The design and use of porous asphalt mixes

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excellence in bituminous products

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Manuals published by Sabita

Manual 1	Construction of bitumen rubber seals
Manual 2	Bituminous products for road construction
Manual 3*	Test methods for bitumen rubber
Manual 4*	Specifications for rubber in binders
Manual 5	Manufacture and construction of hot mix asphalt
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Manual 12	Methods and procedures - Labour enhanced construction for bituminous surfacings
Manual 13	LAMBS - The design and use of large aggregate mixes for bases
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Manual 17	The design and use of porous asphalt mixes
Manual 18	Appropriate standards for the use of sand asphalt
Manual 19	Technical guidelines for bitumen-rubber asphalt
Manual 20	Sealing of active cracks in road pavements
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Manual 22	Hot Mix Paving in Adverse Weather
Manual 23	Code of Practice: Loading bitumen at refineries
Manual 24	User guide for the design of hot mix asphalt
Manual 25	Quality management in the handling and transport of bituminous binders
Manual 26	Interim guidelines for primes and stone precoating fluids
Manual 27	Guideline for thin layer hot mix asphalt wearing courses on residential streets

* These manuals have been withdrawn and their contents have been incorporated in Technical Guideline 1 (see below).

** This manual has been withdrawn and its software programme incorporated in TRH12: *Flexible pavement rehabilitation investigation and design.*

*** These manuals have been withdrawn and their contents have been incorporated in Technical Guideline 2 (see below).

Technical Guidelines

TG1	The use of modified binders in road construction
TG2	Bitumen stabilised materials
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Disclaimer

Preface

In promoting its policy of excellence in asphalt technology, Sabita started a broad based Asphalt Research Programme in 1988 to meet the needs of the road industry in southern Africa. This manual is the result of research into the design and implementation of porous asphalt, undertaken through the Asphalt Technology Development Programme.

The research and development work on porous asphalt addressed the following major issues:

- the development of a laboratory mix design method for porous asphalt;
- the establishment of design criteria;
- the constructibility of porous asphalt;
- an investigation into the performance of these materials.

Scope

This manual gives guidelines on issues such as quality control, and construction procedures are only addressed in so far as they may influence the design criteria which were developed. The details of the findings of these projects are contained in a series of reports[1-16].

Manual 17 addresses the following:

- general considerations regarding the design of porous asphalt;
- a detailed description of the porous asphalt mix design method with guidelines on the interpretation of test results;
- constructibility of porous asphalt;
- quality control of porous asphalt;
- maintenance of porous asphalt;
- practical illustration of the mix design method through a case study;
- an overview of the performance under accelerated trafficking of porous asphalt.

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1. Introduction

Background

History of porous asphalt mixes

Since 1950, so-called "open-graded plant mix seals" have been used in California and other western states of the United States of America to improve wet skid resistance. In South Africa, the National Institute of Road Research (NIRR) conducted experiments in 1953 on the road linking Pretoria and Germiston to investigate the durability of bituminous binders. Amongst the mixes evaluated was an open-graded asphalt which performed well over a period of 11 years. Since 1970, open-graded wearing courses have been used by all major road authorities in South Africa and have also been used successfully on the runways of major airports (e.g. Windhoek and Johannesburg). These mixes, however, seldom had void contents exceeding 18%, were paved in relatively thin layers and tended to ravel at an early age. They also often lost their functional properties as a result of premature clogging of the voids with sand, dust and detritus.

In France, porous asphalt has been used since 1960 to improve wet skid resistance, reduce splash and spray and reduce noise pollution. However, it is only since 1977 that this type of mix has been subjected to systematic investigation. Several trial mixes were laid and their performances evaluated over a period of seven years. By 1984, porous asphalt technology had reached the stage at which it could become commercialised in Europe, to the extent that by 1991, 50 million m^2 of porous asphalt had been laid.

Definition of porous asphalt

Porous asphalt is a wearing course with a void content in excess of 20%. The voids are interconnected, providing a means of conveying rain water to the pavement boundaries. This makes it highly suitable for wet weather conditions, reduces traffic noise and increases skid resistance.

Texture of well-constructed porous asphalt.

Porous asphalt is made up of a combination of a bituminous binder, a high proportion of coarse aggregate and limited amounts of fines and filler. It is manufactured in a conventional hot mix asphalt plant, transported to site, laid and compacted on a sound and impermeable underlying layer.

Advantages of porous asphalt mixes

The improved drainage offered by porous asphalt:

- reduces splash and spray behind vehicles;
- eliminates reflection from the surface of the wet pavement and so improves the visibility of pavement markings;
- improves wet weather skid resistance at high speeds through improved wheel contact with the surface, thereby reducing wet-weather accident rates;
- results in an attenuating effect within the layer, thus reducing the peak outflow of water to storm water systems.

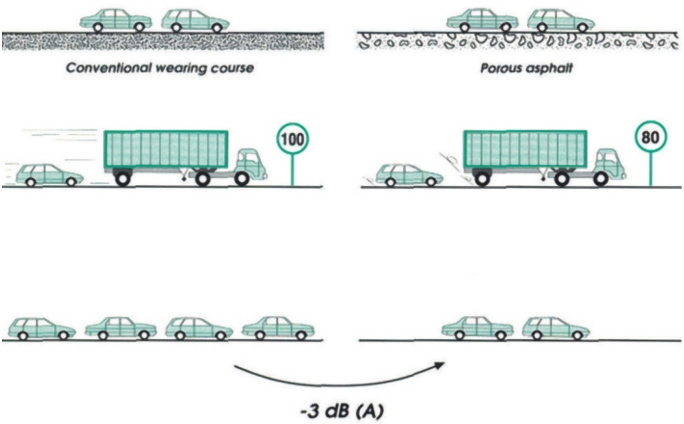

Figure 1. Average reduction of noise level.

Reference: PIARC Technical Committee on Flexible Roads and on Surface Characteristics. *Porous Asphalt.* Publication 08.01B. Permanent International Association of Road Congresses (PIARC), Paris, 1993.

The 3dB(A) average reduction of noise level by porous asphalt with respect to conventional wearing course would be equivalent to reducing traffic speed by 20% or dividing intensity 2, all other things being equal.

The high void content of porous asphalt, combined with layer thicknesses of at least 40 mm, offers the additional advantage that noise generated by vehicle tyres - and to a certain extent by vehicle engines - is absorbed by the layer, thus reducing noise pollution. The noise reduction relative to dense bituminous mixes is generally of the order of 3 dB(A) (dry conditions) to 8 dB(A) (wet conditions), where a 3 dB(A) reduction in noise level is comparable with a 50% reduction in noise pollution. A further advantage of porous asphalt is that the excellent surface smoothness of a well constructed porous asphalt wearing course reduces vibration, thus providing a more comfortable ride with less vehicle wear and tear.

The need for porous asphalt mixes

With the continuous increase of traffic density in urban areas, noise pollution is expected to get correspondingly worse. Since the promulgation of the Environment Act of 1989, containing certain regulations with respect to noise, roads in urban areas may have to meet predefined noise level criteria. These will depend on the location of the road relative to the nature of the adjacent suburb (rural residential, urban residential, industrial, etc). This may result in limitations on the type of surfacing to be used to comply with the noise limits set for a particular district. Porous asphalt, being a cost-effective alternative to noise barriers, offers both road users and urban residents a highly competitive means of addressing the growing concern for the environment in densely populated areas.

In addition, travelling speeds, traffic densities and the percentages of heavy vehicles using the road network have increased steadily in recent years, impairing road safety. Although vehicle design has improved significantly to provide road users with safer and more comfortable means of transportation, over the same period there has been comparatively less innovation in the provision of safer riding surfaces. Porous asphalt, with its high skid resistance and excellent serviceability, fulfils the function of both improving driver safety in all weather conditions and enhancing the comfort of the road user.

A 1993 Gallup poll among car and truck drivers in the Netherlands indicated that 90% of them are in favour of road authorities' policy of applying porous asphalt surface courses on all motorways. Good traffic safety during wet conditions, because of less splash and spray as well as better visibility, and less traffic noise are mentioned as the main advantages over traditional asphalt pavements. Disadvantages, such as a shorter design life or a longer stopping distance during dry conditions (on account of the reduced contact area between pavement and tyres) are not recognised by most drivers[17].

Performance of porous asphalt mixes

The structural and functional performance of porous asphalt depends on the nature of the components of the mix, the mix characteristics, the condition of its support and the nature of the traffic. If designed and maintained correctly, porous asphalt wearing courses subjected to high traffic volumes should have life spans of between 10 and 15 years.

Depending on its location, porous asphalt may have considerable economic advantages over conventional mixes. Significant cost savings can be realised by eliminating the necessity for sound barriers and by reducing wet-weather accident rates.

The need for a new design approach

Empirical mix design methods, such as the Marshall method, are no longer necessarily applicable to asphalt subjected to the present types of loading conditions in the field. Increased axle loads and tyre pressures may dictate a different, more fundamental approach. Also, empirical tests, which were conducted with certain types of mix manufactured with unmodified binders, are no longer applicable because conditions are now outside their respective fields of correlation. In addition to the above, porous asphalt mixes were never included in the original Marshall mix design method.

Mix design parameters currently used for conventional mixes do not provide a sound basis for the evaluation of porous asphalt mixes. As it is their volumetric properties which reduce noise levels and improve the drainage capacity of porous asphalt mixes, void content should form the essence of the mix design strategy. However, on account of the volumetric properties of the mix, factors such as abrasion resistance and resistance to binder run-off should also be investigated.

One of the major mechanisms of failure of porous asphalt is loss of aggregate by traffic attrition, i.e. by abrasion. Innovative testing methods and related design criteria are required to enable these effects to be assessed during the mix design phase. Furthermore, as porous asphalt mixes are more susceptible than conventional dense bituminous mixes to the damaging effects of environmental forces, on account of their higher void contents, the effects of binder ageing, stripping and abrasion loss need to be quantified and addressed during the mix design stage.

Selection of a high binder content will improve durability and resistance to loss of aggregate by abrasion. However, binder run-off may occur during construction, the magnitude of which depends on factors such as grading, binder content, binder type, temperature, length of haul and other construction-related factors.

Research work

Sabita identified the need for an investigation into the design and performance of porous asphalt. The CSIR Division of Roads and Transport Technology (now CSIR Built Environment) was commissioned to undertake this. The project was originally initiated as "Polymer-modified asphalt", focusing on the use of polymer-modified binders in various types of wearing courses. However, an analysis of future prospects for the asphalt industry and its environment resulted in the emphasis of the project being shifted to porous asphalt. The research and development work on the material addressed the following major issues:

- the development of a laboratory mix design method for porous asphalt;
- a comparative study involving a number of polymer-modified binders and different types of grading, in which properties such as resistance to aggregate loss, fatigue, deformation, moisture damage and ageing were investigated.

During the course of the above project, Thermguard (Pty) Ltd granted research funds to enable the characteristics of porous asphalt mixes containing cellulose fibres to be assessed. These fibres are currently used extensively in Europe in the manufacture of porous asphalt.

As bitumen-rubber binders had not been included in the Sabita project, and as bitumen-rubber is used extensively in Europe and USA in the manufacture of porous asphalt, Tosas (Pty) Ltd commissioned the CSIR to investigate bitumen-rubber porous asphalt mixes.

The following issues were covered in this project:

- mix design method for bitumen-rubber porous asphalt;
- the establishment of design criteria for such mixes;
- an investigation into the performance of porous asphalt;
- constructibility of porous asphalt using bitumen-rubber.

Note: Selection of a high binder content will improve durability and resistance to loss of aggregate by abrasion.

2. Design considerations

Introduction

Although open-graded asphalt mixes have been used fairly extensively in South Africa, few of these mixes had void contents in excess of 20% and, in addition, were paved in relatively thin layers. The voids in these mixes often clogged up prematurely, thus diminishing their drainage and sometimes their noise attenuation properties. Also, on account of their relatively low void contents, these mixes did not provide the levels of drainage or noise attenuation provided by porous asphalt.
Open-graded asphalt mixes used before the advent of modified binders were found to be susceptible to binder run-off or drainage and loss of aggregate.

With the introduction of polymer-modified and bitumen-rubber binders and cellulose-fibre additives to the South African road industry, mixes with high void contents and with vastly improved durability can now be manufactured. The greater viscosity of these binders or binder mortars, combined with improved adhesion characteristics and the increased resistance to ageing of some of these binders, enabled higher binder contents to be used in gap gradings (such as

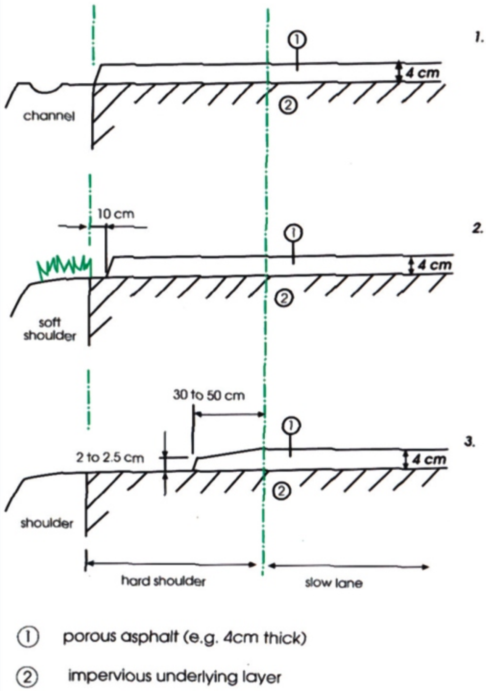

Figure 2. Examples of porous asphalt surfacings extending onto the hard shoulder.

porous asphalt) without risk of binder run-off and with improved resistance of the mix to abrasion under traffic.

Because of the high void content of porous asphalt, which allows the ingress of water, special provisions are required to allow water within the confines of the layer to drain towards the boundaries of the pavement. Also, the stiffness of porous asphalt is less than that of dense bituminous mixes. Care should therefore be taken to ensure that the pavement structure, which supports the porous asphalt overlay, has sufficient bearing capacity and structural strength to carry the design traffic.

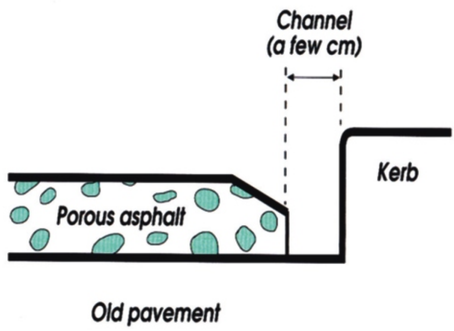

Figure 3. Treatment of the edge of a porous asphalt surfacing on a pavement boxed in between kerbs.

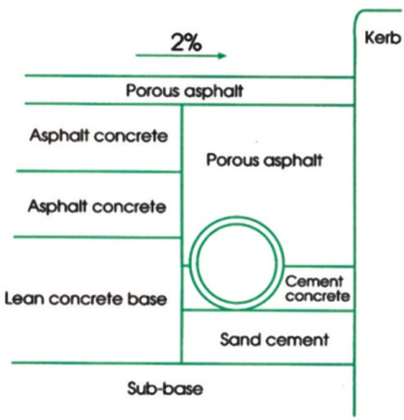

Figure 4. Application of porous asphalt in urban areas, involving the use of a collector drain (Belgium).

Considerations for pavement design

The layer thickness required for porous asphalt is mainly a function of the required water drainage capacity which, in turn, is dependent on the intensity and duration of the design rainfall. A layer thickness of 40mm should have adequate water drainage capacity for normal rainfall. Thinner layers would result in poorer performance with heavy rainfalls and could reduce the durability of the layer. If the purpose of the porous asphalt layer is mainly to reduce noise pollution, layer thicknesses in excess of 40mm are suggested.

Appropriate application of porous asphalt entails good design practices. The following should be considered during the design stage[18,19].

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- A transition zone or a cut-off drain should be constructed between a porous asphalt section and a conventional mix section. This will prevent sheet flow of water coming out of the drainage layer onto the surface of the dense asphalt section, which could impair road safety;
- When porous asphalt overlays an existing pavement structure, the areas which have deformed should first be repaired. When porous asphalt is placed on cracked pavements the cracks should first be sealed. It is important to ensure that the underlying layer is impermeable and that it has a satisfactory load carrying capacity;
- On account of the large volume of voids in porous asphalt, the layer contains a network of channels capable of conveying rainwater. The design of the layer should make provision for this water to pass through the porous layer to lateral collecting drains or to the shoulders. It is therefore necessary to have an underlying layer which is impervious and which has adequate cross fall to prevent the water reaching the base or sub-base or ponding in the porous layer. These side drains should be lower than the top of the impervious layer;
- For pavements with cement-treated bases, it is recommended that a stress-absorbing membrane interlayer (SAMI) be constructed between the existing surface and the porous asphalt layer. This will prevent reflection cracks in the impermeable layer through which water could enter the pavement structure;
- Unlike other mix types, longitudinal joints in porous asphalt layers should not be cut back or primed as this would obstruct drainage. The same is true of the shoulder edge.

Application of porous asphalt

There are a number of applications in which porous asphalt can be used. These are primarily based on properties such as its high porosity, its capacity for reducing noise pollution and its good skid resistance at high speeds in wet weather. Porous asphalt is recommended in areas where water tends to accumulate or where a water hazard could reduce traffic capacity or impair traffic safety. Typical areas are at changes in superelevation, busy motorways or wide pavements (motorways, runways), limited-access roads and highways prohibited to slow-moving traffic. Another possible application is on roads with recognised noise pollution problems, particularly on noisy arterials in urban areas, cross-town freeways or motorway links. Typical examples of areas where porous asphalt can be usefully applied are[20].

- **National and major provincial roads:** The desired properties on such roads are safety, comfort and the suppression of splash and spray. Good skid resistance at high speeds also favours the application of porous asphalt. Reduction in noise pollution is an added benefit. High speed, high volume traffic on such roads also assists self-clearing of the voids in wet weather;
- **Fast trafficked urban roads and major arterials:** The major benefit is the reduction of noise pollution to the benefit of residents in adjoining suburbs, thus eliminating the necessity for sound barriers. However, factors such as oil and fuel spillage should be taken into consideration as these may destroy the binder system and adversely affect porosity. To reduce noise pollution, consideration may have to be given to the provision of porous asphalt layers with thicknesses in excess of 40mm;
- **Areas with poor vertical alignment, particularly large areas:** Ingress of water into the pavement layer tends to reduce the thickness of the film of water on the surface and, consequently, the risk of aquaplaning. A porous layer may also be used for the temporary storage of surface water in urban areas. The application of porous asphalt may thus reduce the necessity to upgrade the draining system to accommodate excess stormwater which the current drainage system cannot handle. Porous asphalt offers the potential of temporarily storing stormwater within the layer and of retarding the outflow into urban drainage systems, due to an increased flow path length and a decreased flow speed.

Caution should be exercised when using porous asphalt in urban or industrial areas where extensive wear from abrasion is expected, where spillage of oil or fuels takes place, at sites with high stresses (such as intersections or steep grades), or in areas where there is a strong risk of cracking, either by shear or fatigue. Roads frequently soiled by waste or wind-blown sand - in these areas, clogging of the voids may result in reduced drainage capacity and increased noise levels. It should be noted that the use of porous asphalt in such applications is not excluded, but extra design and/or maintenance requirements need to be met.

Relevant engineering properties

Engineering properties which are used to characterise asphalt mixes in general are: resistance to permanent deformation, resistance to fatigue, indirect tensile strength and stiffness modulus. On account of its composition, other relevant properties of porous asphalt should also be considered. These include those which have a direct bearing on the expected life of a porous asphalt wearing course, such as binder durability and short and long-term resistance to stone loss.

Resistance to permanent deformation

Because of the nature of the grading of porous asphalt mixes, stone-to-stone contact will develop after only a few passes of a smooth steel-wheel roller and, unless the binder is of such a nature that it cannot hold the aggregate in place, no permanent deformation should occur. It is recommended that the resistance of the mix to permanent deformation be quantified by means of wheel tracking tests or gyratory compaction tests. These will identify the required energy and temperature of compaction so as to minimise post-compaction densification. Unconfined test methods, such as dynamic or static creep tests, underestimate the resistance of porous mixes to plastic deformation. They are therefore not recommended unless they are used in a comparative study in which the relative performance of different types of binder is evaluated.

Resistance to fatigue cracking of porous asphalt

Resistance to fatigue is important in dense bituminous mixes, as insufficient resistance will result in the ingress of moisture to the structural layers below. This will eventually cause the pavement structure to fail prematurely. In the case of porous asphalt, where the layer is designed to permit the ingress of moisture, formation of cracks within the porous structure is less important, unless it promotes loss of aggregate by attrition. The latter aspect, however, is difficult to simulate by means of fatigue tests.

Stiffness and indirect tensile strength

Indirect tensile strength and stiffness moduli are dependent both on the type of grading and on the nature of the binder. The stiffnesses and indirect tensile strengths of porous asphalt mixes are generally significantly lower than those of conventional, dense asphalt wearing courses (generally about half to two-thirds those of dense asphalt mixes, depending on the void content of the mix). Consequently, porous asphalts are less able to distribute traffic stresses than dense asphalt mixes. They should not, therefore, be used as strengthening layers in the rehabilitation of distressed road structures.

Durability

As porous asphalt mixes are exposed to environmental forces, such as moisture, heat and ultra-violet radiation, their durability may be seriously affected relative to dense asphalt wearing courses. If porous asphalt wearing courses are not designed to resist these forces, premature stripping and aggregate loss may occur, resulting in shorter maintenance cycles and lower benefit-cost ratios. The above effects can be countered by the introduction of more binder of a higher viscosity into the mix with the addition of bitumen modifiers or fillers, such as crumb rubber and cellulose fibres. The resulting increase in the thickness of the binder film, combined with an increase in the binder viscosity, will enhance durability, reduce water damage and reduce binder run-off during transport and application. Alternatively, polymer modified binders may be used which, because of their inherent characteristics (lower temperature susceptibility, greater cohesion, marked elastomeric properties and improved low temperature properties), improve the resistance of the mix to the impact of environmental forces. Higher binder contents can be used in mixes containing polymer-modified binders than in those manufactured with unmodified binders. The greater film thickness results in mixes of greater durability.

It is, therefore, recommended that accelerated conditioning tests (moisture and temperature) be conducted on samples of the design mix to ensure that the mix is able to withstand the combined effects of traffic and environment.

Environmental considerations

Improvement in road safety

Porosity test conducted on a porous asphalt: water immediately penetrates into the layer.

One of the major advantages of porous asphalt is that its use improves wet-weather road safety considerably. Porous asphalt mixes are primarily designed to allow drainage of rain water to the outside boundaries of the pavement through a network of channels in the mix. The water film on the surface of porous asphalt wearing courses is generally thinner than that on the surface of dense-graded asphalt mixes because of the relatively open structure of the former. The reason for this is that tyre pressure forces the surface water into the voids. The thickness of the water film on the surface of the layer is consequently reduced. The drainage capacity of porous asphalt is a function of the percentage of voids, the layer thickness and the profile of the cross-section.
This drainage ability of porous asphalt allows vehicle tyres to remain in continuous contact with the surface of the pavement under all conditions, and thus reduces the possibility of aquaplaning. The use of porous asphalt also reduces splash and spray behind vehicles, especially trucks. Porous asphalt surfaces reduce surface reflections from wet pavements, both by day and by night, thus making road marks more visible and rendering the surface safer than conventional wearing courses.

On account of the above, a significant reduction in wet-weather accident rates may be expected after application of porous asphalt on wide pavements, such as three-lane highways or major arterials. This is illustrated by the results given in Table 1[20].

Table 1: Wet-weather accident performance on a highway after widening and application of porous asphalt

Dense-graded, 2 lanes	Dense-graded, widening to 3 lanes	Porous asphalt overlay on 3 lanes
9 accidents in 6 years	52 accidents in 6 years	0 accidents in 3 years

Reduction in noise pollution

Prior to the introduction of porous asphalt, it was generally believed that there was a correlation between noise pollution and skid resistance, where noise pollution becomes greater with an increase in skid resistance. Whereas this belief held some truth for conventional surface treatments and wearing courses, it was later observed that porous asphalt, even at its initial stages of development, formed an exception to this. At high speeds (80 km/h), porous asphalt wearing courses offer good skid resistance (similar to that of surface dressings), while noise levels are similar to or lower than normal asphalt mixes.

Porous asphalt is highly effective in reducing rolling noise both inside and outside vehicles. Greater understanding of the potential offered by this material in the 1980s led to its extensive use in Europe. The reduction in noise level results from:

- sound absorption by the voids of the layer;
- the elimination of air pumping at the tyre/pavement interface;
- the excellent surface evenness of this type of wearing course when properly laid.

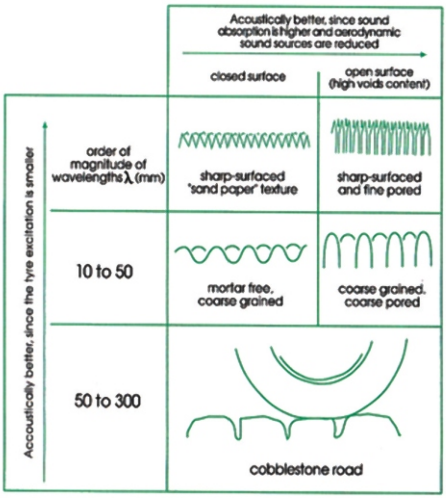


Figure 5. Schematic representation of pavement surfaces with respect to possibilities of optimisation.

Porosity makes porous asphalt pavements behave differently from dense-graded mixes. A smoother surface texture, with a consequent lesser degree of indenting of the aggregates into the tyre surface, makes the vibrations transmitted from the road surface to the tyre less important. Air pumping is also greatly reduced. All these factors have an effect on tyre noise generation and contribute to the main reduction in noise levels. Another factor is the absorption ability of the structure itself. Improved sound attenuation is brought about by the absence of multi-reflections between the tyre and the road (horn-effect), and between the body of the vehicle and the road (exhaust systems and the engine). If both phenomena (low rolling noise and absorption effect) are taken into account, there is an approximate reduction of between 2 to 3 dB(A) for a single vehicle by comparison with that measured on dense-graded bituminous asphalt, or 6 to 10 dB(A) by comparison with that on transversely grooved concrete surfacings.

There are many types of noise barriers - from space to trees and walls: as shown above.

The above reductions are observed in the frequency range of approximately 100 to 1200 Hz on thin layers with dry surfacings (30mm to 60mm). It is, however, recognised that noise reduction effects are generally more pronounced in wet weather. The reduction in noise level has been as much as 8 dB(A) under these conditions.

The measured reductions in noise levels are, however, dependent both on the speed and on the type of vehicle. The main advantages gained by improved attenuation are obtained when light vehicles travel at speeds in excess of 60 km/h. At lower speeds or with heavy vehicles, engine noise predominates. The rolling noise of diesel-powered heavy vehicles is responsible for only a small part of the total acoustic energy, which is mainly produced by the engine and other mechanical noises (vibrations, gear noises, brake noises, exhaust). This is why the influence of an absorbent pavement on heavy vehicle noise is less pronounced. Nevertheless, the absorbent effect on multi-reflections between the body of the vehicle and the road is still significant.

Note: Noise reduction is more pronounced in wet weather. The reduction in noise level has been as much as 8dB(A) under these conditions.

3. Guidelines on mix design

Introduction

As it is the volumetric properties of porous asphalt mixes which reduce the noise levels and improve the drainage capacity, void content should form the essence of the mix design strategy. Binder type and content are equally important, as these influence the selection of an appropriate grading which will have a significant impact on the structural integrity of the mix. Both durability and abrasion resistance depend on the above factors and, in turn, are indirectly dependent on the viscosity properties of the binder/filler matrix. The following steps should therefore be incorporated in the mix design process:

i. selection and testing of mix components (aggregate, binders, fillers);
ii. selection of appropriate grading, based on target void content and related to the type and properties of the binder to be used;
iii. determination of optimum binder content, with binder run-off, volumetric properties, abrasion resistance and durability being taken into account;
iv. evaluation of the design mix, in which resistance to deformation, ageing and moisture damage are taken into consideration.

Selection of mix components

The process of selection of mix components is important so that the desired properties of the asphalt may be obtained. The three main variables which should be considered are:

- binder type;
- aggregate type;
- filler type.

Binder type

The type of binder chosen depends on the nature of the problem encountered during the design process. In porous asphalt wearing courses, where the binder plays a significant role in ensuring that the mix will be sufficiently resistant to the damaging effects of both traffic and environment, the selection of an appropriate binder is of crucial importance. An ideal binder system for use in porous asphalt should have the following properties:

- the viscosity/temperature susceptibility in the temperature range occurring on the road should be low without affecting viscosity at processing temperatures;
- the viscosity/rate of loading susceptibility should be low;
- the resilience should be high;
- the cohesion should be high;
- adhesion should be high;
- durability must be high.

The selection of harder or softer bitumens, depending on the climate, or changing the colloidal structure by increasing the asphaltene proportion, for example by blowing in the manufacturing process, usually results in marginal improvements to the bitumen[21]. However, the creation of a secondary structure in the maltene phase of the bitumen by the addition of small amounts of polymer or of recycled rubber can be made to enhance the properties of the bitumen.

Modification of the rheological behaviour of the bitumen will in these ways lead to a higher performance pavement which will be able to serve longer without extensive ravelling or plastic deformation. Some of the better known bitumen modifiers are listed below. Their characteristics are described in Appendix B, page 67:

- styrene-butadiene rubber, or SBR, elastomer;
- styrene-butadiene styrene, or SBS, elastomer;
- ethylene-vinyl acetate, or EVA, plastomer;
- granulated reclaimed rubber.

In the selection of the binder, factors such as environment, traffic and expected functional performance of the mix should be considered. High viscosity binders such as bitumen-rubber or binders with very high polymer contents are generally recommended for medium to high volume traffic conditions, hot climates and/or mixes with high void contents (in excess of

22%). Polymer-modified and unmodified binders are both recommended for low to medium volume traffic conditions, mild climates and/or porous asphalt mixes with air void contents of between 18 and 22%.

High viscosity binders are recommended for high void content mixes, as the minimum binder requirements for such mixes are high to provide sufficient resistance to abrasion. These binders also have the appropriate rheological properties to prevent binder run-off during construction.

The properties of the bitumen and modified binders should conform with the recommendations given in Sabita publications[22].

Aggregate type

As the material is intended for use in relatively thin and open surfacing layers, coarse aggregates which have good resistance to fragmentation, a good and stable microtexture and an adequate interlock are essential. Fragmentation of the coarse aggregate can lead to particle loss, ravelling and closing up of the surface texture. For this reason a maximum aggregate crushing value (ACV) should be specified. This is given in Table 2.

In addition, it is recommended that, for roads with traffic volumes of more than 800 trucks per day per lane, 100% of the aggregate particles should have two or more fractured faces. This may be reduced to 90% for roads with traffic volumes of less than 800 heavy vehicles per lane per day[18].

Frictional characteristics of the surface necessitate the use of sound, durable, cubical and non-polishing aggregate to maintain a good and durable microtexture. A maximum flakiness index and a minimum polished stone value should, therefore, be specified. Recommendations for these are given in Table 2.

The use of natural sand should be avoided where possible. The use of crushed fine aggregate is recommended to enhance resistance to deformation. Aggregates with high binder or water absorption characteristics should also be avoided. The use of such materials may result in the long-term drying out of mixtures, with corresponding poor durability, shrinkage, cracking and eventual disintegration. The water absorption of both fine and coarse aggregate should therefore be limited. The limiting values are given in Table 2.

Table 2: Recommended aggregate properties

Property	Recommendation
10% FACT	>210kN
ACV	< 21%
Polished stone value	>50
Flakiness index	<25
Sand equivalent value	>45
Water absorption	<1,0%

Filler type

The amount and type of filler is important as it stiffens the binder. For binders of relatively low viscosity, higher proportions of filler may be required. To avoid the presence of a detrimental clay fraction, a sand equivalent value above 45 is required.

One to two percent of mineral filler (commercial limestone powder, hydrated lime or cement) is recommended as it enhances the adhesion properties of the binder and therefore reduces the potential for stripping. It is recommended that hydrated lime complies with the following:

$Ca(OH)_2$ content :	minimum 90%
Passing 0,075 mm sieve :	minimum 90%

Fibres are often added to the mix to stiffen the binder to reduce binder run-off during transportation and lay down operations. The fibres generally used are either of mineral origin (natural fibre or glass fibres) or of organic origin (mostly cellulose fibres). See Appendix C, page 71.

Selection of grading

The selection of an appropriate aggregate grading depends on the type of binder selected and on the design void content. The grading will vary according to the use of [20]:

- Unmodified binders;
- Unmodified binders with the addition of fibres;
- Polymer modified binders;
- Bitumen-rubber binders.

A typical porous asphalt grading envelope is shown in Figure 6.

Unmodified porous asphalt

In this category, mixes with nominal stone sizes of 9,5mm and sometimes 13,2mm are used. The gap in the mix is usually between 2,36mm and 9,5 mm, but may be reduced. There are few fines in the mix, the fraction passing the 2,36mm sieve being less than 15%.

Bitumen content varies between 4,2 and 4,8% (for aggregate with a specific gravity of 2,65). This is the maximum that may be used without risk of binder run-off during transport and application.

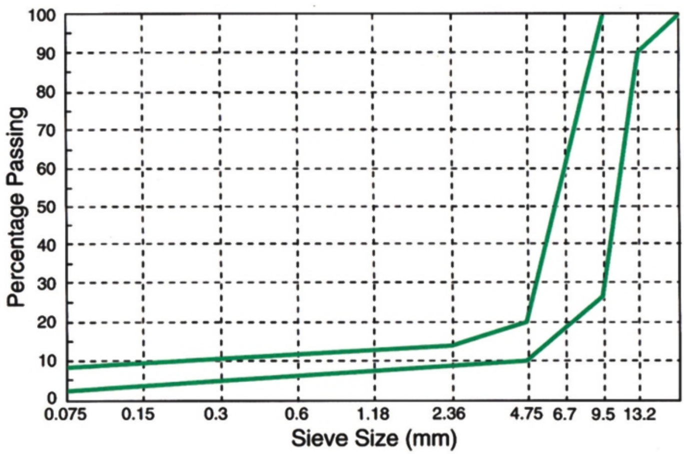


Figure 6. Typical porous asphalt grading envelope

In most European countries, 60/70 penetration grade bitumen (grade B12) is generally used. In exceptional cases, penetration grades 40/50 (grade B24) or 80/100 (grade B8) are used, the selection of these being dependent both on the type of traffic and on the climate.

Unmodified porous asphalt with addition of fibres

These mixes are characterised by binder contents which may be as high as 5,5% by mass of total mix, as a consequence of the addition of fibres to increase the viscosity of the filler/bitumen system. In this case, the aim is to increase the thickness of the binder film so as to enhance durability and to reduce water stripping, drainage during transport and application and the risk of rutting under traffic.

As in the case of unmodified mixes, mixes with nominal stone sizes of 9,5mm and 13,2mm are generally used with low fine aggregate contents to obtain high voids. A gap smaller than that used in porous asphalt mixes containing unmodified bitumen is usually specified (between 2,36mm and 6,7mm). The fine aggregate content (passing the 2,36mm sieve) is usually between 13 and 15% with a filler content of approximately 5% (if 0,3 to 0,5% cellulose fibres by mass of total mix are used).

Porous asphalt mixes containing polymer-modified binders

The binder is generally supplied ready mixed. There are three main types of polymer modifiers (see Binder types, page 27). Typically, mixes with nominal stone sizes of 9,5mm and 13,2mm are used. Binder contents of between 4,5 and 5,6% are slightly higher than those of unmodified porous asphalt. The aggregate passing the 2,36mm sieve varies between 10 and 18% by mass.

The use of polymer-modified binders in combination with cellulose fibres is advantageous. This allows the use of much higher binder contents for improved durability and abrasion resistance with good cohesive properties.

Porous asphalt containing bitumen-rubber binders

This type of binder is produced in a mobile blending unit at the mixing plant. Alternatively, bitumen-rubber may be ready mixed by producers and delivered to the mixing site.

Nominal stone sizes of 9,5mm and 13,2mm with low fine aggregate contents (approximately 11% passing the 2,36mm sieve) and containing between 3,0 and 4,0% of filler (of which 1,0% consists of lime) are generally used to obtain the required voids content.

Porous asphalt is designed to improve the functional characteristics of wearing courses, with reduction in noise and improved safety. To improve these, the void content and porosity of the mix should be maximised. One way of achieving an increase in porosity is by altering the grading of the aggregate.

A feature of porous asphalt mixes is the gap in the grading of the aggregate, usually between the 2,36mm and 6,7mm sieve sizes. Porosity increases as the gap increases, i.e., if the grading shows a narrower distribution of coarse aggregate fractions. Greater porosity can also be achieved by reducing the binder content. This, however, is not recommended as it will impair durability and reduce the ability of the mix to resist aggregate loss through traffic abrasion.

Since bitumen-rubber is very cohesive, it is possible to design open mixes with extremely high void contents, but with binder contents much higher than mixes containing unmodified or polymer-modified binders. Moreover, on account of the merits of rubberised bitumen as regards adhesion, cohesion and elasticity, porous asphalts containing bitumen-rubber as binder are highly resistant to mechanical damage.

Determination of optimum binder content

The optimum binder content is dependent on a number of limiting parameters which directly or indirectly influence the amount of binder to be used. These parameters are:

- **Void content:** The design void content for a given grading controls the maximum amount of binder which can be used;
- **Abrasion loss:** The maximum permissible abrasion loss controls the minimum amount of binder which may be used. Abrasion loss is determined by means of the Cantabro abrasion test[23];
- **Durability:** A minimum binder content of 4,5% is often specified as a measure to ensure that the binder film thickness is sufficient to ensure good durability;
- **Binder run-off:** A maximum binder content is specified in order to prevent excessive binder run-off during transport and construction.

The binder run-off for a given combination of aggregate, binder and fibre additives (if required) is determined by means of the basket drainage test[19].

The optimum binder content is selected from the range determined by these four criteria. The design binder content is specified as the average of the higher of the minimum binder contents (durability and abrasion resistance) and the lower of the maximum binder contents (void content and binder run-off). The results of the procedures involved in the determination of the optimum binder content are illustrated diagramatically in Figure 7[18], page 35.

Sample preparation in the laboratory : In order to determine the optimum binder content for a given grading and selected type of binder, it is suggested that at least four binder contents be investigated, starting at a binder content of 3,5% by mass of total mix, in increments of 0,5%. Five Marshall briquettes at each binder content should be prepared.

Mixing temperatures depend on the type of binder used. On account of the open structure of porous asphalt mixes, mixing temperatures are usually lower than those for dense-graded mixes. Recommendations on mixing temperatures are given in Table 3.

It is suggested that the mix be conditioned prior to compaction to simulate the process of mix production, transport and paving. The following conditioning procedure is recommended:

- Obtain a mechanical mixer with a heated mixing bowl of sufficient capacity to mix up to 5kg of asphalt. A mixing time of 2 minutes is currently recommended. Mixing procedures should comply with the guidelines given in the appendix to method C2 of TMH1[24]- *Procedure for the making of asphalt specimens for the determination of resistance to flow and for voids analysis by the Marshall method;*

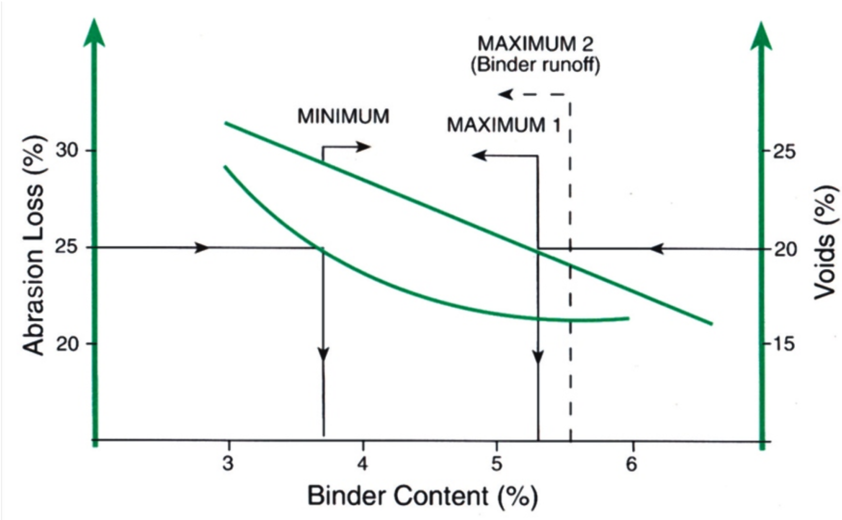


Figure 7: Determination of suitable binder content.

- After it has been mixed, the uncompacted asphalt should be spread out in a bowl to a depth of about 60mm. This is placed in a force draft oven and conditioned for three hours at the specified mixing temperature. Halfway through the process, the material should be remixed with a spatula. It should be noted that mixes containing heterogeneous binders (such as bitumen-rubber binders) with temperature and/or time-dependent properties need not be subjected to the above conditioning procedure.

Table 3: Recommended mixing and compaction viscosities and temperatures

Binder type	Kinematic viscosity or temperature	
	Mixing	Compaction
Unmodified and polymer-modified binders	$700 \pm 50 \times 10^{-6}$ m²/s	$1000 \pm 70 \times 10^{-6}$ m²/s
Bitumen-rubber asphalt	140°C± 5°C	130°C±5°C

Compaction of the briquettes is conducted in similar fashion to the guidelines given in the appendix to method C2 of TMH1[24] with the following provisos:

- The moulds, base plate and hammer should be heated to compaction temperature, before the mixes are placed in the moulds. When the mix is ready, the mould, collar and base plate are placed in position on the compaction pedestal. A piece of round filter paper is placed in the bottom of the mould. The mix is placed in the mould, care being taken to avoid segregation. The mixture is prodded 15 times with a heated spatula around the perimeter and the rest of the surface is prodded 10 times, leaving a slightly dome-shaped surface. A piece of filter paper is placed on top of the mix and the heated hammer is placed in position;
- The samples are compacted at the temperature which will produce the viscosity given in Table 3. If the compaction temperature drops below the specified levels, the mix should be discarded. Under no circumstances should the sample be reheated. The Marshall hammer is used to apply 50 blows to each side of the sample. If crushing of the aggregate is observed, the number of blows may be reduced. However, crushing may be indicative of inadequate aggregate strength and additional tests (such as the Los Angeles rattler test described in ASTM Method C131-81) should be conducted in order to ensure that the aggregate is fit for its purpose. After compaction, the sample is cooled prior to removal from the mould.

Uncompacted mixes are manufactured and cured in the same fashion as above to determine the apparent maximum relative density (Rice's method) and the resistance of the mix to binder run-off. As in the case of asphalt briquettes, at least four binder contents are suggested, starting at 3,5% by mass of total mix in increments of 0,50%.

Determination of mix properties

Three criteria are used in the process of selecting the optimum binder content. These are:

- total air void content (volumetric analysis);
- abrasion loss (Cantabro test);
- loss of binder by run-off (basket drainage or Schellenberger tests).

The procedures and criteria for the above tests are discussed below.

Volumetric properties

Methods of determining the properties required to conduct the design process may be obtained from either TRH8[25] or ASTM26. The required properties are:

- apparent bulk relative density;
- apparent maximum relative density;
- void content.

The density of compacted porous asphalt briquettes is determined from the dry mass of the specimen (in grams) and its volume (in cubic centimetres). To calculate the volume, the diameter of the sample is taken as the internal diameter of the mould (usually 101,6mm), while the height is determined (according to ASTM Method D3549[26]) with callipers or similar device to an accuracy of 0,1mm. The density (mass over volume) is then converted to apparent bulk relative density by dividing the density by 0,99707 g/cm^3, the density of water at 25^{o}C.

Alternatively, the apparent bulk relative density of compacted porous asphalt briquettes can be measured by first coating the sample with paraffin wax, measuring the density in similar fashion to that for dense-graded asphalt mixes, correcting the density to exclude the paraffin wax coating and converting this density to apparent bulk relative density (ASTM Method D1188[26]).

The apparent maximum relative density can be determined by conducting Rice's test on the uncompacted mix. The method is described in TMH1 Method C4[26]: *The determination of the maximum theoretical relative density of asphalt mixes: Rice's method*. Alternatively, the apparent maximum density can be approximated by using the following equation which assumes no binder absorption by the aggregate:

$$D_m = \frac{100}{\frac{A}{G_{ag}} + \frac{P}{S}}$$

where:

Dm	=	apparent maximum relative density
A	=	percent total aggregate in mix
P	=	percent bitumen by mass in mix

G_{ag} = bulk relative density of aggregate
S = relative density of bitumen

The air void content of the mix (voids in mix) is then calculated as follows:

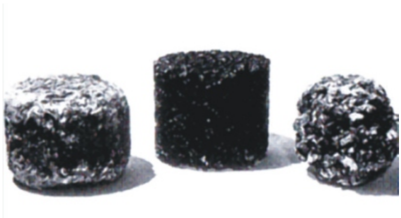
$$V_m = \frac{D_m - G_b}{D_m} 100$$

Where:

V_m = voids in mix (%)
D_m = apparent maximum relative density
G_b = apparent bulk relative density of compacted mix

For a given combination of grading and binder content, the void content should be equal to or greater than the design void content (usually 20%) in order for the mix to be accepted.

Cantabro abrasion test



Results of Cantabro test: good performance (left) sample prior to testing (centre) and poor performance.

The resistance of porous asphalt briquettes to abrasion loss is analysed by means of the Cantabro test[23]. This is an abrasion and impact test carried out in the Los Angeles rattler (ASTM Method C131-81[26]).

In this test, a briquette compacted with 50 blows on each side is used. The mass of the specimen is determined to the nearest 0,1gm, and is recorded as P_1. The test specimen is then placed in the Los Angeles Rattler without the charge of steel balls. The operating temperature is usually 25^{o}C. The machine is switched on and allowed to operate for 300 revolutions at a speed of 30 - 33 rpm. After the required number of revolutions, the test specimen is removed and mass determined to the nearest 0,1gm (P_2). The percentage abrasion loss (P) is then calculated according to the following formula:

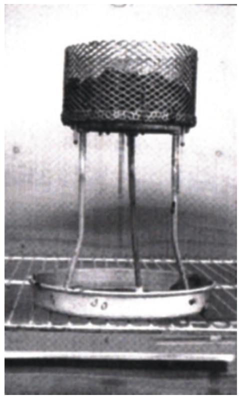
$$P = \frac{P_1 - P_2 \, 100}{P_1}$$

The suggested maximum permitted abrasion loss value for freshly compacted specimens is 20%. However, some countries in Europe specify a maximum value of 25%.

Resistance to abrasion does not only improve with an increase in binder content, but is also related to the rheological properties of the binder. For a given grading and binder content, mixes containing unmodified binders generally have less resistance to abrasion than mixes containing bitumen-rubber binders. The abrasion resistance of mixes containing polymer-modified binders is usually between those of unmodified mixes and bitumen-rubber mixes.

Basket drainage test and Schellenberger test

To maximise durability, binder content should be as high as possible, cognisance being taken of voids content and resistance to deformation. However, on account of their open structure, porous asphalt mixes are more prone to the effects of binder run-off than conventional, dense-graded mixes. These effects are especially important during transportation of the mix and during paving and compaction. The basket drainage test is used to determine the maximum binder content of a particular mix before the effects of binder run-off become excessive.



Basket drainage.

The operational procedure of the basket drainage test is as follows[20].

i. Uncompacted porous asphalt mixes, prepared at various binder contents, are placed in perforated baskets;
ii. The samples are then placed for two hours in an oven set to a temperature which depends on the nature of the binder used;
   - 140°C for 40/50 B24 or 60/70 B12 penetration grade bitumen;
   - 140°C to 180°C for modified binders, depending on their viscosity.

iii. The bitumen which drains through the grid is recovered and weighed. The loss of bitumen is calculated with respect to the initial binder content of the mix.

Alternatively, the Schellenberger drainage test[27] can be used to assess the potential for binder run-off. The test consists of placing 1 000 to 1 100 gms of uncompacted asphalt mix in an 800mℓ glass receiver, which is then placed in an oven set to the appropriate mixing temperature (Table 3). As in the case of the basket drainage test, the amount of binder drainage is determined after removal of the asphalt mix from the receiver and is related to the initial binder content. The results of these binder drainage tests can be assessed either by relating the results to a limiting design criterion or by computing their effects on resistance to abrasion and void content. In the case of the former, it is suggested that the percentage loss in mass be less than 5% of the initial binder mass prior to testing. For the latter, the following applies:

- **Abrasion resistance:** Cantabro abrasion loss should be determined for a mix with an effective binder content equal to the initial binder content minus the percentage loss in binder. If the Cantabro abrasion loss exceeds the minimum acceptable criterion, the mix should be rejected:
- **Voids content:** The voids content should be determined for a mix with an effective binder content equal to the sum of the initial binder content and the percentage loss in binder. If the voids content is lower than the design void content, the mix should be rejected.

When binder run-off takes place during construction, as predicted by the drainage test, it will result in portions of the mix containing either too much or too little binder. This will affect both the void content and the abrasion resistance of the mix. This is the reason for either adding the estimated loss of binder caused by run-off to, or subtracting it from, the design binder content to determine the effects on void content and resistance to abrasion respectively.

Evaluation of design mix

Resistance to permanent deformation

The resistance of porous asphalt mixes to permanent deformation is more difficult to assess than that of conventional mixes on account of the open structure of the former. Either of the two test methods below may be used:

- **Wheel tracking test:** The testing methodology, apparatus and failure criteria to be used should comply with French specifications[28,29]. Such testing devices are, however, not yet available in South Africa.
- **Confined dynamic creep test (triaxial test):** Unconfined uniaxial tests may not be appropriate for the evaluation of porous asphalt. The use of a conventional triaxial cell would appear to be the best method of carrying out confined tests. However, there may be a number of problems which need to be resolved prior to using such a device for routine testing, e.g. temperature control within the cell and the effect of seal friction on load measurement. An alternative method is to modify the dynamic creep test by placing the specimen within a membrane and applying a vacuum to reduce the pressure within the membrane, thus applying confinement. No failure criteria have yet been set for this test[30].

Resistance to ageing

Because of the high void content of porous asphalt, the rate at which the bituminous binder hardens or ages is likely to be greater than that of binders in dense-graded asphalts whose void contents typically range between 3 and 6%. To ensure that polymerisation of the binder in service does not result in an excessive reduction in cohesive and adhesive strength, which in turn may lead to ravelling, it is recommended that the design mix be subjected to an accelerated ageing test.

The recommended conditioning procedure consists of the following phases[31].

i. Five briquettes, prepared at optimum binder content and manufactured according to the procedures outlined on page 34, are placed in a forced draft oven set to a temperature of 60^{o}C. The specimens are heated for 48 hours;

ii. After this initial ageing, the temperature of the forced draft oven is raised to 107°C for an additional 120 hours;
iii. After ageing, the specimens are removed from the oven, placed in a temperature cabinet set at 25°C and stored for four hours prior to testing.

Cantabro abrasion tests are conducted on the five briquettes after conditioning. The average of the abrasion losses obtained should not exceed 30%, while no individual result should exceed 50%.

Resistance to moisture damage

As moisture is one of the critical factors resulting in stripping and ravelling, the resistance of the design mix to moisture damage should be assessed. It is suggested that moisture conditioning be conducted according to the Lottman method[32], which is designed to simulate the long-term effect of moisture-damage as a result of environmental conditions and traffic forces. The following procedure is suggested:

i. **Vacuum-saturation:** Five compacted asphalt briquettes are immersed in jars filled with distilled water, after which the pressure inside the jars is reduced to 100mm Hg for 30 minutes. Following this, the submerged specimens are kept in the jars for an additional 30 minutes at atmospheric pressure;
ii. **Two cycles of accelerated conditioning:** Each wet, vacuum saturated specimen is tightly wrapped in thin plastic wrap. Each wrapped specimen is placed in a heavy-duty plastic bag with about 3mℓ of distilled water, sealed, and placed in a 20°C to -10°C freezer for 15 hours. After removal from the freezer, the wrapped, frozen specimens are then quickly submerged in a 60°C water bath for three minutes. The thawed wrappings are removed and the specimens are immediately replaced in the 60°C bath for 24 hours. After two such freeze-thaw cycles, the specimens are submerged in a cooler water bath set at 25°C prior to testing.

As in the case of the accelerated ageing test, the average Cantabro abrasion loss after conditioning should not exceed 30%, while no individual result should exceed 50%.

Note: As moisture is one of the critical factors resulting in stripping and ravelling, the resistance of the design mix to moisture damage should be assessed.

4. Guidelines on constructibility

Manufacture of porous asphalt

The manufacture of porous asphalt in conventional batch plants or drum mixing plants raises no particular problems by comparison with that of dense bituminous mixes[19,33]. The order of entry into the mixer is generally the same: aggregate, bitumen and, finally, filler. However, it is advisable to employ the Ross Count Method to determine wet mix times for various procedures to determine the best order.

Care should be taken to ensure that the viscosity of the binder is such that the plant pumps can handle it. This is particularly important in the case of bitumen-rubber binders.

When mixing temperatures are established, not only should binder viscosities be taken into account but also the drainage of the binder during transit from the mixing plant to the job site. When modified binders are used, mixing temperatures should not exceed 160°C. In the case of 60/70 penetration grade bitumens, mixing temperatures usually range between 120°C and 140°C.

Paving of asphalt.

Transport of mix to site

The risk of binder run-off during transport is a function of the initial temperature of the mix, the ambient temperature and the length of the haul, especially with mixes containing low viscosity binders at high binder contents. Binder run-off results in:

- the material sliding in large lumps from the trucks, which makes laying more difficult, and;
- the presence of binder-rich areas in the surface after spreading.

Paving and compaction

The temperature of porous asphalt mixes should not be below 120^oC during compaction. Construction may have to be avoided if there is a cold wind. Mechanical laying is normally no more difficult for porous asphalt than for dense asphalt mixes. Static smooth-wheeled rollers having a total mass of 7 - 10 tons are recommended for compaction. The use of vibrating rollers is not recommended as they can crush the coarse aggregate. Compaction can be controlled in the normal way from cores or indirectly by means of *in situ* permeability tests[18,34].

A continuous paving operation is even more important with porous asphalt than it is with dense mixes. A stoppage of the paver will inevitably leave an irregularity in the surface. Such irregularities will lead to slacks developing in the surface under traffic.

It is recommended that each lane be paved to its entire length before proceeding to a new lane. It is also recommended that, if traffic conditions permit, two pavers be used on two parallel lanes to minimise longitudinal joints. Before a new layer is placed next to an existing one, it is recommended that the edge of the existing layer be heated to ensure adequate longitudinal bonding. Longitudinal joints should not be cut back because the action of the cutting wheel tends to block the *in situ* voids, which impairs cross drainage within the layer.

Handwork should be avoided as it is almost impossible to obtain an unblemished surface. In addition, the accelerated cooling which is associated with handwork results in inadequate compaction followed by excessive ravelling under traffic.

Trial sections

The use of trial sections is recommended to assess the mix finally and to hone the contractor's operation. Trial sections need to be of sufficient length to achieve this. The following should be determined from the trial sections:

- optimum screed settings;
- permeability of the layer;
- optimum rolling techniques to ensure optimum compaction without crushing the aggregate;
- mix properties and fine tuning of laboratory-designed mixes to cater for shift factors;
- a precise recording of the process between laboratory and plant to be used for quality control.

Note: The temperature of porous asphalt mixes should not be below 120°C during compaction.

5. Quality Control

Introduction

To ensure that the porous asphalt mix designed in the laboratory is constructed to specification and that its functional and structural properties are to the client's satisfaction, the quality of the mix both during and after construction should be evaluated.

During the execution of the work, the contractor should control the composition of the mix (aggregate grading and binder content) to ensure that it is in accordance with the agreed mix within specified tolerances. In addition, he should ensure that the mixing temperature is correct, that the mix is homogeneous (no segregation of binder or aggregate) and, finally, that the laying operations result in a smooth finished surface of adequate density. Ravelling under traffic of freshly laid mix must be closely monitored.

The degree of compaction can be controlled indirectly by means of surface permeability tests. The volumetric properties and resistance of the mix to abrasion are determined on mix recovered from the paver and compacted in the laboratory or from cores extracted from the pavement.

In the event of performance specifications being endorsed in South Africa, asphalt producers may be encouraged to meet specific client demands, such as skid resistance and noise attenuation requirements. Apart from the fact that such specifications will open new frontiers for the innovative use of bituminous materials in general, they are also particularly well suited to porous asphalt technology.

After the road has been opened to traffic, the wearing course will be assessed to measure the functional benefits for which it was designed. It is recommended that wet skid resistance, drainage capacity, noise, rutting and riding quality are the parameters to be considered.

Volumetric requirements

It is recommended that the average void content per shift for field mixes compacted in the laboratory according to the procedures outlined in the section *Determination of mix properties* on page 36 comply with the following criterion[35].

$$19\% < V_{avg} < 25\ \%$$

and that those of individual briquettes should comply with the following criterion:

$$16\% < V_{core} < 28\ \%$$

The tolerance suggested for the average binder content of 10 samples is optimum binder content 0,3%, while that for the binder content of any one sample should not deviate by more than 0,7% from the optimum.

Thickness requirements

It is recommended that thicknesses determined from carefully controlled levels taken before and after construction or from cores drilled from the completed layer comply with the following criteria:

90th percentile deviation	: 5 mm
maximum deviation	: 8 mm
average deviation	: 2 mm

Abrasion resistance

The abrasion loss of field samples, compacted in the laboratory according to the procedures outlined on page 36 and tested in accordance with the procedure described on page 39, may not exceed 25%, although a maximum abrasion loss of 20% is recommended.

Binder run-off

If it is found that binder run-off occurs during transport or paving operations, it is suggested that basket drainage tests be carried out in order to quantify its severity. If it is found that more than 5% binder is lost in the basket drainage test and that the composition of the mix is within specification, the following remedial actions are suggested:

- reduction in mixing temperature to a level at which compaction densities can still be achieved;
- addition of a binder stabiliser (mineral filler, lime, cement or cellulose fibres) to a maximum quantity dictated by the design void content of the mix; or
- selection of a bituminous binder with higher viscosity.

Water permeability test

The water permeability test enables the drainage capacity, the *in situ* void content and the homogeneity of the finished surface to be assessed. It is therefore considered as an important test for assessment of the quality of a porous asphalt wearing course.

On account of the high void content of porous asphalt mixes, the Marvil drainometer is not suitable for assessing drainage capacity. It is suggested that a device similar to that shown in Figure 3 on page 50 be used. This device, which was developed in 1981 at the University of Cantabria in Santander (Spain)[34], is referred to as the LCS Drainometer. It is currently used in several European countries.

The testing procedure consists of placing the drainometer on the road surface and filling the transparent cylinder (Figure 3) with water to a level approximately 150mm above the top marking of the cylinder. Then 150mm of water is allowed to drain out of the drainometer to wet the porous asphalt layer. When the water level reaches the top marking, recording of the time should commence until the water level reaches the bottom marking. The recorded time T (measured in seconds) can then be used to:

- determine the permeability coefficient (K), using the following equation[34]:

$$\ell n\,(K) = 7{,}624 - 1{,}348\,\ell n(T)$$

- determine the approximate void contents of the porous asphalt layer, using the following equation[18].

$$\text{Voids (\%)} = \frac{58{,}6}{T^{0{,}305}}$$

$$\textit{Voids (\%)} = \frac{58,6}{T^{0,305}}$$

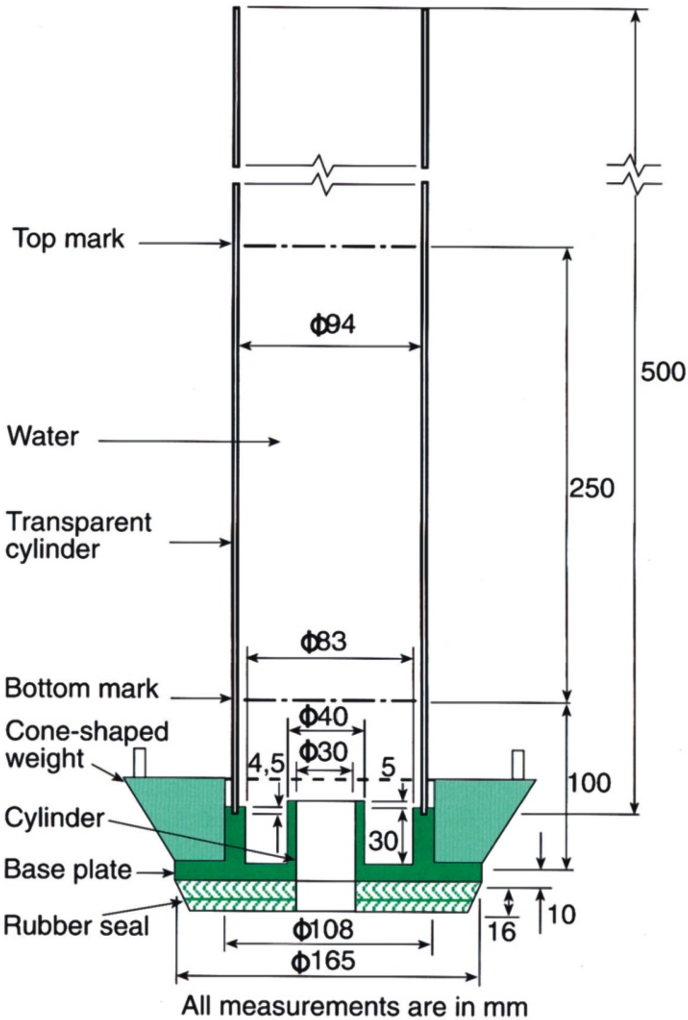


Figure 8: LCS Drainometer

Evaluation of skid resistance

The wet skid resistance of porous asphalt can be measured by means of a Sideways-force Coefficient Routine Investigation Machine (SCRIM) or a brake-force trailer.

The SCRIM consists of a smooth tyre fitted to a commercial vehicle chassis carrying a water tank. This wheel is offset by 20 degrees from the direction of travel of the vehicle. Pressure sensors record the sideways force of the test wheel, which is a function of the coefficient of continuous resistance to skidding.

The brake-force trailer, towed by a light delivery vehicle, utilises either one or two smooth test wheels which measure skid resistance either under controlled slip conditions (ARB braking system) or with the test wheels locked. The skid resistance measured is referred to as the brake-force coefficient (bfc), which is the ratio of the frictional force exerted by the road on the test tyre, measured at a given speed, and the normal load on the wheel.

Both evaluation methods have their advantages and disadvantages. Use of the SCRIM enables measurements to be carried out on a continuous basis with minimum disruptions to traffic flow. The brake-force trailer provides information which correlates better with the actual braking distance of vehicles, but its use could impair road safety, unless it is used in off-peak periods or is fitted with an ARB braking system. The use of the brake-force trailer, rather than the SCRIM, is more often referred to in overseas literature on porous asphalt. Its use may therefore be preferred as its data enables comparisons to be made between local and overseas skid resistance measurements.

Note: There are two evaluation methods to measure the wet skid resistance of porous asphalt - SCRIM and brake-force trailer.

6. Maintenance

Clearing of voids

Porous asphalt surfacing layers slowly silt up in places where traffic is not intense. This problem generally does not occur in the traffic lanes of a highway where self-cleaning of the voids is generated by the tyres themselves. The decrease in void content with time leads to an alteration of the intrinsic qualities of porous asphalt mixes which shift to those of semi-open or even dense-graded asphalt mixes.

The accumulation of waste in the voids of a porous asphalt wearing course will obstruct drainage which will impair the performance of the layer (decreased wet-weather skid resistance, increase in splash and spray, etc). Three alternatives are suggested for determining loss in porosity:

- **visual assessment during or shortly after rain:** ponding of water on the surfacing may be noted or the drainage capacity of the layer can be subjectively assessed;
- **modified-dust monitor:** this device can be used to quantify the changes in splash and spray with time;
- ***in situ* permeability tests:** the LCS drainometer can be used to monitor the changes in drainage capacity in localised areas

The above alternatives enable decision makers to determine the appropriate timing for clearing the voids. Two alternatives are suggested, the selection of which depends on the severity of clogging:

- slight decrease in drainage capacity, no ponding, voids in excess of 18% (determined in accordance with the section *Water permeability test* on page 49): high-pressure wash system mounted on a water truck;
- significant decrease in drainage capacity, ponding, voids less than 18%: high-pressure wash and suction unit mounted on a vehicle.

In both cases, the voids are blasted clean by high pressure water. If severe clogging occurs, the debris is immediately sucked into a container by a fast air-stream. Specialist equipment will be required to carry out these measures.

Preventive maintenance

Of major concern with porous asphalt is loss of aggregate by ravelling resulting from construction operations (mix temperatures too low during paving, insufficient compaction, binder segregation and poor transverse joints) or by hardening of the binder (loss in cohesion and adhesion). Whereas the construction-related problems are difficult to overcome except by removal and replacement, the rate of hardening of the binder can be controlled by periodical applications of rejuvenating agents or extender oils. The latter may, however, result in a reduction in voids contents.

Rehabilitation

At the end of its structural or functional life, the porous asphalt layer can either be:

- milled out and replaced by another porous asphalt layer;
- overlaid with a new porous asphalt layer or with a dense-graded asphalt mix followed by a porous asphalt mix (the danger of entrapped moisture in the old porous layer leading to stripping should not be overlooked); or
- milled out and replaced after hot recycling.

The above alternatives have all been tried in Europe with varying degrees of success. Porous asphalt is a recent innovation and the technology is still too young to enable the most cost-effective option to be determined with any degree of certainty.

Note: The rate of hardening of the binder can be controlled by periodical applications of rejuvenating agents or extender oils.

7. References

1. **Verhaeghe BMJA.** *PMWC: Literature survey on porous asphalt mixes.* Output report PMWC/10, Sabita, Cape Town, May 1991.
2. **Verhaeghe BMJA. PMWC:** *Investigation into the effects of grading, binder content and binder type on the properties of porous asphalt mixes*. PMWC/13, Sabita, Cape Town, July 1991.
3. **Verhaeghe BMJA, Airey GD.** PMWC: *Fatigue properties of unconditioned porous asphalt mixes*. PMWC/15, Sabita, Cape Town, August 1991.
4. **Airey GD.** PMWC: *Fatigue properties of age-hardened porous asphalt mixes.* PMWC/18, Sabita, Cape Town, September 1991.
5. **Verhaeghe BMJA.** PMWC: *Fatigue properties of porous asphalt mixes subjected to age hardening.* PMWC/19, Sabita, Cape Town, January 1992.
6. **Airey GD.** PMWC: *Fatigue properties of vacuum-saturated porous asphalt mixes*. PMWC/20A, Sabita, Cape Town, September 1991.
7. **Airey GD**. PMWC: *Fatigue properties of accelerated conditioned porous asphalt mixes*. PMWC/20B, Sabita, Cape Town, September 1991.
8. **Verhaeghe BMJA.** PMWC: *Fatigue properties of moisture-conditioned porous asphalt mixes*. PMWC/21, Sabita, Cape Town, January 1992.
9. **Verhaeghe BMJA**. PMWC: *Summary report.* PMWC/24, Sabita, Cape Town, August 1992.
10. **Verhaeghe BMJA**. PMWC: *The influence of polymers and fibres on the engineering properties of porous asphalt mixes.* PMWC/25, Sabita, Cape Town, August 1992.
11. **Verhaeghe BMJA.** PMWC: *The influence of polymer fibres on the engineering properties of porous asphalt mixes.* PMWC/25. Sabita, August 1992.
12. **Verhaeghe BMJA.** *Properties of cellulose fibre-modified porous asphalt mixes.* DPVT-C/222, Thermguard (Pty) Ltd, Pretoria, May 1992.
13. **Verhaeghe BMJA.** *Bitumen-rubber porous asphalt mixes: current state-of-knowledge.* DPVT-C\237-2, Tosas (Pty) Ltd, Pretoria, November 1992.

14. **Verhaeghe BMJA, Airey GD.** *Summary report on bitumen-rubber porous asphalt mixes.* DPVT-C\237-3, Tosas (Pty) Ltd, Pretoria, March 1993.
15. **Verhaeghe BMJA.** *Constructibility and initial performance of Arm-R-Drain placed on the Ben Schoeman Highway.* DPVT-C\237-7, Tosas (Pty) Ltd, Pretoria, February 1994.
16. **Du Plessis JL, Verhaeghe BMJA, Rust FC.** *Performance of bitumen-rubber porous asphalt subjected to accelerated trafficking.* DPVT-C/263, Transvaal Provincial Administration, Pretoria, February 1994.
17. **Eurocorner. Netherlands:** *Drivers in favour of porous asphalt.* European Asphalt Magazine, 1/93, Baden-Baden, 1993.
18. **Ruiz A, Alberola R, Pérez F, Sánchez B.** *Porous asphalt mixtures in Spain.* Transportation Research Record 1265, Transportation Research Board, Washington, D.C., 1990.
19. **Van Heystraeten G, Moraux C.** *Ten years' experience of porous asphalt in Belgium.* Transportation Research Record 1265, Transportation Research Board, Washington, D.C., 1990.
20. **Faure B, Vrhe F, Lucas J.** *Techniques nouvelles de couches de roulement: Les enrobes drainants.* Bulletin de Liaison des Laboratoires des Ponts et Chausses No. 172, Ministre de l'quipement, du Logement, des Transports et de la Mer, Paris, 1991.
21. **Zazotto L, Foley D, Rodier CE, Watson RD.** *Modified asphalt - are you really coming?* Proceedings of the Canadian Technical Asphalt Association, Volume 32, 1987.
22. **Technical Guideline 1.** *The use of modified binders in road construction.*
23. **NLT-352/86.** *Characterisation de las mezclas bituminosas abiertas por medio del ensayo cantabro de perdida por desgaste (Characterisation of open-graded asphalt mixtures by the Cantabro wear test)*. CEDEX-MOPU, Madrid, 1986.
24. **Committee of State Road Authorities (CSRA).** *Standard methods of testing road materials.* TMH1, Department of Transport, Pretoria, 1986.
25. **Committee of State Road Authorities (CSRA).** *Selection and design of hot mix asphalt surfacing for highways.* Draft TRH8, Department of Transport, Pretoria, 1987.
26. **American Society for Testing and Materials.** *Annual Book of ASTM Standards,* Volume 04.03., Philadelphia, 1990.

27. **Decoene Y.** *Contribution of cellulose fibres to the performance of porous asphalt.* Transportation Research Record 1265, Transportation Research Board, Washington, D.C., 1990.
28. **Association franaise de normalisation (afnor).** *Normes franaise pour couches deroulement: beton bitumineux drainant.* NF P 98-134, Paris, 1991.
29. **Association franaise de normalisation (afnor).** *Normes franaise pour deformation permanente des mlanges hydrocarbons Part 1: Essai d'ornirage*. NF P 98-253-1, Paris, 1991.
30. **Brown S.** *Simplified methods for determination of fundamental material properties of asphalt mixes.* Proceedings of the Strategic Highway Research Program Conference, The Hague, September 1993.
31. **Von Quintus HL, Scherocman JA, Hughes CS, and Kennedy TW.** *Asphalt-Aggregate Mixture Analysis System (AAMAS).* National Cooperative Highway Research Program Report 338, Transportation Research Board, Washington, D.C., 1991.
32. **Lottman RP.** *Laboratory test method for predicting moisture-induced damage to asphalt concrete.* Transportation Research Record 843, Transportation Research Board, Washington, D.C., 1982.
33. **Gerardu J, Hansen F, Jonker C, Van Der Plas J.** *The use of porous asphalt wearing courses in the Netherlands.* Third Eurobitume Symposium, Volume 1, The Hague, 1985.
34. **NLT-327/88.** *Determination of the in situ permeability of porous pavements using the LCS permeability apparatus.* CEDEX-MOPU, Madrid, 1988.
35. **Ministry of Public Works, Management of Roads.** *Betreft dreinerende bitumineuze mengsels.* Omzendbrief Nr A.169-86/04000, Brussels, April 1986.

8. Appendices

Appendix A: Case study - Ben Schoeman Highway (1993)

Introduction

In this appendix, an example of the application of the mix design method is discussed. The information used was obtained from the use porous asphalt on the Ben Schoeman Highway in Johannesburg[A1]. Approximately 260 000 m^2 of porous asphalt, with a layer thickness of 40mm, was placed between the Corlett Drive off-ramp and the Buccleuch interchange. The decision to employ porous asphalt was based on the need to improve wet weather safety. In this case study, only one grading is considered for the design process. The following topics are addressed:

- selection of appropriate binder and determination of optimum binder content;
- performance of mix subjected to accelerated trafficking;
- initial functional performance of porous asphalt on the Ben Schoeman Highway.

Selection of binder type and binder content

Granulometric properties

The aggregate grading envelope and actual grading selected for the Ben Schoeman Highway contract are given in Table A1. This grading is particularly suited for use with bitumen-rubber binders. The small percentage of aggregate passing the 4,75mm sieve and the low filler content would result in excessive binder run-off during construction if homogeneous binders (unmodified or polymer-modified) were used without stabilising additives (such as fibres). On account of their high viscosity and good adhesive and cohesion properties, the use of bitumen-rubber binders produces a durable product. This has been validated by means of laboratory tests.

The average void content of porous asphalt mixes manufactured with four different bitumen-rubber contents are given in Table A2. As can be seen from the results, a binder content of 6,5% by mass of total mix yields mixes with void contents in excess of 20%.

Table A1: Grading of the Ben Schoeman Highway mixes

Sieve size	Percentage passing sieve size	
	Design grading	Grading envelope
19,0mm	100	100
13,2mm	93	90 - 100
9,5mm	28	25 - 65
4,75mm	11	10 - 15
2,36mm	9	8 - 15
0,075mm	3	2 - 5

Table A2: Average void content of bitumen-rubber mixes

Binder content	Void content
5,5%	23,2%
6,0%	22,3%
6,5%	21,0%
7,0%	19,9%

Abrasion resistance

The resistance of different types of mix to abrasion was evaluated in the laboratory by means of the Cantabro abrasion test. The effects of three binder contents (4,5%, 5,0% and 5,5%) and of four binder types (bitumen-rubber, 80/100 penetration grade bitumen and EVA- and SBR-modified binders) were investigated. An 80/100 penetration grade bitumen was used as basis for modification and each of the polymer-modified binders contained 3% of polymer by mass of total binder. The results are given in Table A3.

Table A3: Average results of Cantabro abrasion tests

Binder content	Binder type			
	Bitumen-rubber	80/100 Pen bitumen	EVA-mod. binder	SBR-mod. binder
	Abrasion loss			
4,5%	38%	43%	39%	36%
5,0%	16%	31%	27%	23%
5,5%	9%	27%	14%	15%

These results indicate that, at a binder content of 4,5% by mass of total mix all mixes, irrespective of binder type, have unacceptably high Cantabro abrasion losses (maximum for the contract was specified as 20%). However, as binder content increases, resistance to abrasion improves significantly. Mixes containing bitumen-rubber binders show the greatest improvement with an increase in binder content. The minimum binder contents required for the mix to have an abrasion loss of less than 20% are:

- bitumen-rubber mix: 4,9%;
- SBR-modified mix: 5,1%;
- EVA-modified mix: 5,3%;
- unmodified mix: 5,9%

From the above, it can be seen that the mix containing bitumen-rubber requires the smallest quantity of binder.

Resistance to binder run-off

Mixes manufactured at four different binder contents (4,0%, 4,5%, 5,0% and 5,5%) were subjected to the basket drainage test to determine their resistance to binder run-off. The results in Table A4 illustrate the susceptibility of binder run-off to variations in binder content. For this particular grading, mixes using bitumen-rubber binders show the least variation in run-off for variation in binder content.

Table A4: Average results of the basket drainage test

Binder content	Binder type			
	Bitumen-rubber	80/100 Pen bitumen	EVA-mod. binder	SBR-mod. binder
4,0%	1,5%	2,1%	1,3%	0,4%
4,5%	1,7%	2,8%	3,2%	2,0%
5,0%	1,9%	14,2%	9,3%	3,3%
5,5%	1,8%	22,1%	14,6%	8,4%

The effects of binder run-off on Cantabro abrasion loss for mixes with binder contents giving a minimum of 20% loss are given in Table A5. The results demonstrate the detrimental effect of binder run-off on resistance to ravelling. Bitumen-rubber mixes are the least affected and, at a minimum design binder content of 5,5%, the mix should have excellent resistance to ravelling, despite a small reduction in effective binder content resulting from possible binder run-off.

Table A5: Effect of binder run-off on abrasion resistance

Binder type	Initial B/C	Run-off[1]	Net B/C	Abrasion loss
Bitumen-rubber	4,9%	2,0%	4,8%	22%
SBR-mod.	5,1%	8,0%	4,7%	27%
EVA-mod.	5,3%	13.0%	4,6%	37%
80/100 Pen	5,9%	>25%	<4,4%	>50%
[1]As a percentage of initial binder content (B/C)				

Based on the above results, a bitumen-rubber binder was selected for the contract. The design binder content was specified as 5,8% by mass of total mix. During construction, 1,0% of mine sand was added to the mix as it was found that the void content often exceeded 25%, on account of fluctuations in the grading towards the coarser side of the target grading. The average and 95% confidence limits for binder content, void content and Cantabro abrasion loss are given in Table A6.

Table A6: As-built data

Property	Statistics	
Binder content	Average 95% confidence limit Min. - Max.	5,7% 5,6% - 5,8% 4,8% - 6,8%
Void content	Average 95% confidence limit Min. - Max.	21,6% 21,1% - 22,0% 17,3% - 26,1%
Abrasion loss	Average 95% confidence limit Min. - Max.	12,2% 10,9% - 13,5% 3,4% - 28,1%

Durability

The durability of the bitumen-rubber porous asphalt mix was determined by freeze-thaw conditioning of specimens, according to the Lottman procedure[A2], followed by Cantabro abrasion tests. The results in Table A7 indicate that freeze-thaw conditioning had little effect on resistance of the mix to ravelling.

Table A7: Abrasion loss before and after freeze-thaw cycling

Average loss prior to conditioning	Average loss after conditioning
10,5%	14,6%

Performance under accelerated trafficking

On behalf of the Transvaal Provincial Administration[A3], the CSIR conducted Heavy Vehicle Simulator tests[A4] on a porous asphalt overlay constructed on a section of Road P6/1 located between Bapsfontein and Bronkhorstspruit in the Gauteng Province. The pavement structure, prior to being overlaid with 40mm bitumen-rubber porous asphalt (the same mix as that used on the Ben Schoeman Highway), consisted of 40mm of compounded seals on a gravel structure with a thickness of 600mm. The surface deflection, determined by the Road Surface DeflectometerA5 (RSD) prior to the HVS tests, was 1,44mm.

The objectives of these accelerated tests were to determine the resistance of porous asphalt to ravelling, fatigue and permanent deformation at both ambient (23^{o}C) and elevated temperatures (37^{o}C). To achieve these objectives, the ambient and heated sections were trafficked with a 40kN dual wheel load for up to 125 000 load repetitions, after which the applied load was increased to 70kN to a total of 175 000 load repetitions. The following information was collected during the tests:

- temperature measurements by means of thermocouples;
- rut measurements (straight edge);
- surface deflections (RSD);
- in-depth deflections and deformations by means of Multi-Depth Deflectometers[A6] (MDDs);
- water permeability of surfacing;
- visual assessment of surfacing.

The progressive rut depths as measured by a straight edge on the surface of both sections (ambient and heated section) and the rut rates for these two sections are shown in Figure A1. As can be seen from the results, surface rutting is a function of both temperature and wheel load, an increase in either one of these variables resulting in greater permanent deformation. The in-depth permanent deformations at the end of each of the phases shown in Figure A1 are given in Table A8. From these results it can be seen that very little deformation took place in the porous asphalt wearing course and that most of the permanent deformation took place in the granular base. This was confirmed by the volumetric properties of cores taken from within and outside the trafficked areas (Table A9) and by the results of permeability tests which did not indicate any significant changes in drainage capacity before or after trafficking.

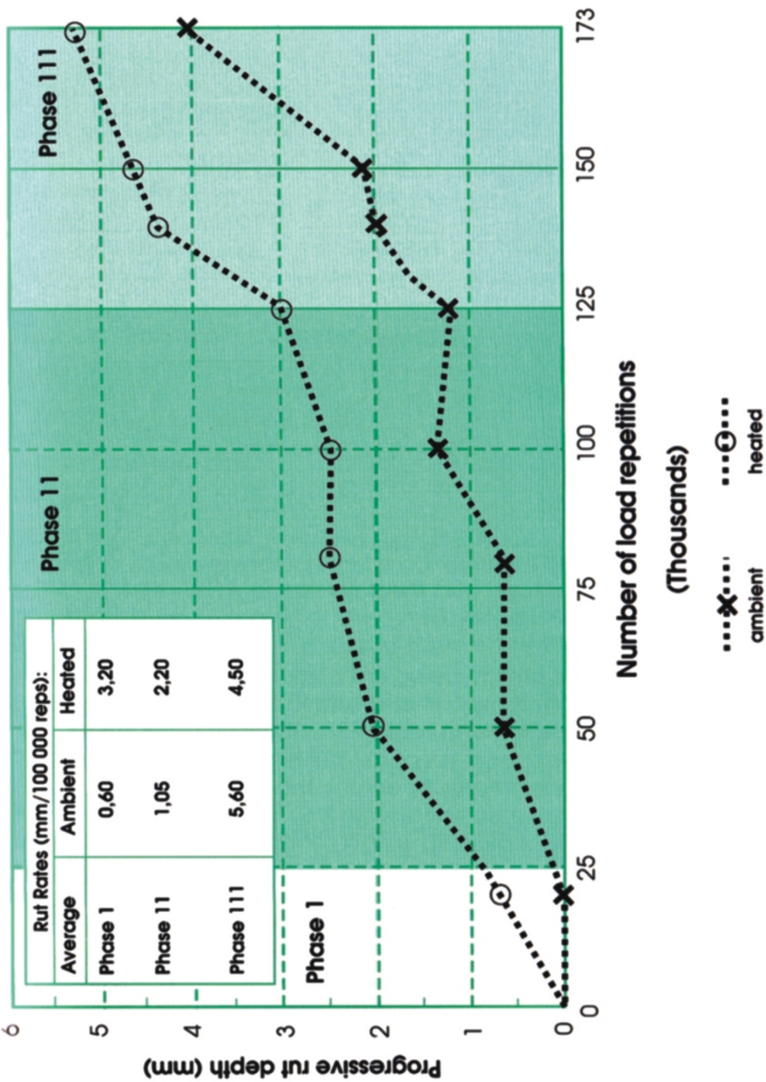


Figure A1. Surface rutting and average rut rates

Table A8: In-depth permanent deformation

Layer	Phase I	Phase II	Phase III
	Permanent deformation		
1. 40mm porous asphalt	0,20mm	0,78mm	1,00mm
2. 265mm Base	2,16mm	5,22mm	5,90mm
3. 150mm Subbase	0,02mm	0,09mm	0,75mm
4. 220mm Selected	0,09mm	0,43mm	1,80mm

Table A9: Average void content of cores

Location and load repetition		Apparent bulk relative density	Void content
Non-trafficked area		1,905	21,7%
After HVS trafficking	Ambient (23°C)	1,934	20,5%
	Heated (37°C)	1,963	19,3%

The RSD deflections prior to being overlaid, after being overlaid with bitumen-rubber porous asphalt and after HVS trafficking (175 000 load repetitions), are given in Table A10. The high initial values are an indication of the poor state of the pavement prior to its being overlaid. Such values are usually associated with pavements which have exceeded their structural design life. The high deflections after the structure was overlaid with 40mm porous asphalt underline the fact that this mix does not contribute significantly to the structural capacity of the pavement and should therefore be excluded from mechanistic design analyses of such pavements.

To confirm this, indirect tensile tests were conducted on porous asphalt briquettes. The results of these are shown in Table A11. Whereas the resilient moduli of conventional dense asphalts (voids of between 3 and 6%) are usually between 2 000 and 4 000MPa and the indirect tensile strengths lie between 800 and 1 200kPa, those of the bitumen-rubber porous asphalt are between one quarter and one half of those of dense-graded mixes. These findings confirm the above statements on structural capacity.

Table A10: Surface deflections before and after trafficking

Type of overlay-repetitions	Ambient temperature	Elevated temperature
Prior to overlay	1,44mm	
After overlaying - 10 reps - 175 000 reps	 1,31mm 2,08mm	 1,46mm 2,10mm

Table A11: Results of indirect tensile tests

Property	Average
Resilient modulus @ 25°C Poisson's ratio @ 25°C Indirect tensile strength @ 25°C	1 010MPa 0,37 276 kPa

Despite the high deflections and high permanent deformation, no ravelling or other signs of surface deterioration (such as fatigue cracking) were visible on the ambient and heated sections. This can be attributed to good aggregate interlock, high binder contents and to the good rheological properties of the bitumen-rubber binder.

References

A1. **Verhaeghe BMJA.** *Constructibility and initial performance of Arm-R-Drain placed on the Ben Schoeman Highway.* DPVT-C/237-7, Tosas (Pty) Ltd, Pretoria, February 1994.

A2. **Lottman RP.** *Laboratory test method for predicting moisture-induced damage to asphalt concrete.* Transportation Research Record 843, Transportation Research Board, Washington, D.C., 1982.

A3. **Du Plessis JL, Verhaeghe BMJA, Rust FC.** *Performance of bitumen-rubber porous asphalt subjected to accelerated trafficking.* DPVT-C/263, Transvaal Provincial Administration, Pretoria, February 1994.

A4. **Horak E, Kleyn EG, du Plessis J, de Villiers EM, Thomson AJ.** *The impact and management of the Heavy Vehicle Simulator (HVS) fleet in South Africa.* Proceedings of the 7th International Conference on Asphalt Pavements, Volume 2, Nottingham, 1992.

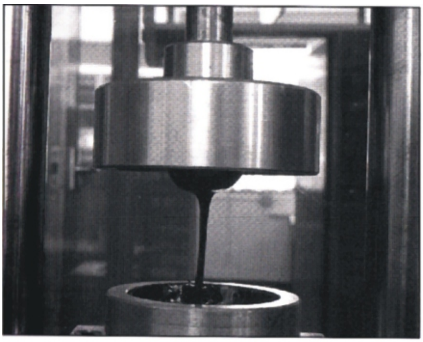
A5. **Basson JEB.** *The measurement of the deflection and curvature of a road surface when loaded by a standard axle.* NITRR Technical Note TP/71/85, CSIR, Pretoria, 1985.

A6. **De Beer M, Horak E, Visser AT.** *The Multi-Depth Deflectometer (MDD) system for determining the effective elastic moduli of pavement layers.* ASTM Special Technical Publication, STP 1026, First International Symposium on Non-destructive Testing of Pavements and Backcalculation of Moduli, Baltimore, USA, 1988.

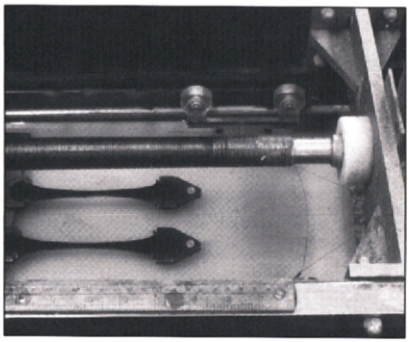
Appendix B: Characteristics of modified binders

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 temperatures (50°C to 60°C), the behaviour of the SBR-modified binder is characterised by greatly reduced viscosities with increasing shear rates by comparison with those of unmodified binders. This implies a greater stiffness of the binder for long loading times (or low frequencies) [B1]. This improvement is significant to resist mix tenderness and to prevent rutting in asphalt. At low temperatures (below 10°C), the presence of the elastomer improves the elastic characteristics of the binder without increasing its stiffness, by contrast to what happens in the case of bitumens with lower penetration values. The modification of a bitumen with SBR may thus result in substantially improved fatigue life by reducing flexural fatigue cracking.



Tenacity test.



Ductility test.

Styrene-butadiene styrene (SBS)

SBS-modified binders behave as cross-linked rubbers below approximately 100^{o}C. Therefore, they add substantially to the strength of modified bitumen at higher road temperatures. Their long polybutadiene chains contribute to flexibility of the binder at very low temperatures. The elastomeric lattice in the bitumen provides the desired properties of elasticity, plasticity and elongation[B2]. Because cross-linking is the result of physical forces only and is reversible with increases in temperature, its contribution to bitumen viscosity at processing temperatures is acceptable because of the presence of styrene sequences which melt at these temperatures. Therefore, the incorporation of SBS into bitumen is relatively easy.

Thermoplastic block copolymers can improve the binder system significantly. Their incorporation can result in:

- reduced penetration;
- higher ring-and-ball softening point temperatures;
- improved low temperature ductility;
- increased toughness and tenacity;
- increased viscosity at higher service temperatures.

Consequently, the use of SBS-modified binders in wearing course mixes can accommodate traffic and environmental variables by improving:

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

Ethylene-vinyl acetate (EVA)

Ethylene-vinyl acetate copolymers are compatible with bitumens, as both the vinyl acetate content and molecular mass or melt flow index[B3] (which is inversely proportional to the molecular mass) can be altered to suit different types of bitumen. The vinyl acetate content, which can vary from a few percent to more than 50%, determines the mechanical properties of the binder and the compatibility of the polymer with the binder. Binders with high vinyl acetate contents have low strength properties, good compatibility, are soft and have great tenacity, whereas binders with low vinyl acetate contents have high strength properties, poor compatibility, poor tenacity and are stiff. Modified binders with high vinyl acetate contents have properties similar to those of elastomeric polymers. Binders with low melt flow indices have better strength but poorer blending properties than do binders with high melt flow indices. EVA-copolymers are noted for improving the workability and resistance to rutting of hot mix asphalt[B4].

Granulated Reclaimed Rubber

Granulated reclaimed rubber, obtained from the recycling of vehicle tyres, when blended with and digested in bitumen (the so-called "wet process") produces a binder referred to as bitumen-rubber. Sometimes, other additives are added to the bitumen-rubber blend, such as high viscosity, high aromatic extender oils, to improve the digestion of the rubber "crumb" in the bitumen. Bitumen-rubber is distinguished from a material generally termed rubberised bitumen (containing polymers such as SBR or SBS) by the fact that bitumen-rubber contains a greater amount of granulated rubber (15 to 25% by mass of total binder) than rubberised bitumen (1 - 6% by mass of base bitumen). In addition, the particle size of the reclaimed rubber is many orders of magnitude greater than that of polymers (1mm compared with 1m). Bitumen and rubber crumb are blended at elevated temperatures to promote chemical and physical bonding of the two constituents.

Alternatively, granulated reclaimed rubber is added to the hot aggregate in a batch, after which the required amount of bitumen is added in normal fashion (plant mixer). The bitumen-rubber-aggregate mix is then stored for a specified duration and at a specified temperature in hot silos so that the rubber will be digested in the bitumen.

The reported benefits of using bitumen-rubber hot-mix surfacing include[B5]:

- flexibility down to -26^{o}C;
- greater binder viscosity at 60^{o}C than conventional or modified binders;
- tougher and more elastic surface;
- greater resistance to ageing;
- recycling of scrap rubber tyres.

Because of its unique elastomeric properties and its high viscosity, which enable higher binder contents to be used, bitumen-rubber is well suited for use in porous asphalt mixes. In addition to the rubber-like properties contributed by scrap rubber, there are valuable compounds in bitumen-rubber which improve the properties of the binder, such as[B6]:

- **Carbon black:** Scrap rubber contains more than 20% carbon black, a UV light degradation inhibiter which has been shown to retard the ageing of the binder;
- **Antioxidants:** These chemicals enhance the durability of bitumen-rubber.
- **Amines:** Amines are closely related to antistrip compounds and may therefore contribute to the long-term adhesion of bitumen-rubber.
- **Aromatic oils:** Aromatic oils are similar to those often used in recycling to rejuvenate age-hardened binders.

References

B1. King GN, Muncy HW, Prudhomme, JB. *Polymer modification: binder's effect on mix properties*. Proceedings of the Association of Asphalt Paving Technologists, Volume 55, Clearwater Beach, 1986.

B2. Zazotto L, Foley D, Rodier CE, Watson RD. *Modified asphalt - are you really coming?* Proceedings of the Canadian Technical Asphalt Association, Volume 32, Montreal, 1987.

B3. Choyce PW, Wooley KG. *Asphalt mixtures with improved resistance to deformation using EVA modified binders.* Proceedings of the 5th Conference on Asphalt Pavements for Southern Africa, Mbabane, Swaziland, 1989.

B4. Davidson, LK. *Fundamental types of modified binders, their application and manufacture.* Seminar on modified binders, Southern African Bitumen and Tar Association, Pretoria, June 1991.

B5. McQuillen JL, Hicks RG. *Construction of rubber-modified asphalt pavements.* Journal of Transportation Engineering, Volume 113, No 4, New York, December 1987.

B6. Huff BJ, Vallerga BA. *Characteristics and performance of asphalt-rubber material containing a blend of reclaimed and crumb rubber.* Transportation Research Record 821, Transportation Research Board, Washington, D.C., 1981.

Appendix C: 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 in relatively small quantities (0,3 to 0,5% by mass of total mix) forms a relatively inexpensive means of improving the engineering properties.

The fibre reinforces the binder system, thus causing an increase in the apparent 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 transportation and paving operations. The durability will also be improved by the use of higher binder contents with resulting greater film thicknesses with reduced drainage. Fibre fillers may have a major cost advantage in comparison with polymer modification of the binder.

Notes