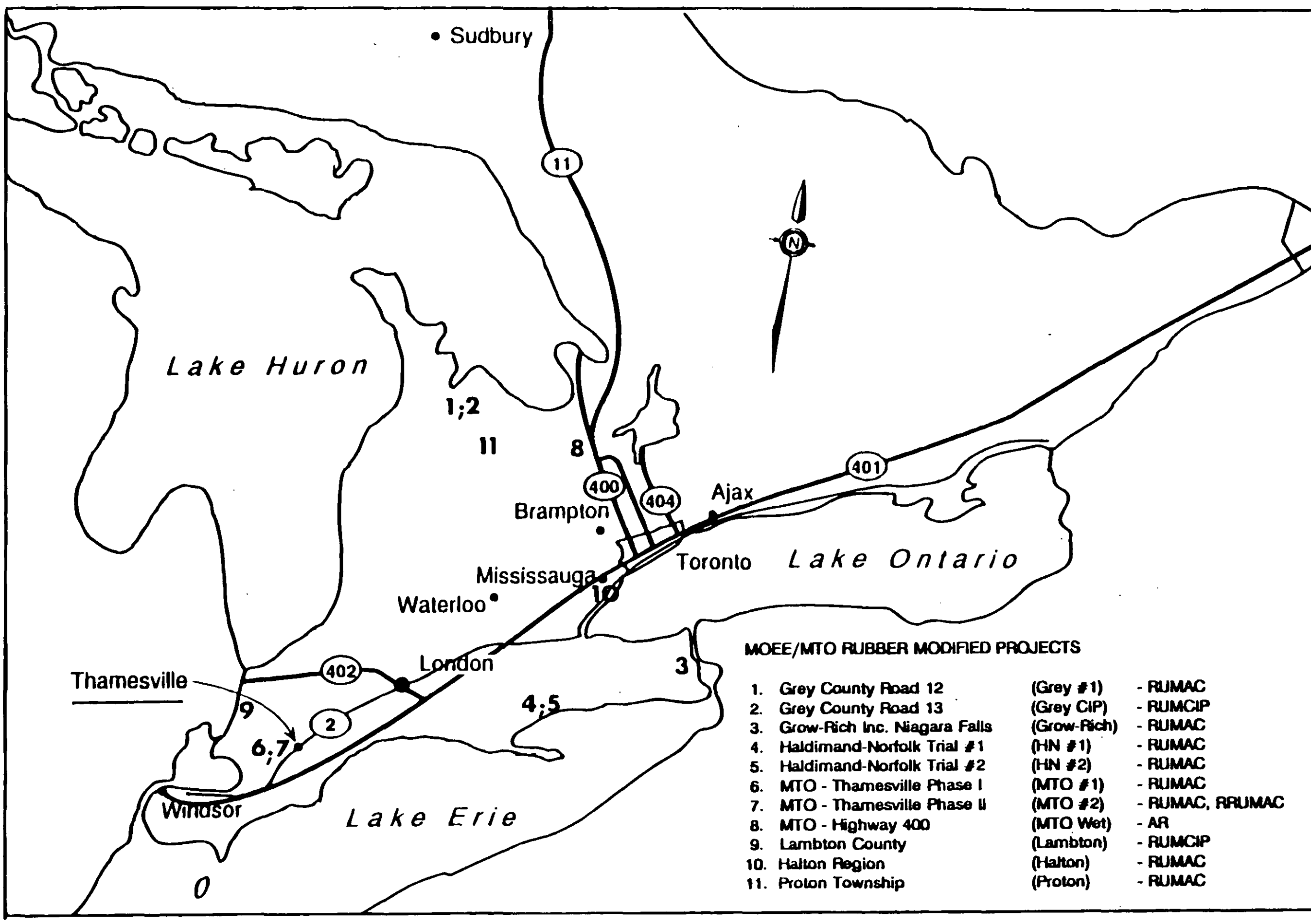

FIGURE 1 MOEE/MTO rubber modified asphalt demonstration project locations (*1*).

Much of the available technical information on CRM use up to 1993 has been reviewed and summarized in a Federal Highway Administration/Environmental Protection Agency (FHWA/EPA) study that is rather inconclusive (*7*). This FHWA/EPA study included the Ontario MTO Thamesville Phase 1 and Haldimand Norfolk Region Trial No. 1 rubber modified asphalt demonstration projects (Figure 1). Also, there is far more practical experience with AR as compared to RUMAC, particularly the generic RUMAC technology adopted for the Ontario demonstration projects.

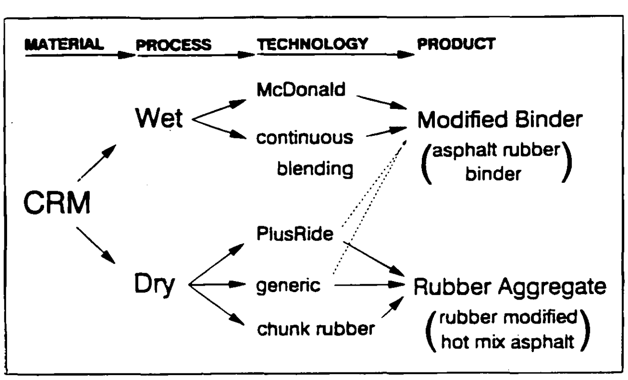

FIGURE 2 Use of recycled rubber from scrap tires (CRM) in asphalt (*5*).

The FHWA/EPA study conclusions for pavement performance and recyclability associated with CRM use in asphalt were (*7*)

1. When properly designed and constructed, there is no reliable evidence to show that pavements containing recycled rubber from scrap car tires will not perform adequately.
2. There is no reliable evidence that asphalt pavements containing recycled rubber cannot be recycled to substantially the same degree as conventional hot-mix asphalt (HMA) pavements.

Several factors need to be noted about the performance and recycling information from the FHWA/EPA study (*7*):

- The economics (life-cycle cost) of CRM use in AR and RUMAC were not considered.
- The differences between AR and RUMAC were not considered in detail.
- The issue of RUMAC reclaimed pavement (RUMAC-RAP) potential leachability was not addressed. However, there does not appear to be a problem in this regard from the available technical information (*8*).

TECHNICAL REVIEW OF ONTARIO DEMONSTRATION PROJECTS

Background and Performance Monitoring

The available reports on the 11 Ontario rubber modified asphalt demonstration projects were supplemented by experienced, independent pavement engineer (study team had no previous engineering involvement in the projects) site visits to each project, both to complete pavement condition evaluations and to review the information with the project engineers. A videotape was made covering the main site visit observations that also includes an overview (November 1989) of the Metropolitan Toronto Transportation Department AR trial sections placed between 1977 and 1980.

It should be noted for the technical review of the MOEE/MTO 1990 to 1992 CRM demonstration projects that, in common with most agencies, this was at a very early leading edge stage on the appropriate CRM asphalt technology learning curve for several reasons:

- Generic dry process RUMAC materials selection, mix design, production, placement, and testing requirements were, and are, still being developed, documented, and implemented [for instance, FHWA will be completing its Phase 2 CRM engineering study in 1999 (communication from B. H. Lord, McLean, Va., 1993)];
- While the "McDonald" technology for AR is well established, the generic wet process continuous blending technology for AR has only recently been established (in Florida, for instance) with the necessary blending equipment for terminal or hot-mix plant production now readily available;
- Use of CRM with cold in-place recycling (RUMCIP) appears to be unique to Ontario; and
- Ontario has been a leader in using cryogenic process recycled scrap tire CRM.

Clearly, it is important to learn from this early MOEE/MTO experience in order to incorporate appropriate CRM asphalt technology in future CRM asphalt paving projects. This was the focus of the technical review.

Technical and environmental project summary fact sheets were prepared for each rubber modified asphalt demonstration project and control section, including the pavement condition. Unfortunately, considerable information had been left out of the documentation for almost every project, such as details on mix production, smoothness of pavement, costing data, monitoring of tire-pavement noise levels, and monitoring of winter snow and ice development and its control. The rubber modified asphalt demonstration project profiles are summarized in terms of technology and application in Table 1.

An overall visual performance assessment of all the demonstration projects should be completed each spring and fall by a qualified pavement engineer. This will provide cost-effective continuing pavement performance information so that the current short-term conclusions and experience can be properly extended.

Demonstration Projects

The eight RUMAC (one also with RRUMAC, MTO No. 2), two RUMCIP and one AR demonstration projects summarized in Table 1 incorporated a wide range of CRM types (ambient and cryogenic), gradations (No. 4, 10, 20 and 80) and contents (1 to 3 percent). Ontario appears to be a leader in the use of cryogenic process CRM, and no apparent differences from ambient process CRM have been noted in the demonstration project reports. However, a direct comparison of cryogenic process CRM with ambient process CRM has not been made for the same RUMAC mix design, production, and placement.

The performance of surface course RUMAC incorporating fairly coarse CRM (No. 4 mesh) appears to be poor, with extensive raveling, considerable pop-outs and poor longitudinal and transverse joints (MTO No. 1 and HN No. 1, for instance). The RUMAC surface course performance appears to have been improved by incorporating No. 10 mesh CRM at a lower addition level of 1.5 percent (Grey No. 1 and HN No. 2, for instance), but this is again a short-term observation that may also reflect other factors such as better paving conditions. Regardless, it is important that the most appropriate CRM type, grading, composition and content, and CRM compatibility be established for typical RUMAC binder and surface courses. It must be recognized that space must be made available for the CRM in the asphalt mix matrix by volumetrically reproportioning the aggregates. This is a difficult proposition unless the CRM grading is similar to one of the fine aggregate gradings or the combined fine aggregate grading.

Equipment

There do not appear to have been any significant difficulties at batch or drum hot-mix plants with incorporating the CRM. However, care must be taken with poly-melt bags to ensure they are fully melted and mixed in. It is not clear how much additional dry mixing time, if any, is required for batch hot-mix plants to incorporate CRM, particularly finer CRM.

Production and Placement

It appears that the production of RUMAC and AR generally went smoothly, with the only significant placement problems associated with compaction of the somewhat tender RUMAC mixes, and the propensity for rubber-tired roller pick-up with the sticky mixes involved. These are somewhat experience-related problems, but the question of whether rubber-tired rollers should be used at all with RUMAC should be resolved. Practical production, placement, and compaction guidance for RUMAC should be developed in conjunction with contractor groups such as the Ontario Hot Mix Producers Association (OHMPA).

Rutting problems were associated with the placement of RUMCIP, and the efficacy of this CRM use must be critically assessed. It is not clear how the simple addition of CRM to cold in-place recycling can improve the process or the subsequent pavement performance. The use of cold in-place asphalt recycling is growing in Ontario as a method of mitigating reflection cracking (Grey County, for instance). It is important that the overall quality of cold in-place asphalt recycling be maintained to foster its use.

Quality Control and Quality Assurance

There were many quality assurance results to review and summarize in terms of RUMAC job mix formula (JMF) requirements and

TABLE 1 Summary of MOEE/MTO Rubber Modified Asphalt Demonstration Projects (2)

PROJECT AND LOCATION[a] IDENTIFICATION[b] /TIRES[c]	DATE	PROCESS[d] MIX TYPE	CRM PERCENT TYPE	PLANT FUEL CONTROL SYSTEM	'COMPARATIVE'[e] PAVEMENT PERFORMANCE	ENVIRONMENTAL MONITORING
Grey County Road 12 Grey #1 33,000	Nov./91 May/92	RUMAC HL 4	1.5 Ambient, No.10	Batch Oil Dry	Similar (Very Good) Poor Areas[e]	Yes
Grey County Road 13 Grey CIP 7,000	Aug./92	RUMCIP CIP	2 Cryogenic, No.4	CIP Process Not Applicable	Under Surface Course Similar (Excellent) Initial Problems	Not Applicable
Grow-Rich Inc. Niagara Falls Grow-Rich 16,000	Nov./92	RUMAC HL 8, HL 3	1.75, 1.75 Cryogenic, No.10, No.20	Batch Gas Dry	Covered by Pile Apparently Good No Control	Yes
Haldimand-Norfolk Trial #1 HN #1 78,000	Oct. to Nov./90	RUMAC HL 8, HL 3	3, 2 Ambient, No.4	Batch Oil Dry	Very Poor (Poor) Poor Areas	Yes
Haldimand-Norfolk Trial #2 HN #2 60,000	Aug./92	RUMAC HL 8, HL 3	3, 2 Cryogenic, No.10	Batch Oil Dry	Similar (Very Good)	Yes
MTO - Thamesville Phase I MTO #1 31,100	Oct./90	RUMAC HL 4	2 Ambient, No.4	Drum Oil Wet	Very Poor (Fair) Ravelling Pop-outs	Yes Comprehensive
MTO - Thamesville Phase II MTO #2 26,500	Oct./91	RUMAC RRUMAC HL 4	2 Ambient, No.10	Drum Oil Wet	Somewhat Poor to Similar (Very Good)	Yes Comprehensive
MTO - Highway 400 MTO Wet Not Known	July/90	AR HL 4, HL 1	0.5 (7 of AC) Ambient, No.80	Drum Gas Dry	Good (Excellent) 50 Percent Less Transverse Cracking	No
Lambton County Lambton 16,000	July/92	RUMCIP	3 Cryogenic, No.4	CIP Process Not Applicable	Under Surface Course (Excellent) No Control Initial Problems	Not Applicable
Halton Region Halton 37,000	Aug. to Sep./92	RUMAC HL 8, HL 3	1.5, 1.3 Ambient, No.10	Batch Gas Dry	(Excellent) No Control Little Traffic to Date	No
Proton Township Proton 7,000	May/92	RUMAC HL 4	1.0, 1.5 Ambient, No.10 (From Grey #1)	Batch Oil Dry	Similar (Very Good) 85/100 and 150/200 Used	No

Notes:
a. See Figure 1 for projects location map.
b. Abbreviations for project identification.
c. Passenger tire equivalents used.
d. RUMAC - rubber modified asphalt concrete (hot-mix asphalt)
RUMCIP - rubber modified cold in-place recycling
RRUMAC - recycled RUMAC
AR - asphalt rubber (rubber modified asphalt cement)
e. 'Comparative' is for September, 1993, overall assessment.
General condition is given in parentheses (Very Good), for instance. For example, for Haldimand-Norfolk Trial #1 (HN #1), the RUMAC HL 3 section's comparative performance to the control HL 3 section is very poor while the general condition of the RUMAC HL 3 section itself is poor.

RUMAC production range (minimum and maximum). There do not appear to be any significant problems in producing AR and RUMAC to the JMF requirements (asphalt cement content, aggregate gradation, and physical properties), but it is difficult with AR and RUMAC to accurately determine the asphalt cement content and complete conventional viscosity testing. Any necessary viscosity testing of AR or properly recovered asphalt cement from RUMAC could be completed using a rheometer, and at present this is not an issue for quality assurance testing. The monitoring of asphalt cement content in RUMAC requires pretesting to establish the amount of CRM that effectively becomes an asphalt cement component (some 10 to 20 percent) and must be adjusted for in conventional solvent-based extraction methods. The use of nuclear asphalt cement gauges has proved most promising (HN No. 2, for instance), provided proper calibration for the RUMAC is completed and the RUMAC is fairly consistent. Again, technical guidance on AR and RUMAC testing should be documented.

Problems and Resolution

Tender and sticky mix problems with the compaction of RUMAC were noted and have been a common problem with other agencies. These have been resolved through care during initial compaction to avoid pushing and shoving and the use of detergent-based release agents. The workability problem of RUMAC should also be considered at the mix design stage to ensure that adequate stability is being provided.

While experience with AR is limited (MTO wet), there should be no problems beyond placing and compacting a sticky mix, and contractors have had considerable experience with placing and compacting similar sticky polymer modified HMA.

No obvious problems were encountered during the processing stage of RUMCIP (Grey CIP and Lambton); however, in both cases extensive rutting and raveling of the cold in-place recycled material were experienced after being subjected to traffic. For the

Grey CIP this was resolved by reprocessing with additional emulsion and a remedial overlay; for Lambton this was resolved by reprocessing with additional emulsion. As indicated, the continuing use of RUMCIP must be critically reviewed. It should be noted that the RUMCIP is actually covered by a conventional HMA wearing surface (HL 4) so that direct observation of the RUMCIP is not possible.

Performance of Pavements

The relative short-term performance of the one wet process continuous blending AR project (MTO wet) has been good compared to the control section, with the AR section in excellent condition and 50 percent less transverse cracking. This favorable performance would generally be anticipated from polymer modified HMA experience. Regardless, wet process "continuous" terminal or site-blended AR should receive more attention.

The initial performance of the two RUMCIP projects was poor.

The relatively short-term performance of the RUMAC (surface course) projects has been quite mixed. But two performance groupings, compared to control sections, can be distinguished; they are

- Very poor: RUMAC surface course typically incorporating 2 percent No. 4 mesh CRM (HN No. 1, MTO No. 1 and to some extent MTO No. 2) and involving late paving season placement; and
- Similar: RUMAC surface course typically incorporating 1.5 percent No. 10 mesh CRM (Grey No. 1, HN No. 2, Halton and Proton) and involving reasonable paving season placement.

These Ontario demonstration project observations support the FHWA/EPA conclusion that properly designed and constructed RUMAC pavements should perform adequately (*7*). It should be noted that these are short-term performance considerations, and the key issue of long-term RUMAC performance remains to be addressed for the demonstration projects. The planned monitoring programs to 1996 for these RUMAC projects will not be adequate for assessing the comparative long-term performance, as conventional HMA surface course typically lasts for 15 years between resurfacings.

ECONOMIC ANALYSIS

Assessment Factors

To evaluate the economic benefits (or deficiencies) of Ontario RUMAC and AR use, a comprehensive economic analysis of conventional HMA, generic dry process RUMAC and AR asphalt pavements was completed, including sensitivity evaluations. The economic analysis focus was on RUMAC, as there is little current Ontario information available on wet process continuous blending AR, with the exception of the MTO 1990 Highway 400 AR (Rouse UltraFine™) test section (*9*). However, Rouse has provided comparative U.S. costing data for wet process continuous blending AR that appear to be appropriate in the Ontario context (communication from M. W. Rouse, Vicksburg, Miss., 1993).

When assessing the short and long-term economic impact of an innovative material such as generic dry process RUMAC, equipment requirements, serviceability and performance factors, societal concerns, and materials costs must be considered. Equipment requirements include any plant or equipment modifications necessary to meet environmental or production requirements, operating costs, maintenance costs, and effect (reduction in particular) on production. Serviceability and performance factors encompass such items as the relationship between any increment in costs and pavement performance, the effect of pavement salvage value on life-cycle costs, the quantity of recycled wastes to be used, and the recyclability of HMA containing wastes or by-products. Societal concerns include whether or not incentives should be provided for materials incorporating recycled wastes and if the waste generators should offer incentives to the highway construction industry to encourage use of the waste. Materials cost issues are somewhat more straightforward and include any increment in materials costs necessary to incorporate the waste into HMA, such as an increase in asphalt cement required, supply of CRM, additional aggregate requirements, and so forth. Each of these factors was evaluated as part of the overall economic assessment of generic dry process RUMAC pavements. This assessment also included consideration of the sensitivity of the analysis to various input parameters; for instance, what is the consequence of a lower CRM price on the overall economic analysis of RUMAC use?

Initial Costing Assumptions for RUMAC Economic Analysis

An initial cost comparison of conventional HMA and generic dry process RUMAC was completed as the first component of the economic analysis. It should be noted that there are minor additional costs (RUMAC mix design and quality assurance costs more than HMA, for instance) and cost savings (RUMAC has 2 to 4 percent more yield than HMA as lower bulk relative density, for instance), that tend to offset but they have not been considered.

From an equipment standpoint, generally no significant environmental or production modifications are involved. The CRM feed systems are quite conventional, particularly for hot-mix batch plants. However, the MOEE Certificate of Approval—Air for the HMA plant must be extended to cover the production of RUMAC. There are some additional staff and equipment requirements, including workers (at least two) to load the CRM into the plant, and a loader and operator to handle the pallets of CRM. The HMA production rate is not affected if a hot-mix drum plant is involved. If a hot-mix batch plant is used, some reduction in production can be experienced in order to ensure that the CRM is effectively distributed through the mix.

The materials requirements for RUMAC are relatively straightforward: for each 1 percent of CRM incorporated in RUMAC, the asphalt cement content increases by about 0.6 percent, based on practical experience. Therefore, if a conventional HL 3 mix has an asphalt cement content of 5.0 percent, a comparable HL 3 RUMAC mix with 1.5 percent CRM and the same aggregates (volumetrically adjusted fine aggregate proportions to accommodate CRM) will require an asphalt cement content of about 5.9 percent. The cost of the individual materials is therefore a major component of the economic analysis. The 1993 price of No. 10 mesh CRM was about $300/tonne plus about 10 percent delivery in the Greater Toronto Area (GTA), with asphalt cement costing about $150/tonne in 1993 plus about $10/tonne delivery in the GTA. The cost of processed CRM should decrease as RUMAC and AR use increases. Consequently, for the economic analysis of RUMAC, the cost implications of CRM at $330/tonne and $220/tonne have been evaluated. A $1/tonne of hot-mix increment for handling the CRM at the plant and 15 percent markup (industry standard practice) on the RUMAC have also been included.

Although incentives are currently not offered for the use of recycled scrap tire rubber (CRM) in RUMAC, some consideration has been given to the "value" of the potential savings in disposal costs owing to the use of scrap tires. Approximately 50 to 60 percent of a scrap tire is recovered through processing for CRM (the average tire mass is about 9 kg, and 5 kg of CRM can be produced from each tire). At the current disposal fee of about $100/tonne in the GTA, an HL 3 RUMAC mix containing 2 percent CRM represents about a $2/tonne of hot mix "saving" in disposal costs. Inasmuch as disposal costs have varied somewhat recently, dependent to some degree on the location (GTA is typically more expensive than other areas of Ontario), and societal factors must be considered, a range of incentives has been assumed for the economic analysis ($50/tonne, $100/tonne and $200/tonne), and of course the baseline case of no incentive.

The following parameters were included in the initial cost comparison of conventional HMA and RUMAC mixes:

Mix Types: HL 3 HMA (current price of about $34/t in GTA)
HL 8 HMA (current price of about $25/t in GTA)
HL 3 (1.5% CRM) RUMAC (requiring 0.9 percent additional AC)
HL 3 (2.0% CRM) RUMAC (requiring 1.2 percent additional AC)
HL 8 (2.0% CRM) RUMAC (requiring 1.2 percent additional AC)
HL 8 (3.0% CRM) RUMAC (requiring 1.8 percent additional AC)

Asphalt Cement Price: $ 150/t plus $ 10/t delivery in GTA

CRM Price: $300/t plus 10 percent delivery in GTA ($330/t total)
$200/t plus 10 percent delivery in GTA ($220/t total)

CRM Addition at Plant: $1/t of hot mix, plus 15 percent markup

Incentive for Scrap Tires:

	CRM Addition Rate		
Incentive	1.5%	2.0%	3.0%
None	0	0	0
$ 50/t	$ 0.75/t	$ 1.00/t	$ 1.50/t
$ 100/t of CRM	1.50/t	2.00/t	3.00/t of CRM
$ 200/t	3.00/t	4.00/t	6.00/t

(t = tonne in columns and tables)

An initial cost comparison of conventional HMA mixes and RUMAC mixes, based on the above parameters, is presented in Table 2. An example cost calculation for an HL 3 (1.5 percent CRM) RUMAC mix is as follows:

TABLE 2 Initial Cost Comparisons of Conventional and RUMAC Mixes (*1*)

MIX TYPE	PRICE/TONNE			
Incentive for Use of Scrap Tires (Per tonne of CRM)	0 (No Incentive)	$ 50.	$ 100.	$200.
HL 3 (Conventional)	34.00			
HL 3 (1½%) RUMAC (0.6% AC/1% CRM) CRM @ $ 300/t + $ 30. Del.	42.50	41.75	41.00	39.50
CRM @ $ 200/t + $ 20. Del.	40.60	39.85	39.10	37.60
HL 3 (2%) RUMAC (0.6% AC/1% CRM) CRM @ $ 300/T + $ 30. Del.	44.95	43.95	42.95	40.95
CRM @ $ 200/t + $ 20. Del.	42.42	41.42	40.42	38.42
HL 8 (Conventional)	25.00			
HL 8 (2%) RUMAC (0.6% AC/1% CRM) CRM @ $ 300/t + $ 30. Del.	34.92	33.92	32.92	30.92
CRM @ $ 200/t + $ 20. Del.	33.42	32.42	31.92	29.92
HL 8 (3%) RUMAC (0.6% AC/1% CRM) CRM @ $ 300/t + $ 30. Del.	40.92	39.42	37.92	34.92
CRM @ $ 200/t + $ 20. Del.	37.05	35.55	34.05	31.05

HL 3 Cost	= $ 34.00	@ $ 220/t =	$ 3.30
CRM (1.5 %) @ $ 330/	= 4.95		
Additional AC (0.9 %) @ $ 160/t	= 1.44		
Labour Cost to Add CRM to Mix	= 1.00		
15% Mark-Up on Additional Items	= 1.11		0.86
	$ 42.50		$ 40.60
Less Incentive ($50/t rate)	= 0.75		0.75
Total:	$ 41.75		$ 39.85

Based on the initial cost comparison figures presented in Table 2, the conventional HMA mixes are less costly than the RUMAC mixes regardless of the incentive selected for disposal savings. At the most optimistic, RUMAC is still about 15 to 20 percent more costly than conventional HMA. If no incentive is attributed to RUMAC and CRM prices remain at their current relatively high level, the RUMAC mixes are approximately 32 to 39 percent higher in initial cost than equivalent conventional HMA mixes. These initial first-cost comparisons are similar to those suggested from recent U.S. RUMAC experience (Rouse 1993 Communication).

Life-Cycle Cost Analysis for RUMAC

To evaluate essentially equivalent pavement alternatives involving alternate materials, it is necessary to consider not only the initial cost of each alternative but also the total cost over its service life. The alternative having the lowest initial cost may not represent the most practical alternative once factors such as maintenance, rehabilitation, and inflation (and in contrast, the value of money invested today for future use, i.e., interest) are taken into account. The most effective method of measuring the cost-effectiveness of alternative designs is life-cycle cost analysis.

A number of life-cycle cost analysis approaches can be employed to evaluate construction materials. However, the most appropriate method appears to be that recommended by Kerr and Ryan (*10*), which has been used by the MTO and Asphalt Institute (AI). This method of measuring the cost-effectiveness of pavement alternatives equates present and future expenditures for each alternative, and associated maintenance and rehabilitation costs, by taking into account both inflation and interest rates over the life of the project. The concept of present value, or "discounting," is used to permit comparison of alternatives that require expenditure over an extended period of time, which allows the designer to consider the dual effects of interest rates (the time value of money) and inflation on project cost.

Despite the occasional relatively large apparent differences between interest and inflation rates, historically the discount rate, or the real difference between interest and inflation rates over an extended period of time (30 years), has been reported by Kerr and Ryan to be generally about 3 to 4 percent for privately financed projects. Recent provincially sponsored major transportation projects have assumed a long-term yield on Government of Canada bonds of 7.5 percent. Therefore, an interest rate of 7.5 percent has been assumed for the life-cycle costing of RUMAC pavements and an average inflation rate of 4 percent over the design life of the pavement, which results in a discount rate of 3.5 percent.

The service life of each alternative must also be taken into consideration for equivalent life-cycle cost comparisons. A conventional asphalt concrete pavement usually requires a major overlay after about 15 years to extend its functional service life. The timing for major maintenance and rehabilitation treatments required for each alternative must be taken into account; and the most appropriate service life must be selected for life-cycle cost analysis. For instance, the functional service life of an asphalt concrete pavement without major rehabilitation is about 25 years.

HMA and RUMAC Life-Cycle Cost Comparisons

Comparative life-cycle cost analyses of generic dry process RUMAC and conventional HMA mixes are presented in Table 3. To test the sensitivity of the life-cycle cost analyses to initial cost variations, life-cycle cost analyses were completed for three initial costs for each RUMAC type evaluated in Table 2. The highest initial cost (higher CRM price and no incentive) and the lowest initial cost (lower CRM price and maximum incentive for disposal savings) were used, as well as the average of the two. These figures were used to determine the cost per lane-km of pavement for each HMA and RUMAC mix, assuming a thickness of 40 mm for the surface course life-cycle cost evaluations and 50 mm for the binder course comparisons.

The life-cycle costing was conducted for a 30-year service life, with various performance assumptions and maintenance scenarios (both optimistic and pessimistic). For instance, each HL 3 RUMAC surfacing was life-cycle costed for replacement (milled off and replaced with the same mix type) at intervals of 5, 10, 15, and 20 years, respectively. Monitoring of the generic dry process RUMAC projects completed to date suggests that the mixes containing 1.5 percent CRM should last between 10 and 15 years, while 5 to 10 years is expected for some mixes containing 2 percent or more CRM when raveling will necessitate provision of an overlay.

The life-cycle costing of the conventional HMA and RUMAC surface course mixes also assumed that routine maintenance activities such as crack sealing, pothole filling, and so forth would be provided on a regularly scheduled basis. For example, crack sealing of an asphalt pavement would typically be completed within the first 2 years of construction or major rehabilitation (overlay) and again 5 years thereafter (properly applied, hot poured rubberized crack sealants last between 5 and 7 years). The same schedules and level of maintenance were assumed for both conventional and RUMAC mix types, with additional analyses completed assuming that the RUMAC mix would require half the maintenance.

Similar life-cycle cost analyses were completed for the conventional HMA and RUMAC binder course mix types. As these mixes would be covered with a surface course layer, the life-cycle costing does not include any routine maintenance operations, and only reflects the schedule for replacement (milling and replacement with the same mix type). Replacement schedules of 20, 25, and 30 years were costed for both conventional HMA and RUMAC binder course mixes.

The life-cycle cost analyses indicate that the lowest life-cycle costs are obtained for the conventional HL 3 surface course and HL 8 binder course mixes. Even when a relatively low CRM price and maximum incentive is assigned to the RUMAC mixes, the life-cycle costs of the RUMAC alternatives are still more than the conventional mixes. Even if the RUMAC mixes require half the level of maintenance, they are still more costly. Only when the RUMAC surface course design life is extended to 20 years, with low CRM pricing and maximum incentive, and compared to a 15-year design life for conventional HMA surface course is the life-cycle cost less than conventional. However, this is considered to represent a very optimistic scenario from the Ontario generic dry process RUMAC performance data to date.

TABLE 3 Life-Cycle Cost Analysis Summary for Conventional and RUMAC Mixes—30-Year Life (*1*)

MIX TYPE	LIFE CYCLE COST, dollars/lane-km			
	REPLACEMENT FREQUENCY			
SURFACE COURSE	5 YEARS	10 YEARS	15 YEARS	20 YEARS
HL 3 CONVENTIONAL			49753	
HL 3 (1½%) RUMAC				
CRM @ $ 300/t + 30 Del. + No incentive [42.50/t]	128703	74234	54632	41919
CRM @ $ 200/t + 20 Del. + maximum incentive [37.60/t]	121340	69971	51392	39438
Mean [40.05/t]	125024	72104	53013	40679
HL 3 (2%) RUMAC				
CRM @ $ 300/t + $ 30. Del. + no incentive [44.95/t]	132382	76364	56251	NA
CRM @ $ 200/t + $ 20. Del. + maximum incentive [38.42/t]	122572	70684	51934	NA
Mean [41.69/t]	127484	73528	54096	NA
BINDER COURSE	20 YEARS	25 YEARS	30 YEARS	
HL 8 CONVENTIONAL	26079	23756	21778	
HL 8 (2%) RUMAC				
CRM @ $ 300/t + $ 30. Del. + no incentive [34.92/t]	31266	28674	26467	
CRM @ $ 200/t + $ 20. Del. + maximum incentive [29.92/t]	28178	25742	23672	
Mean [32.42/t]	29720	27208	25077	
HL 8 (3%) RUMAC				
CRM @ 300/t + $ 30. Del. + no incentive [40.92/t]	34976	32192	29822	
CRM @ $ 200/t + $ 20. Del. + maximum incentive [31.05/t]	28872	26405	24304	
Mean [35.99/t]	31928	29302	27066	

Life-Cycle Cost Analysis for AR

The life-cycle cost analysis for wet process continuous blending AR was somewhat simplified compared to the detailed RUMAC analysis, in order to use U.S. data in the Ontario context. Several assumptions were made for the AR analysis: surface course (HL 3) use will be typical; Rouse technical and costing data are appropriate (about 20 percent increase in hot-mix materials cost, or $5/tonne of hot mix, attributable to AR incorporation, which also appears reasonable for Ontario) (Rouse 1993 communication); and no external incentives (tire buffings can be readily used in lieu of CRM). The life-cycle cost analysis was completed for several performance assumptions: HL 3 surface course service life is typically 15 years; AR HL 3 surface course service lives of 15 years and 20 years (Metropolitan Toronto Transportation Department apparently experiencing longer service life, for instance); same maintenance required for HL 3 and AR HL 3; and one-half the maintenance required for AR HL 3. The initial cost of the two mixes is taken as $34/tonne for conventional HL 3 and $39/tonne for AR HL 3.

Comparative life-cycle cost analyses for AR HL 3 and conventional HL 3 are presented in Table 4 for the various performance assumptions. If the incorporation of wet process continuous blending AR in HL 3 decreases the maintenance cost or extends the service life, as anticipated, then there is certainly a potential for considerable savings on a life-cycle cost basis. This is the position taken by U.S. proponents of AR use, who also emphasize the technical advantages of AR such as durability enhancement in open-graded hot mix, stress absorbing membrane (SAM), stress absorbing membrane interlayer (SAMI), and applications of a sulfur-asphalt module (Rouse 1993 communication).

SUMMARY OF ENVIRONMENTAL IMPACTS FINDINGS

The air emissions test results of the conventional HMA and RUMAC processes overlapped and exhibited a wide variability indicating that, except for the compound 4-methyl-2-pentanone

TABLE 4 Asphalt Rubber (AR) Life-Cycle Cost Analysis Summary—30-Year Life (*1*)

MIX TYPE	LIFE CYCLE COST, dollars/lane-km	
	REPLACEMENT FREQUENCY	
	15 YEARS	20 YEARS
HL 3 CONVENTIONAL Regular Maintenance	49753	
AR HL 3, Same Maintenance As HL 3	53167	40887
AR HL 3, Requiring half the maintenance as HL 3	47241	34509

(otherwise known as methyl isobutyl ketone or MIBK), there was no discernible difference between the emissions of the two processes. The wide variability is believed to be influenced by plant operation and maintenance practices and not because of differences due to the use of rubber modified asphalt. However, in five of the six demonstration projects where emissions testing was conducted, MIBK was emitted during RUMAC production and either was not detected or was emitted in orders of magnitude that were lower during conventional HMA production. In sufficient quantities, MIBK is a skin and mucous irritant and moderately toxic by inhalation but is not considered a carcinogen.

Occupational health exposures monitored for the two processes also measured overlapping levels that, in most instances, were at or below the detection limits for the compounds of interest. Worker exposures for the two processes of conventional HMA and RUMAC were similar.

The two issues of solid waste leachate and liquid effluent quality were not characterized for rubber modified asphalt. Although it is believed that these wastes are similar to conventional HMA, until this characterization is undertaken for rubber modified asphalt processes these issues will continue to be raised.

Available asphalt technology, whether conventional HMA, RUMAC, or AR, appears capable of meeting environmental regulatory agency criteria provided the process is designed, managed, and operated properly. This applies to air emissions, solid waste, liquid effluents, and occupational health.

NEED FOR RESEARCH AND DEVELOPMENT

Further research and development is needed in a number of areas of AR and RUMAC asphalt technology, pavement performance, and recyclability. They were identified during the review of the available technical information on CRM use in asphalt and the evaluation of the Ontario demonstration projects. These range from major research and development needs, such as research on the long-term performance of RUMAC pavements compared to conventional HMA pavements to relatively minor needs such as guidance to contractors on the best placement and compaction procedure(s) for RUMAC. Obviously, before the long-term performance of RUMAC pavements is considered through laboratory performance testing (SHRP protocols, for instance), accelerated pavement testing, and the monitoring of prototype pavement sections, RUMAC must be properly designed and constructed (*1*). The economic analysis of AR and RUMAC use (life-cycle costing) cannot be finalized until realistic long-term performance information is available. Technology transfer is a key element of this overall process that should also consider appropriate waste management incentives, if any, to establish technically sound, economically attractive AR and RUMAC use.

CONCLUDING COMMENTS

It is recognized that technical issues still require resolution to optimize the application of rubber modified asphalt technology and that further development will be undertaken in areas such as long-term performance. During this research, the environmental component should not be overlooked when appropriate.

Several asphalt technology recommendations have been made in the areas of CRM selection, generic dry process RUMAC placement, RUMAC long-term performance, life-cycle cost comparisons, wet process continuous terminal or site blending of AR, test procedures for AR and RUMAC, and influence of repeated RUMAC recycling. It is important that user agencies, contractors, and pavement consultants be kept informed, and involved, in the development of CRM use in asphalt paving in Ontario.

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REFERENCES

1. *Evaluation of Rubber Modified Asphalt Demonstration Projects.* John Emery Geotechnical Engineering Limited (JEGEL) for Ministry of Environment and Energy, 1994, 79 pp. and appendices.

2. Fromm, H. J. *Rubber Asphalt Test Roads—Progress Report 1981.* MSP-81-02. Ontario Ministry of Transportation and Communications, Downsview, Ontario, Canada, 1981, 11pp.
3. George, J. D. Asphalt Pavement with Concrete Base. *Proc., 21st Annual Conference, Canadian Technical Asphalt Association*, Victoria, British Columbia, Nov. 1976, pp. 269–281.
4. *Pavement Management System Technical Update and Pavements Information Underfunding Analysis.* John Emery Geotechnical Engineering Limited (JEGEL) for Metropolitan Toronto Transportation Department, 1993.
5. Heitzman, M. A. Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier. In *Transportation Research Record 1339*, TRB, National Research Council, Washington, D.C., 1992, pp. 1–8.
6. Kennepohl, G. J. *Scrap Tire Applications in Ontario's Transportation Industry.* Report PAV-92-08. Ontario Ministry of Transportation, Research and Development Branch, Downsview, Ontario, Canada, 1993, 23pp.
7. *A Study of the Use of Recycled Paving Material—Report to Congress.* Report FHWA-RD-93-147, EPA/600/R-93/095. FHWA and Environmental Protection Agency, Washington, D.C., 1993, 50pp.
8. Thompson, E. A. and R. Haas. Fumes from Asphalt and Leachates from Pavements: Are They Harmful? *Proc., 37th Annual Conference, Canadian Technical Asphalt Association*, Victoria, British Columbia, Nov. 1992, pp. 47–71.
9. Joseph, P. E. and G. J. Kennepohl. *Trial Sections with Polymer-Modified Asphalts on Highway 400.* Report PAV-91-03. Ontario Ministry of Transportation, Research and Development Branch, Downsview, Ontario, Canada, 1991, 35pp.
10. Kerr, W. O. and B. A. Ryan. *Avoiding the Pitfalls of Life-Cycle Cost Analysis.* Washington Economic Research Consultants, Washington, 1987, 19pp.

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