PROPERTIES OF POLYMER- AND FIBRE-MODIFIED POROUS ASPHALT MIXES

B.M.J.A. Verhaeghe[1], F.C. Rust[2], R.M. Vos[3], A.T. Visser[4]

[1]Project Manager: Asphalt Technology
CSIR Roads and Transport Technology
Pretoria, South Africa

[2]Programme Manager: Road Engineering
CSIR Roads and Transport Technology
Pretoria, South Africa

[3]Technical Manager
Sabita
Cape Town, South Africa

[4]Professor: Civil Engineering
University of Pretoria
Pretoria, South Africa

Abstract

In view of the increasing traffic volumes in South Africa and especially with regard to the impact of that on noise pollution and wet-weather accident rates in urban areas, the Southern African Bitumen and Tar Association expressed a need for an investigation into porous asphalt, which, in recent years, has become popular in European countries for addressing environmental and safety needs. A project focusing on the use and properties of porous asphalt mixes containing polymers and cellulose fibres was defined. This paper addresses the relative performance of modified porous asphalt mixes and aspects relating to the design of such mixes, based on a laboratory study. It was found that polymer-modification of the binder enhances the relevant engineering properties of porous asphalt.

1. INTRODUCTION

Open-graded asphalts have been used successfully in South Africa to improve skid resistance and reduce noise (Visser et al, 1). These mixes, however, had their problems. They tended to ravel at an early age and often lost their functional properties by the premature clogging of voids. Porous asphalt has a void content usually in excess of 20 per cent, which is greater than that of open-graded mixes. On account of their favourable volumetric properties, porous asphalt mixes have the potential to further improve the above functional parameters.

In order to be economically viable, porous asphalt wearing courses should have design lives of at least ten years. Owing to the high void content of these mixes, their structural strength is relatively low and environmental forces such as moisture, oxygen, heat and ultra-violet rays may seriously affect the durability of the mix, by comparison with the impact of these forces on the rate of deterioration of dense-graded asphalt wearing courses. If wearing courses are not adequately designed to resist these forces, stripping and aggregate loss may take place prematurely, resulting in shorter maintenance cycles and a lower benefit-cost ratio.

In view of the beneficial functional properties of porous asphalt, both the South African road authorities and the South African asphalt industry expressed a need for an investigation into the properties and durability of this type of mix. The purpose of this paper is to compare the structural performance of porous asphalt mixes containing polymeric or organic additives with that of porous asphalt mixes made with conventional, unmodified binders. The effects of additive type, grading and binder content on performance parameters, such as resistance to plastic deformation, fatigue, abrasion, moisture-induced damage and age hardening, are evaluated. The investigation was, however, limited to a laboratory study and the findings have not, therefore, been related to actual field performance.

2. CHARACTERISTICS AND APPLICATION OF POROUS ASPHALT MIXES

Porous asphalt wearing courses are bituminous bound mixes with discontinuous gradings whose void contents are in excess of 20 per cent (preferably) and in which the nature of the voids is such that rainwater can be conveyed through a system of interconnecting voids to the boundaries of the pavement. They are manufactured from a combination of a bituminous binder (modified or unmodified), a high proportion of coarse aggregate (aggregate fraction retained on the 4,75 mm sieve in excess of 80 per cent) and limited amounts of fines and filler (filler content of between 2 and 5 per cent). The asphalt is heated, blended and mixed at a central plant, after which it is transported to, laid and compacted on a sound and impermeable support.

The qualitative improvements brought about by the high void contents of porous asphalt wearing courses can be summarised as follows:

- possibility of aquaplaning is reduced;
- splash and spray behind vehicles is reduced (Figure 1);
- reflection from the surface of the wet pavement is avoided and thus the visibility of pavement markings is enhanced (Figure 1);
- noise inside and outside vehicles is reduced;
- vibration inside vehicles is reduced, thus inducing more comfort for the driver and passengers, and reducing damage to electronic devices;
- wet skid resistance is improved through improved adhesion at high speeds, resulting in a decrease in wet-weather accident rates (Table 1);
- water is temporarily stored within the layer, and
- traffic congestion may be reduced.

TABLE 1: Wet-weather accident performance on a highway after widening and after application of porous asphalt (Faure et al, 2)

dense-graded, two lanes	dense-graded, widening to three lanes	Porous asphalt overlay on three lanes
9 accidents in 6 years	52 accidents in 6 years	0 accidents in 3 years

FIGURE 1: Functional benefits of porous asphalt

However, as a result of the relatively open structure of porous asphalt, the binder is likely to undergo accelerated ageing due to oxidation, which in turn will increase the stiffness of the material and decrease the ductility of the binder system. This may lead to early fatigue failure and to ravelling. Also, porous asphalt has relatively low structural strength (low stiffness, indirect tensile strength and shear strength) compared with that of dense-graded asphalt mixes and the relatively thin binder films holding the aggregate structure together may be insufficient to counter the loss of aggregate particles as a result of moisture attack and of the abrasive forces of traffic. Higher binder contents may result in a reduction in the rate of oxidation and may increase resistance to abrasion. However, an increase in binder content may result in both an increase in binder drainage during construction and a decrease in void content for a given aggregate grading which, in turn, will reduce the functional benefits of porous asphalt.

In view of the beneficial functional properties of porous asphalt mixes, their most common application is in areas where water tends to accumulate or where a water hazard could decrease traffic capacity or impair traffic safety, such as at changes in superelevation, busy motorways or wide pavements (motorways, runways), limited-access roads and highways prohibited to slow-moving traffic. Another application is on roads with recognized noise pollution problems, particularly on noisy arterials in urban areas, cross-town freeways or motorway links. With respect to the weaker structural properties of porous asphalt relative to those of dense-graded mixes, porous asphalt should not be used in urban or industrial areas where there is extensive wear from abrasion, where impacts or spillage of oil or fuel take place, at high stress sites (such as intersections), on areas in which there is a strong risk of reflective cracking (unless the existing surface is efficiently sealed), either by shear or fatigue, or on roads which are frequently soiled with waste, as clogging of the voids may reduce drainage capacity and increase noise levels (Van Heystraeten and Moraux, 3).

3. CHARACTERISTICS OF THE ADDITIVES

Modification of the binder with a number of selected additives enhances the structural properties and the durability of, for instance, dense asphalt mixes. Consequently, new frontiers were opened for the innovative use of modified binders in porous aggregate structures, where the structural properties and durability of the mix are highly dependent on the properties of the binder and binder content. The modifiers used not only improve properties such as resistance to fatigue and deformation but also enable higher binder contents to be used, which may result in increased durability and stone retention without causing binder run-off during the construction process.

In this paper, the influence of modification by means of Styrene-Butadiene Rubber (SBR), Stryrene-Butadiene Styrene (SBS), Ethylene-Vinyl Acetate (EVA) and cellulose fibres on the engineering properties of porous asphalt mixes is investigated. The characteristics of the different types of modifiers are given below and the physical properties of the polymer-modified binders are summarised in Table 2.

3.1 Styrene-Butadiene Rubber (SBR)

Styrene-butadiene rubber is an elastomeric polymer which is added in latex form to a base bitumen under agitation. At high service temperatures (50°C to 60°C), the behaviour of the SBR-modified binder is characterized by greatly increased viscosities and shear rates by comparison with those of unmodified binders. This is indicative of greater stiffness of the binder for long loading times (or low frequencies). This improvement is important in order to resist mix tenderness and to prevent rutting in asphalt. At low service temperatures (below 10°C), the presence of the elastomer improves the elastic characteristics of the binder without increasing its stiffness, in contrast to what happens in the case of bitumens with lower penetration values. The modification of a bitumen with SBR may thus result in a substantially improved fatigue life by reducing flexural fatigue cracking.

3.2 Ethylene-Vinyl Acetate (EVA)

Ethylene and vinyl acetate copolymers are compatible with bitumens, as both the vinyl acetate content and molecular mass or melt flow index (which is inversely proportional to the molecular mass) can be altered to suit different types of bitumen. The vinyl acetate content, which can vary between a few per cent and more than fifty per cent, determines the mechanical properties of the binder and the compatibility of the binder with the polymer. High vinyl acetate contents give low strength properties, good compatibility, soft blends and great tenacity, and *vice versa*. At high vinyl acetate contents, the modified blend has properties similar to those of elastomeric polymers. Low melt flow indices give higher strength properties than do high melt flow indices but do not blend as easily. EVA-copolymers are noted for improving the workability and resistance to rutting of hot mix asphalt.

3.3 Styrene-Butadiene Styrene (SBS)

SBS-modified binders behave as cross-linked rubbers below approximately 100°C. They, therefore, add substantially to the strength of modified bitumen at high road temperatures. The long polybutadiene chains contribute to the flexibility of the binder at very low temperatures. The elastomeric lattice in the bitumen provides the desired properties of elasticity, plasticity and elongation. When SBS-modified binders are applied in wearing courses, these binders can improve:

- adhesion to aggregate;
- chip retention (initial and long term);
- fatigue resistance and low temperature flexibility;
- resistance to permanent deformation, and
- resistance to bleeding and fatting up.

3.4 Cellulose fibres

Cellulose fibres are currently being used extensively in porous asphalt friction courses in several countries of northern Europe. The introduction of fibres into bituminous mixes forms a relatively inexpensive means of improving the engineering properties of mechanically modified asphalt mixes. The fibre reinforces the binder system, thus causing an increase in the viscosity of that system. The resulting mix could have greater stability and possibly higher resistance to fatigue cracking than similar mixes containing no fibres. The fibres can also prevent binder run-off during mixing, transportation and paving operations, especially in the case of porous asphalt mixes or of other mixes with discontinuous gradings. The durability of asphalt mixes may also be improved by the use of higher binder contents with resulting greater film thicknesses, but with reduced gravitational drainage of binder through the material.

TABLE 2: Physical properties of binders

Property	Control: 80/100 Pen	Control +		
		4% EVA	4% SBR	4% SBS
Penetration (25°C)	86	105	69	64
Softening Point (Ring & Ball)	45,2°C	55,5°C	61,0°C	51,0°C
Elastic Recovery (10°C)	11,0%	50,0%	63,5%	72,0%
Fraass Brittle Point	-9,5°C	-10,0°C	-9,0°C	-9,0°C

4. LABORATORY CONDITIONING AND TESTING SYSTEMS

In order to investigate the effects of moisture and heat on the engineering properties of porous asphalt mixes, these mixes were subjected to the following conditioning procedures:

- vacuum-saturation followed by freeze-thaw cycle (moisture conditioning), and
- temperature-conditioning in forced draft oven.

Moisture conditioning was performed according to the Lottman method (Lottman, 4 and 5) which is designed to simulate the effect of moisture in the asphalt mix at the peak of saturation in the field (vacuum-saturation phase) and the ultimate, long-term effect of moisture-damage, which occurs in the asphalt mix (after the effects of saturation) due to the forces of environment and traffic (freeze-thaw phase).

Temperature conditioning for the simulation of age hardening was performed in accordance with the methods outlined in the Asphalt-Aggregate Mixture Analysis System (AAMAS)-project (Von Quintus et al, 6). Conditioning consists of placing samples in a forced draft oven for 2 days at 60°C after which the oven temperature is raised to 107°C for an additional 5 days.

In order to quantify the differences in performance between modified and unmodified porous asphalt mixes, the following properties were determined:

• binder run-off;	(unconditioned samples)
• aggregate loss through abrasion;	(unconditioned samples)
• indirect tensile stiffness (resilient modulus);	(conditioned samples included)
• indirect tensile strength;	(conditioned samples included)
• fatigue life;	(conditioned samples included)
• dynamic creep modulus;	(unconditioned samples)

Binder run-off was determined by means of the basket drainage test. In this test, porous asphalt mixes prepared at various binder contents are placed uncompacted in perforated baskets. The baskets containing the samples are then placed for two hours in an oven which is set at normal mixing temperature. The binder which drains through the grid is recovered and the loss of binder is calculated with respect to the initial binder content (Faure et al, 2).

Aggregate loss through abrasion was determined by means of the Cantabro abrasion test (Calzada, 7; NLT-352/86, 8). This is an abrasion and impact test carried out in the Los Angeles rattler (ASTM, 9). In this test, a Marshall sample compacted with 50 blows on each side is used. The mass of the test specimen is obtained to the nearest 0,1 gram and placed in the Los Angeles Rattler without the abrasive charge of steel spheres. The operating temperature is usually 25°C. The machine is switched on and allowed to operate for 300 revolutions at a speed of 3,1 to 3,5 rad/sec (30 to 33 rpm). After the required number of revolutions, the test specimen is removed and the mass again determined. The percentage abrasion loss is then calculated and expressed as a percentage of the initial mass.

The indirect tensile test (Kennedy et al, 10) was used to measure the indirect tensile stiffness and indirect tensile strength of porous asphalt mixes. The test has, however, been modified by placing the lateral measurement device directly on the sample (Dunaisky and Hugo, 11). The improved accuracy of measurement yielded a significant increase in the validity of the Poisson's ratios calculated. For the determination of stiffness, a repeated load of 2,0 kN and a total frequency of 1 Hz were used (0,1 s loading and 0,9 s rest period). Three indirect tensile tests were conducted for each combination of grading, binder type, binder content and conditioning method.

A third-point loading fatigue apparatus was manufactured to enable the fatigue properties of porous asphalt mixes to be evaluated. Beams (400 x 75 x 54 mm), obtained from slabs compacted in a steel-wheel slab compactor, were loaded in the test frame with four clamps with a spacing of 100 mm between clamps. Samples were tested in constant strain mode (1 280 microstrain or 0,5 mm deflection), using a 10 Hz Sine loading frequency. The tests were performed at a temperature of 10°C. Formulae suggested by Irwin (Irwin and Gallaway, 12) were used to calculate the elastic moduli, initial stresses and strains. Four fatigue tests were conducted for each combination of grading type, binder type and conditioning method.

A unconfined, uniaxial dynamic creep test (0,5 Hz, 100 kPa, 40°C, 3,600 load repetitions), which gained wide acceptance in the UK (Cooper and Brown, 13) was used to assess the permanent deformation characteristics of asphalt briquettes. This test, which is designed and calibrated for dense-graded asphalt mixes, may not be suitable for evaluation of the deformation resistance of porous asphalt mixes in absolute terms, but nevertheless provides useful information on the relative performance of porous asphalt mixes containing different types of binders.

5. PROPERTIES OF UNCONDITIONED POROUS ASPHALT MIXES

The gradings and void contents of five porous asphalt mixes are given in Table 3. Also shown in the table are the various tests performed on these mixes.

TABLE 3: Gradings, bulk relative densities and void contents

Sieve size (mm)	Grading A		Grading B	Grading C	Grading D
19,0	100		100	100	100
13,2	95,0		87,0	87,0	77,0
9,5	50,0		60,5	62,0	45,0
4,75	11,0		21,5	22,0	26,0
2,36	9,0		15,0	16,0	19,0
1,18	8,0		13,5	12,0	15,0
0,600	6,5		11,5	8,0	12,5
0,300	5,5		9,0	7,0	10,0
0,150	4,5		7,0	6,0	7,5
0,075	3,5		5,0	4,0	5,0
Aggregate type:					
Quartzite	X	-	X	X	X
Dolerite	-	X	-	-	-
Void contents:					
Binder content of 4,0%	22,9	24,7	17,0	18,1	16,3
Binder content of 4,5%	21,9	24,0	16,2	17,0	14,6
Basket drainage test	-	X	-	-	-
Cantabro abrasion test	X	X	X	X	X
Indirect tensile stiffness	X	-	X	-	-
Indirect tensile strength	X	-	X	-	-
Fatigue life	X	-	X	-	-
Dynamic creep test	X	-	X	X	X

6. ENGINEERING PROPERTIES OF POROUS ASPHALT MIXES

6.1 Resistance to binder run-off

The binder drainage test, combined with determination of volumetric properties, is often used to determine the target binder content for porous asphalt mixes in order to maximize binder content so as to optimise durability, whilst eliminating possible binder drainage (Colwill et al, 14). Basket drainage tests were conducted on mixes manufactured from grading A (dolerite) and containing a wide variety of binder types. The results, as shown in Table 4, illustrate the advantage of adding cellulose fibres in preventing binder run-off from the aggregate. If it is assumed that a maximum of five per cent of binder can be allowed to be drained off at mixing temperature, then the following maximum binder contents may be specified for mixes manufactured according to the aggregate distribution specified for grading A:

- unmodified binders: 4,7 per cent
- polymer-modified binders: 5,3 per cent
- mixes containing fibres: >5,5 per cent

TABLE 4: Results of basket drainage test (Grading Type A)

Binder type	Temperature	Binder Content	Loss of Binder
60/70 Pen	140°C	4,0 % 4,5 % 5,0 % 5,5 %	1,1 % 3,8 % 8,7 % 20,8 %
80/100 + SBR	140°C	4,0 % 4,5 % 5,0 % 5,5 %	0,4 % 2,0 % 3,3 % 8,3 %
60/70 Pen + 0,3 % Cellulose Fibres	160°C	4,0 % 4,5 % 5,0 % 5,5 %	0,6 % 0,3 % 0,6 % 0,4 %
80/100 + EVA	160°C	4,0 % 4,5 % 5,0 % 5,5 %	0,8 % 0,9 % 3,3 % 7,2 %

6.2 Resistance to abrasion

The prevailing failure mechanism of porous asphalt mixes is loss of aggregate from the pavement surface. The deterioration process usually takes place relatively slowly and on this basis, a structural service life of between 10 and 15 years can be predicted. The Cantabro abrasion test can be used to determine the minimum amount of binder required to provide a porous asphalt mix with sufficient resistance to abrasion. The maximum abrasion loss is specified as 25 per cent for mixes with total air void contents in excess of 20 per cent (Ruiz et al, 15).

Both binder content and voids in the mineral aggregate (VMA) have more significant influences on abrasion loss than does binder type, as shown by the results in Table 5. Nevertheless, these results indicate that, where the binder is modified with a SBS-elastomer, the average losses from these porous asphalt mixes on account of abrasion are less than those of mixes containing other types of binder. In addition, at low binder contents, the modification of porous asphalt mixes by the addition of cellulose fibres results in mixes with poor resistance to abrasion. However, at high binder contents, the addition of cellulose fibres may improve the resistance to abrasion, relative to that of mixes made with unmodified binders (Table 6).

TABLE 5: Effects on grading type and binder type on abrasion loss

Grading Type	VMA Range	Binder Contents			
		4,0 %	4,5 %	5,0 %	5,5 %
		Abrasion Loss (%)			
A	27 % - 31 %	49,2	42,2	19,8	12,7
B	24 % - 27 %	14,4	11,5	8,8	6,0
C	25 % - 27 %	14,0	11,9	10,3	7,4
D	22 % - 26 %	15,0	11,0	8,2	5,0
Binder Type (grading B)					
60/70 Pen		14,8	9,4	7,5	-
80/100 Pen		17,7	6,4	4,1	-
Control + 4% EVA		11,2	10,3	7,6	-
Control + 4% SBR		17,3	14,7	11,4	-
Control + 4% SBS		9,3	6,9	5,3	-
0,3 % Fibres		34,1	19,8	13,2	-

TABLE 6: Results from the Cantabro abrasion test

Binder Type:	Binder Content				
	4 %	5 %	6 %	7 %	8 %
	Abrasion Loss (%)				
80/100 Pen	14,1%	10,3%	6,5%	-	-
80/100 Pen + 0,3% Fibres	17,7%	5,6%	5,0%	-	-
60/70 Pen + 0,3% Fibres	-	8,0%	7,6%	3,7%	-
60/70 Pen + 0,5% Fibres	-	-	4,2%	2,3%	1,8%

6.3 Bearing capacity

The stiffnesses of porous asphalt mixes are less than those of conventional, dense-graded wearing courses. These mixes, therefore, have less ability to distribute traffic stresses than dense-graded mixes. They should therefore not be used as strengthening layers in the rehabilitation of distressed road structures. The stiffnesses of porous asphalt mixes are generally about half to two-thirds those of dense-graded mixes, depending on the amount of voids within the mix (the higher the void content, the lower the stiffness of the mix). The results in Table 7 indicate that stiffness, when measured by means of third-point loading flexure (constant strain mode), is not significantly affected by the type of binder used (mixes containing polymer-modified binders versus mixes manufactured with unmodified binders). However, when stiffness is measured in constant stress mode (indirect tensile test), the results indicate that mixes containing polymer-modified binders have greater stiffnesses than those containing unmodified binders or fibre-modified binders.

TABLE 7: Average stiffnesses of two porous asphalt gradings

Binder Type:	80/100 Pen	+ 4% EVA	+ 4% SBR	+ 4% SBS	Fibres
			GRADING A		
Stiff 1 (MPa)	1 470	1 540	1 390	1 490	1 060
Stiff 2 (MPa)	1 340	1 430	1 840	2 100	1 200
ITS (kPa)	320	460	470	510	410
			GRADING B		
Stiff 1 (MPa)	2 050	2 140	1 960	2 070	1 430
Stiff 2 (MPa)	2 160	2 230	2 550	2 960	1 320
ITS (kPa)	480	640	680	690	500

Stiff 1: Initial elastic modulus (fatigue test)
Stiff 2: Resilient modulus (indirect tensile test)
ITS: Indirect tensile strength (indirect tensile test)

6.4 Stability and fatigue

With the exception of aggregate loss, other mechanisms of structural failure, such as rutting and cracking, are not expected to have a strong bearing on service life (unless the porous asphalt overlays active cracks which could cause severe problems by ingress of moisure to the granular layers!). On account of the nature of the grading, the coarse skeleton of porous asphalt should be adequate to resist plastic deformation, given that the aggregate is sound, durable and of high strength and that the porous asphalt layer is well compacted and supported. Although, on account of the grading, wheel tracking tests are preferred to unconfined compression tests such as the dynamic creep test, the latter test is nevertheless useful for measurement of the relative effects of binder modification on the cohesive and frictional properties of porous asphalt mixes.

The effect of binder modification on dynamic creep modulus is shown in Figure 2. The addition of 4 per cent of EVA to bitumen results in a doubling of the dynamic creep modulus. The addition of elastomers or cellulose fibres has intermediate effects on the resistance of porous asphalt mixes to plastic deformation.

The fatigue lives of two different types of porous asphalt mixes are given in Table 8, while the average decrease in modulus with an increase in the number of load repetitions is shown in Figure 3 (Grading A) and Figure 4 (Grading B). These results indicate that an increase in void content may result in a decrease in fatigue life. On the other hand, the use of binders modified by the addition of elastomers improves the fatigue resistance of unconditioned porous asphalt mixes considerably, while mixes made with plastomer-modified binders have fatigue lives similar to or better than those made with unmodified binders, depending on the grading of these mixes. Statistically, the effects of binder type and void content on fatigue life were found to be highly significant.

The fatigue performances of the different types of porous asphalt mixes are reflected by the indirect tensile strengths of these mixes (Table 7), by their void contents and by the fatigue performances of binder films (Table 8). The latter tests were conducted on the third-point loading fatigue apparatus, where 2,5 mm thick binder films were placed on discontinuous copper plates (gap of 1 mm in centre of plate) and fixed in the third-point loading fatigue apparatus. The binder films were then tested in constant-strain mode (temperature of 5°C, deflection of 1,5 mm and frequency of 10 Hz) until failure occurred. The number of repetitions to failure was recorded.

TABLE 8: Average fatigue lives of two porous mixes and binder films

Binder Type:	80/100 Pen	+ 4% EVA	+ 4% SBR	+ 4% SBS
GRADING A (23% voids)				
Fatigue Life:	31 500	29 200	117 600	111 500
GRADING B (17% voids)				
Fatigue Life:	58 400	106 600	132 100	130 800
BINDER FILMS				
Fatigue Life:	16 000	22 000	69 000	131 000

NOTE: The fatigue life of mixes is defined as the number of repetitions required to decrease stiffness to 50 per cent of its initial value. The fatigue life of binder films is defined as the number of repetitions required to fail a specimen.

6.5 Ageing and stripping characteristics

As a result of the relatively open structure of porous asphalt, the binder is likely to age more rapidly on account of **oxidation**, which in turn will increase the stiffness and indirect tensile strength of the material, and reduce its fatigue life (Table 9). Under site conditions, the penetration of conventional bitumens has been found to drop sharply in the first few months.

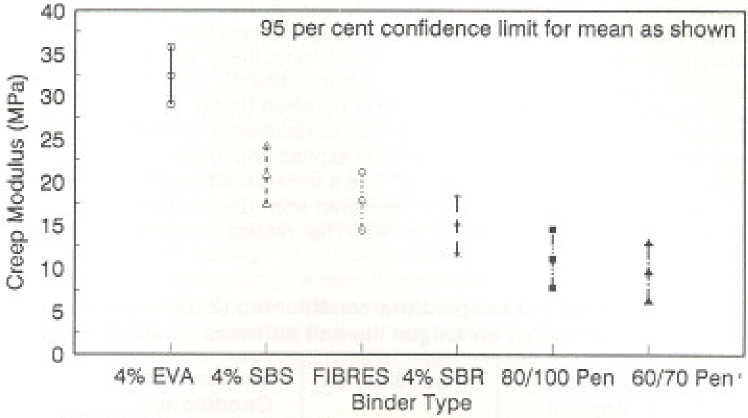

FIGURE 2: Effect of binder type on dynamic creep modulus

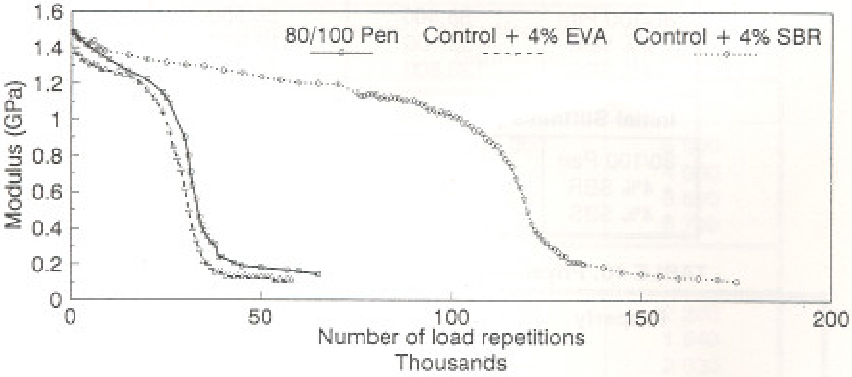

FIGURE 3: Fatigue test - Grading A: Typical decrease in modulus

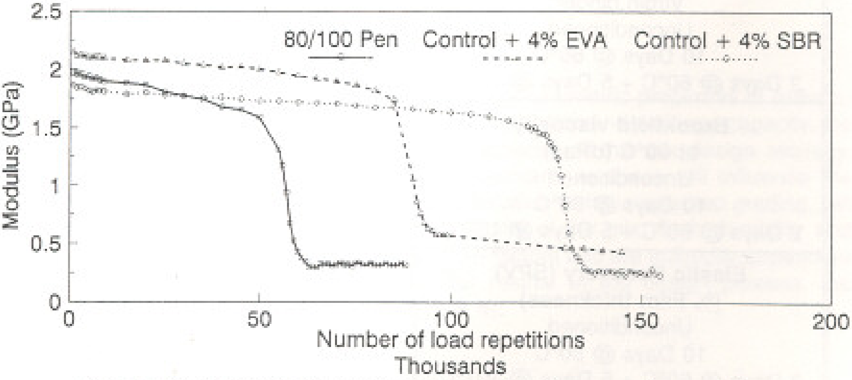

FIGURE 4: Fatigue test - Grading B: Typical decrease in modulus

It has been shown (Van Heystraeten and Moraux, 3) that after three years, 80/100 penetration grade bitumens have penetration values of less than 25 dmm and ring and ball softening points exceeding 60°C. After that period, the process seems to stabilize. Binders containing recycled elastomers (bitumen-rubbers), age at a slower rate. The ageing of binders with elastomers is midway between that of conventional bitumens and bitumen-rubbers. The physical properties of recovered unmodified and modified binders from temperature-conditioned porous asphalt briquettes (10 days @ 60°C and 2 days @ 60°C followed by 5 days at 107°C in a forced draft oven) are compared with those of virgin binders and of binders recovered from unconditioned porous asphalt briquettes. These are given in Table 10. The results conform with the above observations.

TABLE 9: Effect of temperature-conditioning (2 days @ 60°C + 5 days @ 107°C) on fatigue life and stiffness (Grading B)

Porous Asphalt	Unconditioned	Temperature-Conditioned
Fatigue Life (Repetitions)		
80/100 Pen	58 400	35 500
+ 4% SBR	132 100	115 600
+ 4% SBS	130 800	89 900
Initial Stiffness (MPa)		
80/100 Pen	2 050	2 420
+ 4% SBR	1 930	2 280
+ 4% SBS	2 070	2 210

TABLE 10: Physical properties of recovered binders

Property	Control: 80/100 Pen	Control +	
		4% SBR	4% SBS
Penetration (25°C - dmm)			
Virgin binder	86	69	64
Unconditioned	45	43	36
10 Days @ 60°C	43	38	37
2 Days @ 60°C + 5 Days @ 107°C	30	27	26
Brookfield viscosity at 60°C (dPas)			
Unconditioned	3 150	8 000	14 400
10 Days @ 60°C	3 210	12 000	19 500
2 Days @ 60°C + 5 Days @ 107°C	6 130	19 500	53 700
Elastic Recovery (SPV) (% Film thickness)			
Unconditioned	-	361	321
10 Days @ 60°C	-	340	273
2 Days @ 60°C + 5 Days @ 107°C	-	301	205

The ingress of water can lead to **stripping** in the lower part of the surface layer, which will adversely affect both the cohesive properties of the material and adhesion to the underlying base course. At the end of the service life of the pavement, adhesion to the underlying pavement can effectively be reduced to zero if stripping takes place. The results of fatigue tests carried out on moisture-conditioned porous asphalt mixes (after vacuum-saturation and after vacuum-saturation followed by a freeze-thaw cycle) and those of tests carried out on unconditioned samples are given in Table 11. If the results of Table 11 are compared with those in Table 9, it can be seen that moisture causes more structural damage to porous asphalt mixes than does binder hardening due to temperature-conditioning, where freeze-thaw cycling results in a significant reduction in fatigue life. It can also be seen that, after freeze-thaw cycling, the fatigue lives of all mixes are of similar magnitude, which implies that polymer-modification may not be able to alleviate severe conditions of moisture-damage.

TABLE 11: Effect of moisture-conditioning on fatigue life and stiffness (Grading B)

Porous Asphalt	Unconditioned	After Vacuum-Saturation	After Freeze-Thaw Cycle
Fatigue Life			
80/100 Pen	58 400	33 000	6 600
+ 4% SBR	132 100	90 600	4 900
+ 4% SBS	130 800	41 500	8 600
+ 4% EVA	106 600	85 900	8 700
Initial Stiffness (MPa)			
80/100 Pen	2 050	2 260	2 200
+ 4% SBR	1 930	2 260	1 940
+ 4% SBS	2 070	2 370	2 030
+ 4% EVA	2 140	2 180	2 120

7. POROUS ASPHALT MIX DESIGN

As porous asphalt mixes are characterized by their volumetric properties in order to fulfil the functional requirements in terms of noise reduction and drainage capacity, the void content of these mixes should form the essence of the mix design strategy. Binder type and binder content are equally important, as these will influence the selection of an appropriate grading and, in combination with the selected grading, will have a significant impact on the structural integrity of the mix. Both durability and abrasion resistance are dependent on the above factors and are indirectly dependent on the viscosity properties of the binder/filler matrix. In the design process, the following steps should be incorporated (Figure 5):

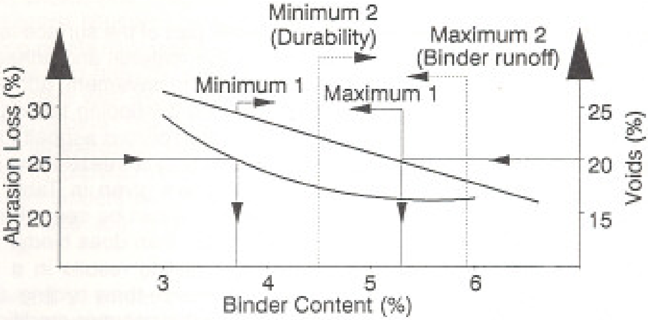

FIGURE 5: Selection of appropriate binder content

7.1 Selection of mix components

Aggregates should be sound, durable, with high strength (ACV of not more than 25 per cent), low flakiness index and high polished stone value. Only crushed aggregate should be used in porous asphalt mixes. The binder should be durable and, combined with filler and fines, be sufficiently viscous to prevent binder run-off taking place during construction. The use of binder or mix additives, such as polymers, recycled crumb rubber or fibres, may be considered in order to enhance durability, to improve resistance to deformation and fatigue and to prevent binder run-off.

7.2 Selection of appropriate grading

The selected grading should be such that, after introduction of the binder, the voids in the mix are not less than 20 per cent. Usually a gap in the grading curve is specified between the 2,36 mm and 9,5 mm sieve sizes. The magnitude of the gap depends both on the type of binder used and on the design void content. In order to obtain the target void content, the grading should consist of a high proportion of coarse aggregate (aggregate fraction retained on the 4,75 mm sieve in excess of 75 per cent) and should incorporate limited amounts of fines and filler (filler content of between two and five per cent), these proportions being dependent on the type of binder selected. High viscosity binders (such as bitumen rubber or pure bitumens modified by the addition of cellulose fibres) enable porous asphalt mixes to be manufactured with very low filler and fines contents, while mixes containing pure bitumen (usually a 60/70 penetration grade) require a certain amount of filler and fine aggregate in order to prevent binder run-off.

7.3 Determination of maximum binder content

For a selected grading, the maximum permissible binder content is governed by the design void content (usually in excess of 20 per cent) and by the binder content at which excessive binder run-off takes place. The binder drainage test, combined with volumetric properties, is often used to determine the target binder content of porous asphalt mixes in order to optimise durability whilst eliminating the possible occurrence of binder drainage during blending, mixing, transportation, laying and compaction of the porous asphalt. The voids in the bottom section of the porous asphalt layer will fill as a result of binder run-off and the functional performance of the mix will, consequently, be reduced. At the same time, the effective binder content of the upper part of the layer, which is exposed to the abrasive forces of traffic, will also be reduced.

7.4 Determination of minimum binder content

The minimum binder content is specified as the binder content at which the cohesive properties of the asphalt mix are such that the asphalt can no longer withstand the abrasion forces exerted on it by traffic, as determined by means of the Cantabro abrasion test. The minimum binder content is defined as the binder content at which the maximum permissible abrasion loss of 25 per cent is obtained.

When a suitable grading and binder type and an acceptable range of binder contents has been determined, such that the mix has the required properties (acceptable void content, abrasion resistance and resistance to binder run-off), an optimum binder content should be selected, cognisance being taken of economical factors and constructability. Finally, it is advisable to conduct wheel tracking tests (stability) and accelerated conditioning tests (moisture damage and binder oxidation) on the design mix in order to ensure that the mix will be able to withstand the combined effects of traffic and environment.

8. CONCLUSIONS

The main purpose of this paper was to compare the performance of porous asphalt mixes containing different types of organic and polymeric additives. This objective was accomplished by means of a laboratory study where the effects of a number of independent variables (additive type, grading type and binder content) on various performance parameters were evaluated. Based on the data presented and discussed in this paper, the following conclusions are made:

- As void content increases, stiffness, tensile strength, fatigue life and compressive strength decrease. On account of their poorer mechanical properties compared with conventional dense asphalts, porous asphalt mixes are not suitable for use as strengthening layers.

- Modification of the binder with plastomeric polymers (EVA) improves the compressive strength of porous asphalt mixes and, consequently, their resistance to rutting by comparison with those of unmodified porous asphalt mixes. The addition of fibres or elastomeric polymers (SBR and SBS) also improves their resistance to plastic deformation, but to a lesser extent.

- Loss due to abrasion, being one of the major failure mechanisms of porous asphalt, is dominated by both the void content and the binder content of the mix. Mixes with high void contents and low binder film thicknesses are more susceptible to abrasion damage than those with low void contents and high binder film thicknesses. During the mix design phase, a balance needs to be achieved between a desired void content to fulfil functional requirements and binder content to limit abrasion damage. The type of binder used does not have a significant influence on the abrasion resistance of fresh material.

- Polymer-modification of the binder results in a significant increase in the fatigue resistance of porous asphalt. In particular, modification with elastomers (SBR or SBS) has a significant bearing on improved fatigue resistance.

- Moisture-damage was simulated in the laboratory by means of the Lottman test. After freeze-thaw cycling, a significant reduction in fatigue life and some reduction in stiffness were observed. It was also observed that, after freeze-thaw cycling, the fatigue lives of both the unmodified- and modified porous asphalt mixes were similar, which implies that polymer-modification of the binder may not be able to alleviate severe conditions of moisture-damage.

- Results of tests conducted on unconditioned and temperature-conditioned porous asphalt mixes indicate that after ageing, stiffness and indirect tensile strength increase, while fatigue life decreases. These trends are confirmed by the increase in binder viscosity and decrease in elastic recovery.

- Although the manufacture of porous asphalt with high void contents at the moment of application poses no great problem, its maintenance in good condition through time and under traffic presents a major difficulty. The modification of the binder by means of polymeric additives to improve the rheological properties of the binder system or the addition of fibre to enable thicker binder films to be used, may result in less maintenance being required and, at the same time, in improvement of the structural performance of the porous asphalt wearing course.

Porous asphalt combines comfort and safety (improved wet skid resistance, less spray, no reflection, good evenness) with less rolling noise than that observed on traditional asphalt overlays. From this point of view, the use of porous asphalt as a road surfacing material is a major technological innovation. With the availability of polymeric and organic additives, porous asphalt mixes with void contents in excess of 20 per cent can now be manufactured while ensuring that relatively low structural maintenance is required.

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