LABORATORY DESIGN AND PERFORMANCE OF STRESS ABSORBING MEMBRANE INTERLAYER (SAMI) INCORPORATING WASTE RECYCLED PLASTICS

Latif Budi Suparma[1]

ABSTRACT

An extensive laboratory investigation has been carried out into utilising recycled waste plastics in continuously graded asphaltic concrete road surfacing mixtures. The resultant composites were referred to as ***Plastiphalt****. Overall, the results obtained from the investigation indicated conclusively that Plastiphalt mixes can be produced using current technology, whilst utilising selected recycled wastes and still have better strength and durability properties compared to conventional bituminous mixes. In this paper, further work is presented describing laboratory investigations into utilising the recycled waste plastics in other flexible pavement structure, i.e. the application in Stress Absorbing Membrane Interlayers (SAMI's).*

In this investigation, recycled waste plastics, limestone sand, and Ordinary Portland cement (as filler) were combined in various proportions and mixed with a range of bitumen contents to formulate SAMI's. The objective of SAMI's is to delay the onset of reflective cracking which is a very common form of failure in bituminous road surfacings overlaying distressed bases. The first component of the investigation was to optimise mix proportions so as to overcome the potential shrinkage problems of the LDPE (plastic type) component. A satisfactory bituminous SAMI was thus produced containing 28% by volume of LDPE. Flexural fatigue tests were subsequently carried out on Hot Rolled Asphalt (HRA) beams overlaying LDPE SAMI mixes and the results were compared to full depth HRA control beams and to beams with Sand Bitumen SAMI's. The number of additional cycles to failure of the LDPE SAMI beams when compared to conventional asphalt beams was found to exceed 60%.

Keywords: Waste, recycled, Polyethylene, SAMI, Plastiphalt

INTRODUCTION

The growing urbanity has brought with it increasing commercial traffic causing road pavements to deteriorate faster than anticipated. This has culminated in the upsurge of research activities in pavement materials in general and asphalt mixtures in particular in a bid to improve design, optimise the use of materials and also to identify effective methods in construction. Though these damaged pavements are being restored through maintenance and rehabilitation, they require huge financing. The properties of bituminous pavements are therefore of significant importance to its life. For instance the performance and durability of a pavement is reflected by the proportion in which binder, aggregate and additive are blended.

On the other hand, it has also been established that for a given defect in an asphalt pavement, there are myriad of causal effects. Ravelling of a surface may be due to poor quality and/or inadequate bitumen, air voids content, water susceptibility of the mix, the number of commercial vehicular traffic, etc (Epps, 1986) and cracking may be due to thermal and/or traffic induced fatigue (Yeates, 1993). During both the first (1989) and second (1993) world conferences on reflective cracking in pavements the preface stated was:

> 'The rehabilitation of cracked roads by overlaying is rarely a durable solution. In fact, the cracks rapidly propagate through the new asphalt layer…. with current financial restrictions, road maintenance authorities have to find solutions with a good cost-benefit ratio. Many solutions have been proposed … these solutions are supported by numerous studies … In spite of these efforts, it seems that universal crack repair treatment with good durability is still lacking'.

In order to meet the challenge of ever increasing traffic, researchers have intensified their activities into the design of improved pavement materials. The aim is to improve design, optimise the use of materials and identify efficient processes of road construction. Currently, one of the vital areas of the science and technology of road design and construction involves a comprehensive appreciation of the behaviour of materials as well as their application in different environmental conditions. The task for engineers in this millennium will be the reuse and recycling of materials for conservation of energy and preservation of the environment.

Recycled waste plastics, derived from municipal solid waste, have been investigated at the Civil Engineering Materials Unit (CEMU), the University of Leeds as a partial aggregate replacement for use in

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[1] *Latif Budi Suparma, Ir, M.Sc., Ph.D., Lecturer at Department of Civil Engineering, Faculty of Engineering, Gadjah Mada University*

bituminous composites. Granulated Low Density Polyethylene (LDPE) pellets and Polypropylene (PP) flakes have been successfully incorporated into dense graded Asphaltic Concrete and gap graded Hot Rolled Asphalt mixtures respectively in proportions of up to 30% by volume of the composites (Zoorob and Suparma, 2000^a and 2000^b). The successful outcome of the project, especially the incorporation of recycled waste LDPE plastics in the Asphaltic Concrete, prompted us at the CEMU to consider the use of such waste derived plastics in other road pavement applications. Further applications was investigated i.e. the use of recycled waste LDPE as a constituent of Stress Absorbing Membrane Interlayers (SAMI).

BACKGROUND TO THE PHENOMENON OF REFLECTIVE CRACKING

Reflective Cracking

Finn *et al.* (1978) defined reflection cracking as a surface replication of the joints and cracks that are in the underlying layers of the pavement and foundation materials. Road surfaces undergo functional deterioration once they are open to traffic with cracks being the most common feature. It is therefore imperative that early attention is given to their repair to prevent severe structural deterioration of the pavement, which may require a costly reconstruction option. Due to the fact that an overlay is cheaper and also permits an early restoration of traffic flows it is commonly preferred to reconstruction to overcome functional failures in pavements.

An area of major concern is the overlay of old concrete pavement with bituminous mixes. Bituminous mixtures do not have the capacity to resist large shear and tensile stresses set up as a result of thermal expansion and contraction in the concrete.

1. Nature and Origin of Cracks

Columbier (1997) indicated that pavements are made up of materials varying very widely both in nature and in properties – unbound aggregates, bitumen bound materials, materials treated with cementitious binders, etc. Structures formed with these materials are liable to fracture by many causes; giving rise to cracks of highly different shapes and natures. Overlays applied on cracked pavements experience a variety of stresses as a result of traffic and environmental stresses and also due to these different forms of cracks. He asserted that controlling crack reflection through pavements is a complex task, which requires a correct diagnosis of the nature and causes of the crack in directing the choice of a solution. He further intimated that the possible origins of cracks are fatigue, shrinkage, movement of the subgrade, constructional defects, ageing and environmental exposure.

Fatigue. This is due to the pavement having carried cumulative traffic beyond the limit of its design life often resulting in the appearance of cracks.

Shrinkage. A pavement is considered as of infinite length and any impediment to shrinkage will give rise to cracks; this is particularly so if the friction with the underlying surface is strong enough to subject that layer to stresses greater than its tensile strength.

Movement of the Subgrade Soil. Local loss in bearing capacity resulting from one of the following may cause cracks, which propagate through the various layers of the pavement: a) increased moisture content in poorly drained subgrade; b) slow settlement of a compressible subgrade; c) land slip; d) loss of moisture of clayey soils in dry periods; and e) frost heave of subgrade.

Constructional Defects. Errors in pavement design or poor constructional practice may lead to variation in bearing capacity, weak spots in longitudinal joints between adjacent paving lanes and slippage between layers due to lack of proper bonding. Cracks may result from each of these circumstances under the action of traffic.

Ageing and Environmental Exposure. Bituminous Materials become brittle with time and unable to accommodate the tensile strains caused by thermal contraction due to age hardening of the binder and exposure to the environment. This phenomenon may cause the initiation of cracks from the surface of the wearing coarse.

2. Mechanism of Reflective Cracking

Three basic fracture modes can be distinguished for in-service field conditions (Figure 1). These are as a result of repeated traffic loading, changes in temperature and a combination of both horizontal and vertical movements occurring in the original pavement layers. These movements have been recognised to be the cause of crack growth in pavements.

Paris and Erdogan (1963) proposed an empirical relationship for the rate of crack growth under these repeated loading conditions applying the principles of fracture mechanics:

$$\frac{dc}{dN} = A(\Delta K)^n \qquad (1)$$

Rearranging and integrating Equation 10.2 yields:

$$N_f = \int_0^h \frac{dc}{A(\Delta K)^n} \qquad (2)$$

where:

c = crack length;

h = overlay thickness;

ΔK = amplitude of stress intensity factor for the given mechanism of cyclic loading ($\Delta K = K_{max} - K_{min}$);

N_f = number of load cycles to fracture;

A, n = fracture parameters, material constants for the overlay mix.

When the stress intensity factors under in service field conditions for each crack growth mechanism and the fracture parameters A and n for an overlay mixture are known the Paris and Erdogan law can be used to predict overlay life against reflection cracking.

3. *Review of methods used to inhibit reflective cracking in road pavement*

Historically thicker overlays have been resorted to as a method of treating cracks in pavements. However in recent years other methods of mitigating and prevention of reflection cracks have evolved. Rust (1986) lists the following mechanisms: a) surface applications or membranes; b) overlays; c) composite systems containing stress relieving interlayer; and d) other methods such as recycling, heater scarifying and rejuvenation, crack filling etc.

Surface applications or membranes. Several methods have been used as surface applications and membranes to tackle the problem of reflection cracking. One such method is surface dressing. Although the method provides a seal to the cracks this has been shown to be temporary. Investigation has shown that surface dressing as a mitigating measure is ineffective with the road surface deteriorating to its original condition in less than 6 months of its laying (Rust, 1986).

The use of thin rubberised bituminous mixtures known as Stress Absorbing Membrane (SAM) has been reported to be successful in retarding reflection cracking. This involves spraying rubber-modified bitumen followed by spreading of aggregates as cover (Olsen, 1973).

However, after reviewing a few experiments it was concluded that it appears an overlay of 50mm minimum is necessary for substantial delay of alligator crack reflection, a thickness of 75mm minimum is desirable over block cracking and 90mm overlay if cement treated base is involved.

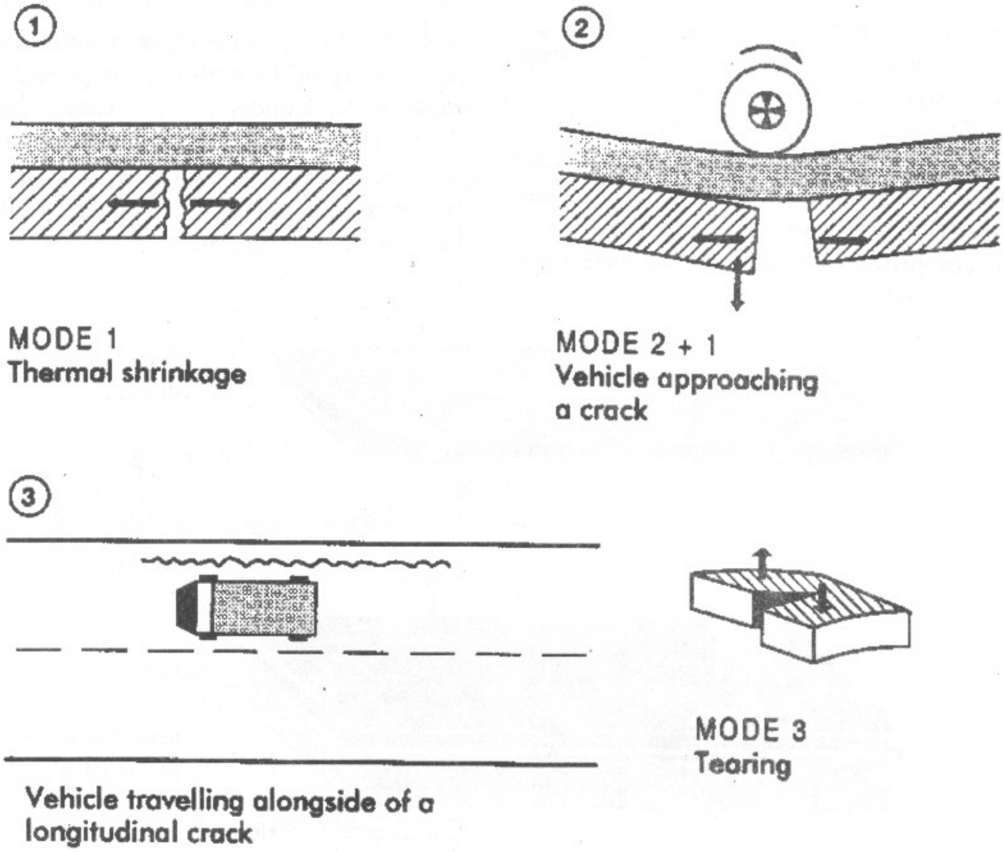


Figure 1. Modes of movements that cause crack propagation

Composite systems containing stress relieving interlayers. There is a wide range of commercially available interlayer products, which can be classified into a limited number of categories. Often used are sand asphalt, SAMI's, nonwovens, grids and steel netting reinforcement. Different methods are used to fix these layers to provide good adhesion to the underlayer and the choice depends on the product. Examples are tack coat, binder layer, slurry seal and nailing. The role of an interlayer in a road structure depends on the type and can be:

1) To take up the large localised stresses in the vicinity of cracks and, hence, reduce the stresses in the bituminous overlay above the crack tip. The product in that case acts as reinforcement; this is the case for most grids and steel netting reinforcement;
2) To provide a flexible layer able to deform horizontally without breaking in order to allow the large movements taking place in the vicinity of the crack. This is the case for impregnated nonwovens, SAMI's and sand asphalt; and

To provide a waterproofing function and keeping the road structure impermeable even after the reappearance of cracks in the road surface. This is the case for nonwovens and SAMI's (Vanelstraete and de Bondt, 1997).

A given system acts as reinforcement if its overall Stiffness Modulus is higher than that of the bituminous overlay. Dempsey and Mukhtar (1996) during the conduct of a detailed study of the causes of reflective cracking and the behaviour and performance of AC overlays with interlayers developed a system called Interlayer Stress Absorbing Composite (ISAC) Layer. This is comprised of a visco-elastic membrane which is a blend of vulcanised rubber (25-30% by weight) and appropriate viscosity asphalt (70 –75% by weight) laid between a high stiffness geotextile on top and a low stiffness geotextile beneath (Figures 2 and 3). Based on laboratory and field evaluations for three years, they concluded that the AC overlay performed exceedingly well when it was treated with the ISAC layer compared with a controlled overlay and it also out performed two commercially available products for the control of reflection cracking.

Other methods. An alternative to the traditional overlay in solving the problem of deteriorated road surface is recycling the existing surface material and mixing with new material to provide a new layer.

Milling of one or more layers of the pavement surface during the recycling process causes an increase in the fines content of the old material. Furthermore due to ageing, the viscosity of the bitumen in an old pavement surfacing gets higher and thus becomes more brittle. There is therefore the need to re-mix the reclaimed material, followed by relaying and compaction, with new clean aggregates and bitumen to meet the required gradation, air voids and stability. The recycling process may afford considerable savings in terms of the overlay material (Rust, 1986).

Scarifying with heaters up to a depth of 25mm and adding rejuvenating agents i.e. emulsions to soften the existing old pavements layers resulting in lowering of the viscosity of the bitumen component tends to cause cracks to heal under traffic loading and temperature (Rust, 1986). Rejuvenated and re-compacted old pavement materials provide an increased layer thickness (old material and overlay) through which cracks have to propagate.

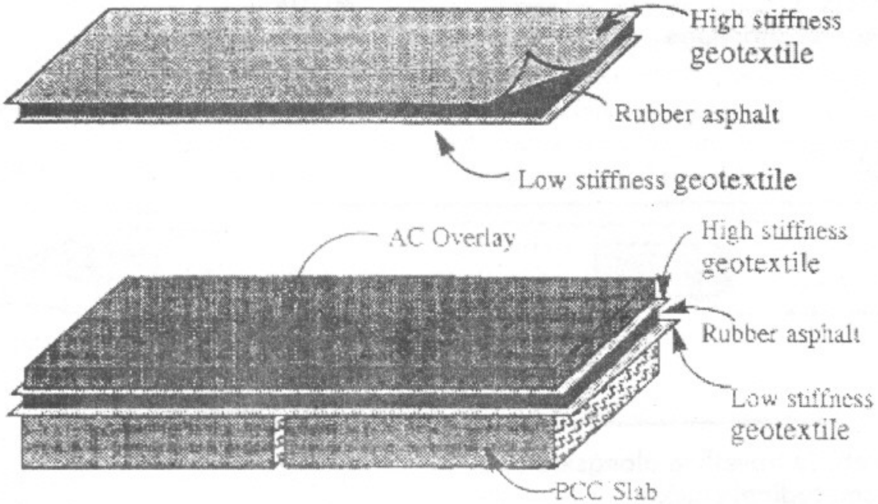


Figure 3. ISAC Layer Located in a pavement System (After Dempsey and Mukhtar, 1996)

EXPERIMENTAL METHODS

Materials

Plastic-aggregate composites used for the SAMI mixtures were manufactured with different proportions of the following constituents: recycled waste LDPE pellets (particle size ranging from 1.18–5.0 mm) with SG of 0.87, natural quartzitic sand (SG of 2.69), and Ordinary Portland Cement (OPC) filler (SG of 3.18). At the first attempt, the composition of LDPE by volume (approximate) was varied between 20-60%.

For each SAMI mixture composition, 100-pen. grade bitumen was introduced to each mixture type in the following proportions: 9.0, 9.5 and 10.0% by mass of the mixed aggregate (Table 1).

SAMI Specimen preparation

The mortar (sand and OPC) was preheated for at least 4 hours prior to mixing at 150°C. The 100-pen bitumen was preheated for 2 hours at 150°C and finally the LDPE pellets were preheated for only 1 hour at 125°C. The aggregates were mixed dry for about two minutes to ensure uniform distribution of the different sizes before adding the required amount of bitumen. Mixing was then continued until all the aggregates were uniformly coated. The resultant mixture was then compacted in a 500x100x100mm mould using a vibrating hammer compactor to a depth of 12 mm.

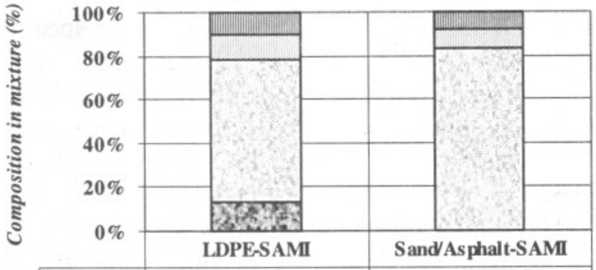
One of the main concerns when utilising recycled waste plastics in bituminous composites, especially a thin SAMI layer, is the unavoidable shrinkage upon cooling from compaction to ambient temperature. In this investigation, the selection of an optimum design SAMI mixture was based upon the mixture containing the highest amount of LDPE pellets which showed no shrinkage. The results indicated that there was no shrinkage of the specimens containing 35% by volume LDPE pellets at 10% bitumen content. This composition was selected as the SAMI mixture for further reflective cracking tests.

In addition to testing the LDPE SAMI for its ability to retard reflective cracking, a Sand/Asphalt SAMI (sand + filler + bitumen) was also investigated to eliminate the possibility of sand being the main contributor of any improved fatigue characteristics. The Sand/Asphalt SAMI was formulated by removing all the LDPE from the selected design LDPE-SAMI mixture volumetrically, whilst maintaining the proportion of filler and bitumen. Therefore, the bitumen content of the Sand/Asphalt SAMI mixture remained at 10% by mass of total mixture. Figure 4 presents the material compositions of the design LDPE-SAMI and Sand/Asphalt-SAMI investigated in this study.

To assess the relative performance of the two SAMI types (LDPE and Sand/Asphalt) with respect to their ability to delay reflective cracking, the fatigue assembly shown in Figure 5 was used. To achieve the above objective, the fatigue performance of HRA beams with and without the thin SAMI layers described earlier was determined. A conventional 35/14 HRA wearing course mixture (beneath which the SAMI would be located) was adopted for casting the beam samples for investigating the effectiveness of a selected SAMI mixture in delaying reflection cracking. The 35/14-HRA mixture contained 14mm maximum aggregate size and consisted of 35% limestone coarse aggregates, 55% natural quartzitic sand and 10% OPC filler, blended with 7.5% 50-penetration grade bitumen.

Table 1. Aggregate composition of SAMI mixtures, percent by mass.

Material	Specific Gravity	Mix designation (% of total mixture)							
		A	B	C	D	E	F	G	H
LDPE	0.87	7.3	9.5	11.9	14.5	17.4	20.5	24.0	32.2
Sand	2.70	78.8	76.9	74.9	72.6	70.2	67.5	64.6	57.7
OPC Filler	3.18	13.9	13.6	13.2	12.8	12.4	11.9	11.4	10.2
$SG_{\text{mixed aggregate}}$		2.383	2.288	2.194	2.099	2.004	1.909	1.815	1.626
Composition of LDPE by volume of aggregates		20%	25%	30%	35%	40%	45%	50%	60%



	LDPE-SAMI	Sand/Asphalt-SAMI
▦ Bitumen	10.00	7.8
☐ OPC	11.54	9.1
☐ Sand	65.38	83.1
▨ LDPE	13.09	

Figure 4. Composition by mass of materials in LDPE-SAMI and Sand/Asphalt-SAMI mixtures

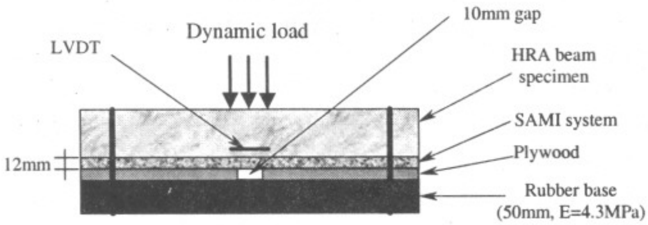


Figure 5. The schematic view of the experimental arrangement

Fatigue testing was carried out at a controlled test temperature of 20°C and the testing conditions were as follows:

1. Contact stress under the load of 450kPa applied repeatedly in a constant stress mode of loading;
2. One cycle per second loading frequency;
3. The test beams were divided into two identical sets. Half the specimens were tested using a load rise time of 120msec. (time from zero to maximum load), whilst the other half of the specimens were tested with a rise time of 130msec.

RESULTS AND DISCUSSION

Fatigue performance

Two load rise times, 120msec and 130msec, signifying relatively fast traffic speeds were applied to supplement the single stress level during the tests. The fatigue relationships were obtained by plotting the initial tensile test strain data versus number of cycles to failure (N_f) data on a log-log scale and determining the equation of the best fit line. The relative locations of the fatigue lines provides an indication of the relative fatigue performance.

A better assessment of the fatigue life of a bituminous mixture would be to measure the initial strain level that is generated during initial pulses of loading and relate that to fatigue life. Using the definition of Bjorklund (1985) a plot of the relationship between the accumulated displacement against the number of stress pulses was plotted for all the specimens. To determine the initial strain value for any one test, the strain value at the intersection of the extrapolation of the two linear parts of the cumulative strain versus time lines was used. The experimental strain/time curve is characterised by an initial period of large strain build up and a secondary part that illustrates a constant rate of increase in strain amplitude. The number of cycles to failure (N_f) of the specimen is defined as the number of pulses at which the specimen completely fails. Fatigue line equations were calculated for each composite beam, although the coefficient of correlation was found not to be high (less than 0.9). Table 2 presents fatigue line equations for all the beam SAMI composites tested in this investigation.

The test results indicated that the initial strain values for LDPE-SAMI and FD-HRA (full depth HRA beam) were almost the same, indicating that the initial stiffness values of the beams with and without the LDPE SAMI were very similar. On the other hand, the number of cycles to failure (N_f) for the LDPE SAMI beams at the same stress level were higher compared to the full depth HRA beams. The Sand/Asphalt-SAMI beams had much higher initial tensile strain values and as a result lower number of pulses to failure, indicating a reduction in beam stiffness. This implies that crack propagation would be much slower in the LDPE-SAMI beams than in either of the other two composites.

Table 2. Fatigue line equations for beam SAMI composites

Beam composite type	Equation based on initial strain	Equation based on number of cycles to failure	R^2
Full Depth-HRA	$\varepsilon = 6402.9 \times N_f^{-1.2841}$	$N_f = 9.21 \times 10^2\ \varepsilon^{-0.78}$	0.80
LDPE-SAMI	$\varepsilon = 3.6516 \times Nf^{-0.5329}$	$Nf = 1.14 \times 101\ \varepsilon^{-1.88}$	0.79
Sand/Asphalt-SAMI	$\varepsilon = 0.066 \times Nf^{-0.0655}$	$Nf = 9.50 \times 10\text{-}19\ \varepsilon^{-15.27}$	0.73

Efficiency of beam specimen

The failure criterion of maximum measured strain at the same stress level was used to assess and compare the specimens in terms of their ability to delay crack propagation. The efficiency equation used by Rigo, et al., (1989) discussed earlier was modified to enable comparison of the beam specimens in terms of crack propagation, i.e.

$$EFF = {(N_{max})_S}\Big/{(N_{max})_R} \qquad (3)$$

where: $(N_{max})_S$ = the number of cycles needed to obtain a reflective crack propagating through the overlay for a given system; $(N_{max})_R$ = the same but for the case where no interlayer is placed.

Table 3 shows the efficiencies of the various beam specimens relative to the average of Full Depth HRA beams.

Table 3. Comparison of efficiencies of beam specimens

Specimen	Average Nf		Efficiency	
	120ms	130ms	120ms	130ms
FD-HRA	32558	25406	1.00	1.00
LDPE-SAMI	52800	32384	1.62	1.27
Sand-SAMI	2706	2768	0.08	0.11

The effects of higher bitumen content may be argued to have contributed to the superior fatigue behaviour of the beams incorporating the LDPE SAMI when compared to the full depth HRA. Nonetheless, it is the opinion of the writer that the 50-pen grade bitumen used in the Full Depth HRA beam may have compensated, in terms of increased beam stiffness, for any 'excess' 100-pen grade bitumen in the SAMI. It can therefore be safely concluded that the plastic pellets do play a significant role in the improved fatigue life of the LDPE SAMI beams. Furthermore the fact that the Sand/Asphalt-SAMI which had the same bitumen content and grade as the LDPE SAMI did not show such improvement is a pointer to this claim. The SAMI material is more capable of dissipating the energy resulting from the crack tip during the passage of traffic on cracked road bases and in delaying both crack initiation and propagation compared to the full depth HRA.

CONCLUSIONS

1. The quantity of LDPE found to show no shrinkage was up to and including 28% by volume of the total SAMI mixture (13% by mass). However shrinkage is very dependent on the bitumen content.
2. Although the indirect tensile stiffness modulus of compacted specimens composed of a conventional HRA mix were slightly higher than those of specimens composed of the LDPE SAMI mix, the higher stability and flow (and to a minor extent, the bitumen content) values of the SAMI specimens seem to be the prime factors for its superior fatigue life. The beams containing a thin LDPE SAMI showed superior resistance to crack initiation compared to both control beam types, i.e. Full Depth Asphalt and Sand/Asphalt-SAMI beams.
3. Asphalt beams reinforced with a thin layer of LDPE SAMI outperformed the full depth asphalt beams in terms of crack propagation. The efficiency criterion adopted for the investigation showed that the beams incorporating the LDPE SAMI were 62% more efficient than beams of the same thickness composed entirely of HRA.

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