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Foamed Asphalt Mixes

Mix Design Procedure

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Abstract:
Foamed asphalt epitomizes the asphalt industry’s drive towards energy efficient, environmentally friendly and cost-effective solutions for road-building. Foamed asphalt refers to a bituminous mixture of road-building aggregates and foamed bitumen, produced by a cold mix process. Although the foamed bitumen process was developed more than 40 years ago and lauded by researchers the world over, it is believed that the lack of standardized design procedures has contributed to the limited implementation of the technology in South Africa, with practitioners favouring more familiar and well documented products. Recently there has been significant interest in the product, especially in the in-situ method of construction, and hence the need for a standard mix design procedure has now become essential. One element of foamed asphalt technology which may prove to be an impediment to standardization is the emergence of various proprietary bitumen foaming techniques.

This report focusses on the development of a mix design method for foamed asphalt mixes, based on research work conducted at CSIR Transportek on behalf of SABITA. An extensive survey was undertaken of the worldwide practice with regard to foamed asphalt mix design, which included literature surveys and liaison with recognized experts. A mix design procedure was developed, encompassing all the necessary elements from the selection of aggregates and binder to the determination of the optimum engineering properties of the mix. This was followed by a laboratory program designed to verify the proposed mix design procedure. It is believed that the proposed mix design procedure is independent of the type of bitumen foaming process used and should, therefore, be acceptable to practitioners.

Keywords:
foamed bitumen, foamed asphalt, expanded asphalt, expanded bitumen, FOAMMIX, FOAMSTAB

Proposals for further research:

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

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1 INTRODUCTION

1.1 General

An essential ingredient in the success of the South African pavement industry is the sustained research, development and implementation of new and alternative road-building methods, motivated by reasons of economy and the scarcity of pavement materials. It is generally accepted that soil stabilization techniques are suitable for upgrading poor quality materials so that these materials may be used to their full potential in the pavement structure. Bitumen soil stabilization technology has been the focus of recent research initiatives which have resulted in refined mix design procedures for products such as GEMS and ETBs, i.e. bitumen emulsion-treated materials. A common aspect of bitumen soil stabilization is the incorporation of small amounts of binder, in a cold mixing procedure, which vastly increases the shear (cohesion) strength, fatigue resistance and moisture resistance of the treated materials. Although cold mix bituminous products were used in South Africa prior to the research initiatives, their use and benefits are now gaining increased acceptance within the industry.

The use of foamed asphalt, an alternative cold mix procedure, has also had limited application in the construction of road pavements in South Africa. However, no standardized mix design procedure is available. Although the foamed bitumen process was developed more than 40 years ago and lauded by researchers the world over, it is believed that the lack of standardized design procedures has contributed to the limited implementation of this technology in South Africa, practitioners favouring more familiar and well documented products.

1.2 Aim and Scope

The objective of this project is to develop and verify a mix design procedure for foamed asphalt. This document contains a literature review of published research findings on foamed asphalt. Information from previous research and current practice was used to develop guidelines for foamed asphalt mix design for use in South Africa.

1.3 Definition of Foamed Asphalt

The term ‘foamed asphalt’, as used in this document, refers to a mixture of pavement construction aggregates and foamed bitumen. The foamed bitumen, or expanded bitumen, is produced by a process in which water is injected into the hot bitumen, resulting in spontaneous foaming. The physical properties of the bitumen are temporarily altered when the injected water, on contact with the hot bitumen, is turned into vapour which is trapped in thousands of tiny bitumen bubbles. However the foam dissipates in less than a minute and the bitumen resumes its original properties. In order to produce foamed asphalt, the bitumen has to be incorporated into the aggregates while still in its foamed state.

2 OVERVIEW AND ADVANTAGES OF FOAMED ASPHALT

2.1 General

The potential of foamed bitumen for use as a soil binder was first realised in 1956 by Dr. Ladis H. Csanyi, at the Engineering Experiment Station in Iowa State University. Since then, foamed asphalt technology has been used successfully in many countries, with corresponding evolution of the original bitumen foaming process as experience was gained in its use. The original process consisted of injecting steam into hot bitumen. The steam foaming system was very convenient for asphalt plants where steam was readily available but it proved to be impractical for in situ foaming operations, because of the need for special equipment such as steam boilers. In 1968, Mobil Oil Australia, which had acquired the patent rights for Csanyi's invention, modified the original process by adding cold water rather than steam into the hot bitumen. The bitumen foaming process thus became much more practical and economical for general use.

Foaming increases the surface area of the bitumen and considerably reduces its viscosity, making it well suited for mixing with cold and moist aggregates. Foamed bitumen can be used with a variety of materials, ranging from conventional high-quality graded materials and recycled pavement materials to marginal materials such as those having a high plasticity index. Foamed asphalt can be manufactured in situ or in a central plant. Binder contents are based on the mix design, and are determined as percentage (by weight) required for the mix to have optimum properties.

2.2 Advantages of Foamed Asphalt Mixes

The following advantages of foamed asphalt are well documented:

- The foamed binder increases the shear strength and reduces the moisture susceptibility of granular materials. The strength characteristics of foamed asphalt approach those of cemented materials, but foamed asphalt is flexible and fatigue resistant.

- Foam treatment can be used with a wider range of aggregate types than other cold mix processes.

- Reduced binder and transportation costs, as foamed asphalt requires less binder and water than other types of cold mixing.

- Saving in time, because foamed asphalt can be compacted immediately and can carry traffic almost immediately after compaction is completed.

- Energy conservation, because only the bitumen needs to be heated while the aggregates are mixed in while cold and damp (no need for drying).

- Environmental side-effects resulting from the evaporation of volatiles from the mix are avoided since curing does not result in the release of volatiles.

- Foamed asphalt can be stockpiled with no risk of binder runoff or leeching. Since foamed asphalt remains workable for very extended periods, the usual time constraints for achieving compaction, shaping and finishing of the layer are avoided.

- Foamed asphalt layers can be constructed even in some adverse weather conditions, such as in cold weather or light rain, without significantly affecting the workability or the quality of the finished layer.

3 DESIGN CONSIDERATIONS

3.1 General

In this section the key design parameters that need to be considered in a mix design for foamed asphalt materials are discussed. The objective of a foamed asphalt mix design is to select the mix proportions, one of which is bitumen content, in order to achieve:

C optimum values for laboratory-measured properties;
C the structural and functional requirements of the in-service mix, and
C retention of the relevant engineering properties at in-service conditions of temperature, moisture and loading conditions.

Laboratory tests conducted on foamed asphalt should evaluate resistance to deformation, as well as variations in cohesion and strength with moisture and temperature. As the strength of foamed asphalt mixes is extremely sensitive to moisture conditions, these should be taken into account in the test methods. Because foamed asphalt mixes can take on characteristics ranging from granular materials to those of high quality asphalt materials, the test method selected should be able to handle a wide range of material types.

3.2 Bitumen Properties

Foamed bitumen, also referred to as expanded bitumen, is a hot bituminous binder which has been temporarily converted from a liquid to a foam state by the addition of a small percentage of water (typically 2 per cent). The foamed bitumen is characterized in terms of expansion ratio and half-life. The **expansion ratio** of the foam is defined as the ratio between the maximum volume achieved in the foam state and the final volume of the binder once the foam has dissipated. The **half-life** is the time, in seconds, between the moment the foam achieves maximum volume and the time it dissipates to half of the maximum volume

3.2.1 Foaming Potential

The foaming characteristics of bitumen play an important role during the mixing stage of foamed asphalt production. It can be expected that maximized expansion ratios and half-lives will promote binder dispersion within the mix. Castedo Franco and Wood (1983) found that any bitumen, irrespective of grade or origin, could be foamed with an appropriate combination of nozzle type, water, air and bitumen injection pressure. However, Abel (1978) found that:

C bitumen which contained silicones could have reduced foaming abilities;
C bitumens with lower viscosities foamed more readily and had higher foam ratios and half-lives than bitumens with higher viscosities, but the use of high viscosity bitumens resulted in superior aggregate coating;
C anti-stripping agents intensified the foaming ability of bitumens, and
C acceptable foaming was only achieved at temperatures above 149° C.

Brennen et al (1983) found that the half-life and expansion ratio of the foam produced from any particular bitumen was affected by the volume of foam produced, the quantity of water used and the temperature at which the foam was produced. Higher foaming temperatures and increased quantities of water both resulted in increased expansion ratios, but resulted in decreased half-lives. In the laboratory, the size of the container was found to affect the foam parameters (Ruckel et al,1982). Ruckel et al (1982) recommend limits of 8-15 for the expansion ratio and at least 20 seconds for the half-life. By using certain surface-active additives it is possible to produce highly expanded and stable foamed bitumens with expansion ratios greater than 15 and half-lives greater than 60 seconds (Maccarrone et al, 1994).

Bowering and Martin (1976) showed that the cohesion and compressive strength of mixes were significantly greater when high expansion (15:1) foamed bitumen was used. Maccarrone et al (1994) suggested that high expansion foamed bitumen resulted in improved aggregate coating and, hence, in improved mix properties.

3.2.2 Grade of bitumen grade

The results of previous research do not show any appreciable differences between the measured properties of foamed asphalt mixes produced with different grades of bitumen (Lee, 1981). This is probably related to the fact that much of the shear strength of foamed asphalt mixes is due to aggregate interaction rather than binder cohesion (see section 3.3). However, the load rate and temperature-dependent behaviour of foamed asphalt mixes (see sections 3.7.2 and 3.7.5) are indicative of the viscoelastic binder activity. This aspect needs to be investigated further.

3.2.3 Foamed Bitumen Content (BC)

In foamed-asphalt mixes the optimum bitumen content often cannot be clearly determined as it can in the case of hot-mix asphalt. The range of binder contents (BC) that can be used is limited by the loss in stability of the mix at the upper end of the range and by water susceptibility at the lower end. It appears that one significant parameter is the ratio of binder content to fines content, i.e. the viscosity of the binder-fines mortar plays a significant role in mix stability (see section 3.3). Table 3.1 may be used as a guide to select the appropriate binder content based on the fines content of the mix. Akeroyd and Hicks (1988) also proposed the use of a proportional binder-fines relationship to select the binder content, ranging from a binder content of 3,5 per cent binder for 5 per cent fines content to a binder content of 5 per cent for 20 per cent fines content. However this approach may not be applicable for all types of material, because of the varying binder absorption characteristics of fines which, in turn, depend on the source (parent) material.

TABLE 3.1 : Foamed bitumen content (after Ruckel et al, 1982)

% passing 4,75 mm sieve	% passing 0,075 mm sieve	% Foamed bitumen
< 50 (gravels)	3 - 5	3
	5 - 7,5	3,5
	7,5 - 10	4
	> 10	4,5
> 50 (sands)	3 - 5	3,5
	5 - 7,5	4
	7,5 - 10	4,5
	> 10	5

3.3 Aggregate Properties

Research has shown that a wide range of aggregates may be used with foamed-bitumen, ranging from crushed stone to silty sands and even to ore tailings, as shown in Table 3.2. Certain types of soil may require lime treatment and grading adjustments to enable them to perform satisfactorily. Figure 3.1 shows the Mobil foam stabilization grading chart (Akeroyd and Hicks, 1988). Materials conforming to Zone A of the chart have been found to be suitable for foam treatment for heavily trafficked roads. Materials conforming to Zone B are suitable for lightly trafficked roads, but could be adjusted to Zone A materials by the addition of coarse fractions. Materials in Zone C are deficient in fines and are not appropriate for foam stabilization unless fines are added.

The fines content of the aggregate is an important consideration and should preferably be above 5 per cent (Ruckel et al, 1982). The ability of foamed bitumen to selectively mix with and coat the fines (minus 0,075 mm particles) has been well documented. The resultant filler (mix of bitumen and fines), which has a significantly higher viscosity than the raw bitumen, acts as a mortar between the coarse aggregates and hence increases the strength of the mix. However, the relationship between the fines content and bitumen content is critical because excess bitumen in the mortar will tend to act as a lubricant and result in loss of strength and stability. Sakr and Manke (1985) showed that foamed asphalt mixes with higher percentages of fines had higher stabilities, while Bissada (1987) showed a similar trend for tensile strength. Semmelink (1991) also showed that the fines content played a crucial role in determining the strength, stability and workability of foam-stabilized sands.

In a limited study, Sakr and Manke (1985) showed that the stability of foamed asphalt mixes is affected to a greater extent by the aggregate interlock than by the viscosity of the binder, its behaviour thus differing from that of hot-mix asphalt. This implies that foamed asphalt mixes are not as temperature susceptible as hot-mix asphalt, and support the finding that the viscosity (grade) of the bitumen used is not very critical for foamed asphalt mixes (see section 3.2.2). Sakr and Manke (1985) also found that the angularity of fine aggregates is an excellent indicator of suitability for foam stabilization. A minimum particle index of 10 was suggested in order to achieve good stabilities.

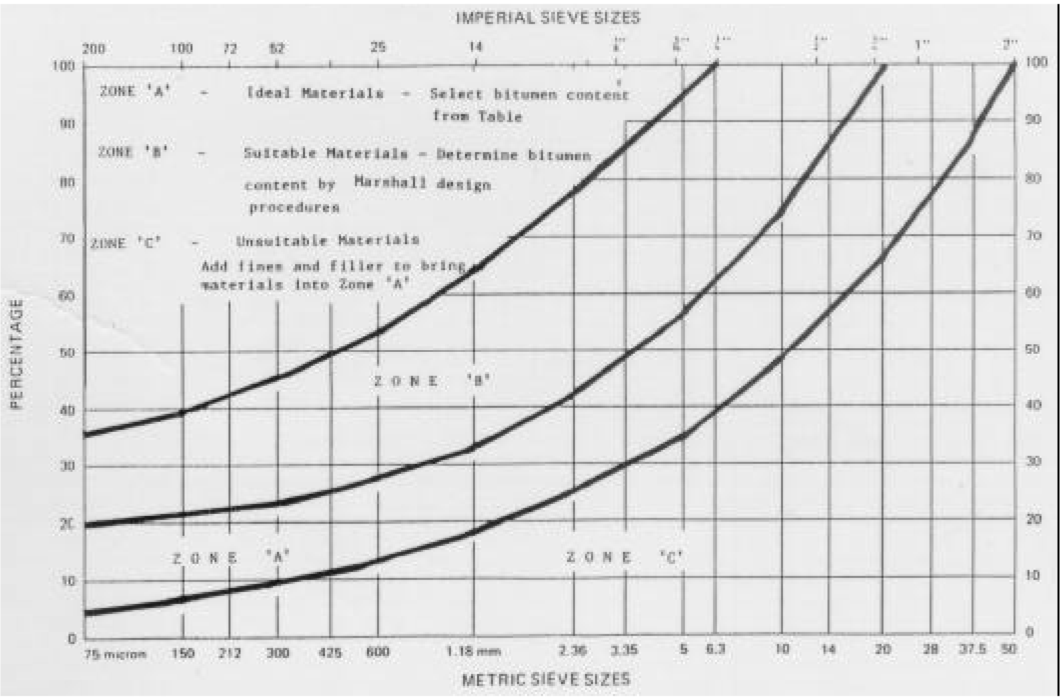

Figure 3.1 : Aggregate grading zones for foamed asphalt (Akeroyd & Hicks, 1988)

Table 3.2 : Foam treated materials (adapted from Bowering & Martin, 1976)

Soil type	Opt. range of binder contents (%)	Additional requirements
well graded clean gravel	2 - 2,5	
well graded marginally clayey / silty gravel	2 - 4,5	
poorly graded marginally clayey gravel	2,5 - 3	
clayey gravel	4 - 6	lime modification
well graded clean sand	4 - 5	filler
well graded marginally silty sand	2,5 - 4	
poorly graded marginally silty sand	3 - 4,5	low pen bitumen; filler
poorly graded clean sand	2,5 - 5	filler
silty sand	2,5 - 4,5	
silty clayey sand	4	possibly lime
clayey sand	3 - 4	lime modification

3.4 Moisture Conditions

The moisture content during mixing and compaction is considered by many researchers to be the most important mix design criteria for foamed asphalt mixes. Moisture is required to soften and breakdown agglomerations in the aggregates, to aid in bitumen dispersion during mixing and for field compaction. Ruckel et al (1982) recommend that the moisture-density relationship be considered in the formulation of trial mixes. Insufficient water reduces the workability of the mix and results in inadequate dispersion of the binder, while too much water lengthens the curing time, reduces the strength and density of the compacted mix and may reduce the coating of the aggregates. The optimum moisture content (OMC) varies, depending on the mix property that is being optimized (strength, density, water absorption, swelling). However, since moisture is critical for mixing and compaction, these operations should be considered when optimizing the moisture content.

Investigations by Mobil Oil suggest that the optimum moisture content for mixing lies at the “fluff point” of the aggregate, i.e. the moisture content at which the aggregates have a maximum loose bulk volume (70 % - 80 % mod AASHTO OMC) . However, the fluff point may be too low to ensure adequate mixing (foam dispersion) and compaction, especially for finer materials. Bowering (1970) observed that where inadequate foam dispersion occurred as a result of insufficient mixing moisture, the compacted densities were low and no benefit was gained from the foamed bitumen treatment. Lee (1981) found that the optimum mixing moisture content occurs in the range of 65 - 85 per cent of the modified AASHTO OMC for the aggregates. This optimum range of moisture contents for mixing was confirmed by Bissada (1987).

The concept of optimum fluid content as used in granular emulsion mixes may also be relevant to foamed asphalt. This concept considers the lubricating action of the binder in addition to that of the moisture. Thus the actual moisture content of the mix for optimum compaction is reduced in proportion to the amount of binder incorporated. Castedo Franco and Wood (1983) also agree that the best compactive moisture condition occurs when the total fluid content (moisture + bitumen) is approximately equal to the OMC.

Sakr and Manke (1985) developed a relationship (Equation 3.1) to calculate the moisture content for maximum density of foamed asphalt mixes, which considers the modified AASHTO OMC, and percentage of fines (PF) of the aggregate and the bitumen content (BC). As suggested by the equation, the higher the bitumen content the lower the compaction moisture content. While this equation may not apply to all materials, the concept is relevant.

$$MMC = 8{,}92 + 1{,}48 OMC + 0{,}4 PF - 0{,}39 BC \qquad \textbf{Equation 3.1}$$

The optimum moisture content for mixing is approximately 10 to 20 per cent higher than the compaction moisture (MMC), as predicted by Equation 3.1. In order to prevent the time-consuming task of drying the mix after mixing (to achieve the MMC), Sakr and Manke (1985) suggested that the MMC be used for both mixing and compaction, as no significant differences in mix properties were observed when this procedure was used.

In recent years the gyratory compaction method has gained popularity for the preparation of samples in the laboratory. Because the gyratory compaction effort is usually higher than the

Modified AASHTO effort, the OMC obtained is lower than Modified AASHTO OMC. Hence, when gyratory compaction is used for the preparation of foamed asphalt, the OMC(gyratory) is advocated for mixing and compaction (Maccarrone et al, 1994) (as opposed to the moisture content on the dry side of OMC as used in Mod AASHTO compaction).

3.5 Curing Conditions

Studies have shown that foamed asphalt mixes do not develop their full strength after compaction until a large percentage of the mixing moisture is lost. This process is termed curing. Curing is the process whereby the foamed asphalt gradually gains strength over time accompanied by a reduction in the moisture content. Ruckel et al (1982) concluded that the moisture content during the curing period had a major effect on the ultimate strength of the mix. However, Lee (1980) provided experimental evidence which suggested that moisture loss was not a prerequisite for strength gain in foamed asphalt mixes. Whichever the case, a laboratory mix design procedure would need to simulate the field curing process in order to correlate the properties of laboratory- prepared mixes with those of field mixes. Since the curing of foamed asphalt mixes in the field occurs over several months, it is impractical to reproduce actual field curing conditions in the laboratory. An accelerated laboratory curing procedure is required, in which the strength gain characteristics can be correlated with field behaviour, especially with the early, intermediate and ultimate strengths attained. This characterization is especially important when structural capacity analysis, based on laboratory-measured strength values, is required.

Most of the previous investigations have adopted the laboratory curing procedure proposed by Bowering (1970), i.e. 3 days oven curing at a temperature of 60° C. This procedure results in the moisture content stabilizing at about 0 to 4 per cent, which represents the driest state achievable in the field. The strength characteristics of samples cured in this manner are representative of the in-service state approximately a year after construction (Maccarrone, 1995). Concerns have been expressed over the binder ageing which may occur at a curing temperature of 60° C. Also, since this temperature is above that of the softening point of common road-grade bitumens, changes in bitumen dispersion within the mix are possible during curing. These issues will be addressed during the laboratory validation phase of this study. An alternative approach suggested by Lewis (1998) would be to oven dry the foamed asphalt to a constant mass, at a lower temperature (40° C).

3.6 Temperature Conditions

The optimum mixing temperature of the aggregates for foamed asphalt mixes lies in the range of 13° C to 23° C, depending on the type of aggregate, Temperatures below this range result in poor quality mixes (Bowering and Martin,1976). Foamed asphalt mixes may also be prepared with heated aggregates which will increase the binder dispersion within the mix and aid in the coating of the larger aggregates.

3.7 Engineering Properties

The results of previous studies all confirm that strength parameters such as Resilient Modulus, CBR and stability are optimized at a particular intermediate binder content. The most common method used in the selection of the design binder content was to optimize the Marshall stability and minimize the loss in stability under soaked moisture conditions. The major functions of foamed bitumen treatment are to reduce the moisture susceptibility, to increase fatigue resistance and to increase the cohesion of the untreated aggregate to acceptable levels. The design foamed bitumen content could also be selected as the minimum (not necessarily optimum) amount of binder which would result in a suitable mix.

3.7.1 Moisture Susceptibility

The strength characteristics of foamed asphalt mixes are highly moisture-dependent. This is because of the relatively low binder contents and high void contents of foamed asphalt mixes. Castedo Franco et al (1983) found that additives such as lime reduced the moisture susceptibility of the mixes. Cement was also found to be as effective as lime, and cheaper (Lewis, 1998). Higher bitumen contents also reduce moisture susceptibility because higher densities are achievable, leading to lower permeabilities (lower void contents), and to increased coating of the moisture-sensitive fines with binder.

3.7.2 Temperature Susceptibility

Foamed asphalt mixes are not as temperature-susceptible as hot-mix asphalt, although both the tensile strength and modulus of the former decrease with increasing temperature. Bissada (1987) found that, at temperatures above 30° C, foamed asphalt mixes had higher moduli than equivalent hot-mix asphalt mixes after 21 days' curing at ambient temperatures. In foamed asphalt, since the larger aggregates are not coated with binder, the friction between the aggregates is maintained at higher temperatures. However the stability and viscosity of the bitumen-fines mortar will decrease at high temperatures, thus accounting for the loss in strength.

3.7.3 Unconfined Compressive Strength (UCS) and Tensile Strength

Bowering (1970) suggested the following UCS criteria for foamed asphalt mixes used as a base-courses under thin surface treatments (seals): 0,5 MPa (4 day soaked) and 0,7 MPa (3 day cured at 60° C). Bowering and Martin (1976) suggested that in practice the UCS of foamed asphalt materials usually lie in the range 1,8 MPa to 5,4 MPa and estimated that the tensile strengths of foamed asphalt materials lay in the range 0,2 MPa to 0,55 MPa, depending on moisture condition. They also found that foamed asphalt had strength characteristics superior to those of emulsion-treated materials at bitumen contents above 1,5 per cent. Maccarrone (1998) recommended that, for good performance, cured foamed asphalt samples should have minimum Indirect Tensile Strengths of 100 kPa when tested in a soaked state and 200 kPa when tested dry. Curing has a significant influence on the strength of foamed asphalt mixes (Van Wijk and Wood, 1983).

3.7.4 Stiffness - Resilient Modulus

As with all viscoelastic bituminous materials, the stiffness of foamed asphalt depends on the loading rate, stress level and temperature. Generally, stiffness has been shown to increase as the fines content increases. In many cases the resilient moduli of foamed asphalt mixes have been shown to be superior to those of equivalent hot-mix asphalt mixes at high temperatures (above 30° C). Foamed asphalt can achieve stiffnesses comparable to those of cement-treated materials, with the added advantages of flexibility and fatigue resistance (Ramanujam and

Fernando, 1997).

3.7.5 Abrasion Resistance

Foamed asphalt mixes usually lack resistance to abrasion and ravelling and are not suitable for wearing/friction course applications.

3.7.6 Density and Volumetrics

Generally density increases to a maximum and voids in the aggregate decreases to a minimum as the binder content of a foamed asphalt mix increases. Many studies have shown that the strength of foamed asphalt mixes depends to a large extent on the density of the compacted mix. Hence it is foreseeable that density and mix volumetrics could be used as criteria to determine the optimum binder content of a foamed asphalt mix.

3.7.7 Fatigue Resistance

Fatigue resistance is an important factor in determining the structural capacity of foamed asphalt pavement layers. Foamed asphalt mixes have mechanical characteristics that fall between those of a granular structure and those of a cemented structure. Bissada (1987) considers that the fatigue characteristics of foamed asphalt will thus be inferior to those of hot-mix asphalt materials. Little et al (1983) provided evidence of this when he showed that certain foamed asphalt mixes exhibited fatigue responses inferior to those of conventional hot-mix asphalt or high quality granular emulsion mixes. These findings are contradictory to those resulting from the approach adopted by Maccarrone et al (1993) who suggest that the fatigue characteristics of foamed asphalt are similar to those of hot-mix asphalt.

4 MIX DESIGN

4.1 General

The most commonly used mix design method for foamed bitumen has been that based on Marshall stabilities and densities. Generally, it has been observed that the Marshall stabilities of foamed asphalt mixes tended to increase to a maximum as the binder contents increased. The Marshall design criterion used to determine the optimum binder content is when the ratio between the wet and dry stabilities is at a maximum, i.e. the bitumen content at which the mix retains most of its strength when soaked. However, in recent times asphalt design methods, including foamed bitumen mix design, have seen a shift away from the Marshall methods, the emphasis now being placed on dynamic test procedures such as the dynamic creep test and the indirect tensile test. Based on experience in Australia, Lancaster et al (1994) recommended that the binder content selected for foamed asphalt mixes be based on the highest resilient modulus value. However, following recommendations by Lewis (1998), it is proposed that the Indirect Tensile Strength test be used to select a design binder content.

Based on the review of previous published investigations, the following mix design procedure is proposed. Procedures recommended in this mix design still need to be validated by laboratory investigation and are subject to change. Only the basic steps are outlined in this section, precise laboratory procedures being discussed in Appendix A.

4.2 Binder Characterization and Preparation

The foaming characteristics of a particular bitumen type need to be optimized for producing foamed asphalt mixes. This is achieved by measuring the half-life and the expansion ratio of foamed bitumen produced using various percentages of water. Usually five tests are conducted with the foaming water content varying from 1 per cent to 3 per cent at 0,5 per cent increments. The temperature of the bitumen before foaming should be in the range 180° C - 200° C. It is recommended that the half-life of the foamed bitumen be at least 12 seconds and the expansion ratio be at least 10:1. Additives may be used to catalyse the foaming. However, the use of these has a significant cost implication.

4.3 Aggregate Characterization and Preparation

The grading and the PI of the aggregates should be determined. The grading is adjusted, if required, by adding fines or coarse material so that the final grading conforms to the grading envelope in Figure 4.1. For low volume roads, aggregate gradings which lie above the target grading (finer), on sieves larger than 0,06 mm, may be acceptable. Materials which have a PI greater than 12 should be treated with lime to reduce the PI. In addition, it is common practice (Lewis, 1998) to add 1 - 2 per cent cement to the mix to aid in bitumen adhesion. The Modified AASHTO optimum moisture content of the aggregates is determined.

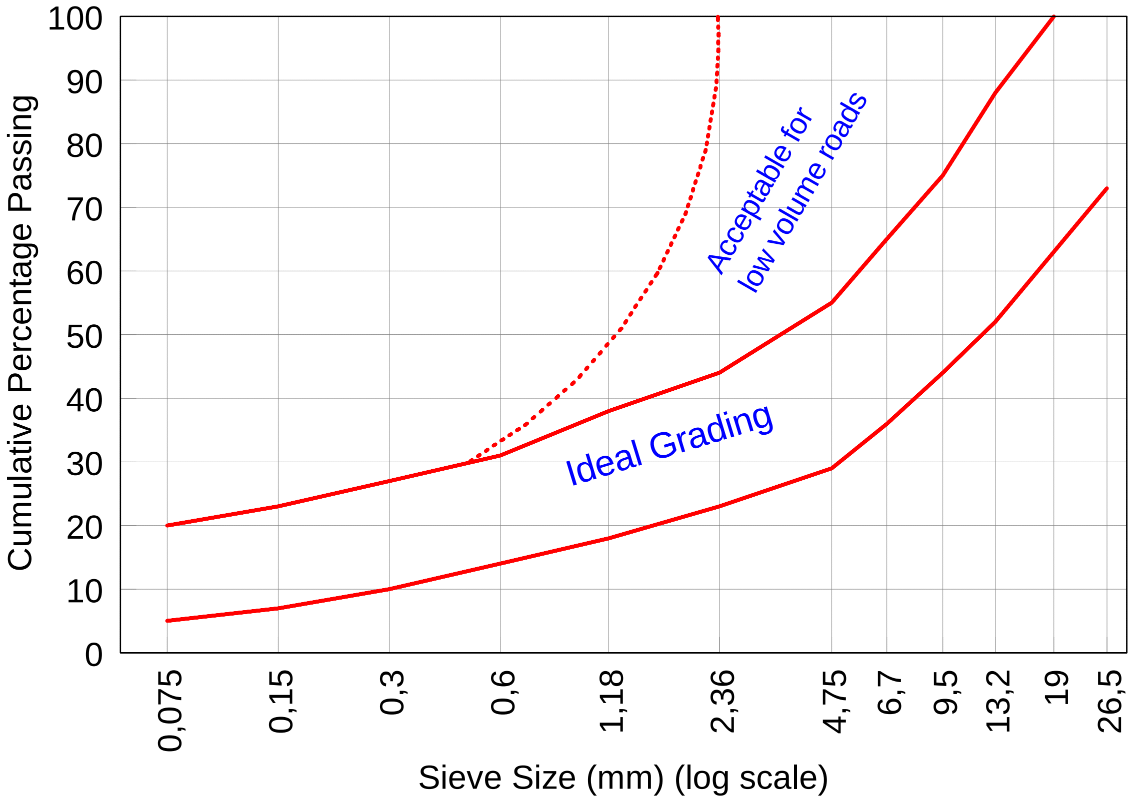

Figure 4.1 : Grading envelope for foamed asphalt mixes

The aggregates should be oven dried to a constant mass. The dried aggregates are riffled into 5 batches of 10 kg each. These will be used to produce 5 batches of foamed asphalt samples at various binder contents.

4.4 Binder Content (BC) for Trial Mixes

An appropriate range of foamed bitumen contents, using Tables 3.1 and 3.2 as a guide, is selected for the trial mixes. Five batches of trial mixes are normally prepared at binder contents differing by one per cent.

4.5 Moisture Content

The moisture content for mixing and compaction is a crucial mix design parameter, which has traditionally been selected at the 'fluff' point of the aggregates (70 - 80 per cent modified AASHTO OMC). However, it is recommended that the moisture content for mixing and compaction be selected at the greater of 'OMC minus the BC' and the 'fluff point' (refer to section 4.4).

4.6 Mixing and Compaction

Each 10 kg sample of aggregate and the required mass of foamed bitumen (and lime or cement if required) are mixed in a mechanical mixer at the moisture content prescribed in section 4.5. The foamed asphalt is stored in sealed containers to prevent moisture loss, until all five batches have been mixed. Duplicate samples are removed from each foamed asphalt batch for the determination of moisture content and bitumen content. The remaining foamed asphalt will be used to prepare compacted foamed asphalt specimens for further testing.

For further foamed asphalt testing, it is suggested that eight samples be prepared from each batch: 6 samples for indirect tensile tests and 2 samples for volumetric evaluation. Specimens are compacted, using the Marshall hammer, to a 100 mm nominal diameter and 65 mm nominal height. Specimens of this size normally require about 1,15 kg of material. A compactive effort of 75 blows on each face is recommended.

4.7 Curing, Testing and Design Binder Content Determination

The foamed asphalt samples should be subjected to an accelerated curing procedure before undergoing any tests. The widely used procedure of 3 days' oven curing at 60° C is recommended. Indirect tensile strength testing is conducted to determine the ultimate strengths of both dry and soaked samples. Experts in the ARRB (Maccarrone,1997) recommend that the dry and soaked indirect tensile strength should be at least 200 kPa and 100 kPa respectively. The **design binder content** should be selected as the binder content at which the soaked indirect tensile strength is at a maximum.

Resilient modulus testing at the design binder content is recommended. It has been noted in CSIR Transportek's laboratories that the loading time of 100 ms for the standard indirect tensile resilient modulus test may be too harsh for foamed asphalt samples. It is therefore recommended that a loading time of 50 ms (at 25° C) as proposed by Lancaster et al (1994) be adopted for foamed asphalt resilient modulus testing. Lancaster (1994) also proposed that the acceptance criteria for foamed asphalt mixes, with respect to resilient modulus, be at least 1500 MPa and 6000 MPa for soaked and dry samples respectively. However, the resilient modulus requirements depend on the structural requirements of the pavements.

Dynamic Creep testing at the design binder content is suggested in order to evaluate the permanent deformation characteristics of the foamed asphalt mixes. A minimum dynamic creep modulus of 20 MPa is proposed.

5 LABORATORY VERIFICATION

5.1 General

A laboratory testing program was conducted to verify the design procedure proposed in section 4. The main purpose was to ensure that the mix design could be achieved using the proposed test methods and to identify any shortcomings in the design procedure.

5.2 Laboratory program

In order to enable the results from this study to be used with confidence, it was decided to base the test mixes on actual in-service foamed asphalt pavements in KwaZulu-Natal. As Theyse (1997) had conducted a study on these pavements, test results were readily available for comparison purposes.

The required mixes were produced at Bitutek Laboratories in Durban, according to the procedures described in section 4. No major problems were reported with the mixing or compaction procedures. Compacted samples were tested using the dynamic loading facilities at CSIR Transportek. The trial mixes were subjected to Indirect tensile tests for determination of the design binder content. Additional samples were prepared at the design binder content, for further indirect tensile tests, dynamic creep tests and bending beam tests. The test results are tabulated in Appendix B.

Three aggregate gradings were considered, as shown in Table 5.1. The grading curves are shown in Figure 5.1. It can be seen that mix A does not conform to the grading envelope recommended in section 4.3. Mix A was treated with 2,5 per cent Fly-ash and 2,5 per cent lime to increase the fines content.

Table 5.1: Aggregate gradings

Mix	A	B	C
Source	Sodwana aeolian sand	Shongweni weathered granite	Shongweni weathered granite
Sieve Size (mm)	% Passing		
19,0		100	100
13,2		93	96
9,5		80	90
6,7		69	82
4,75		60	74
2,36		44	57
1,18	100	33	43
0,600	99	23	33
0,300	72	15	24
0,150	6	9	17
0,075	1	7	13

Table 5.2: Binder contents for trial mixes

Aggregate Type	Nom. Binder Contents (B12 or 60/70 pen.)
Mix A: Sodwana aeolian sand	3; 4; 5
Mix B: Shongweni weathered granite	3; 4; 5
Mix C: Shongweni weathered granite	4; 5; 6

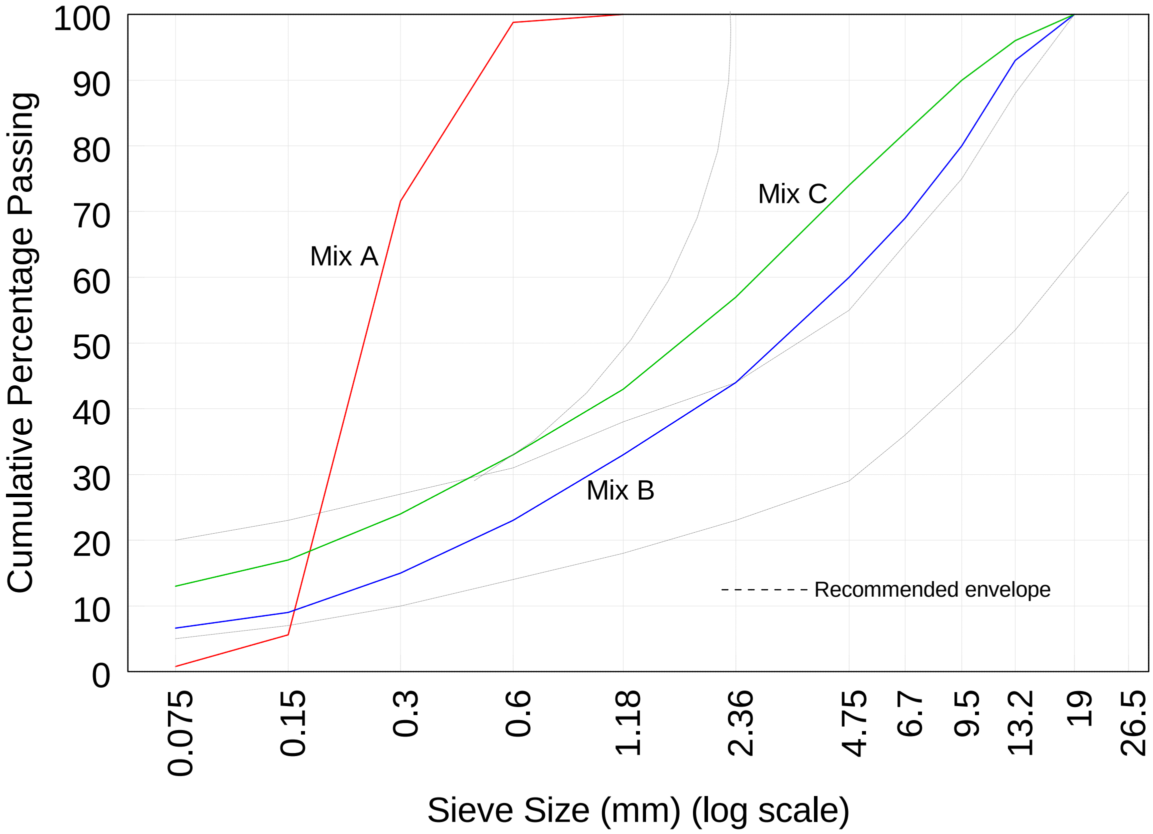

Figure 5.1 : Aggregate grading curves

5.3 Test Results for the trial mixes

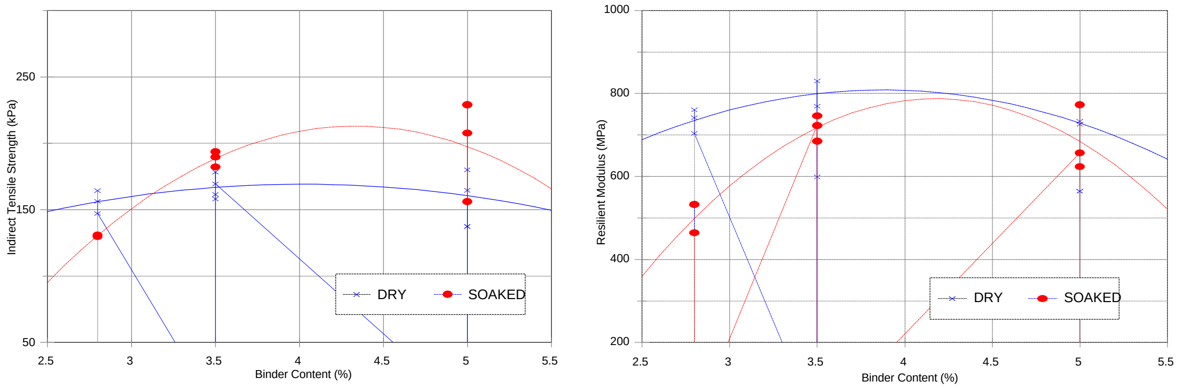

Figure 5.2: Indirect Tensile Test - Mix A

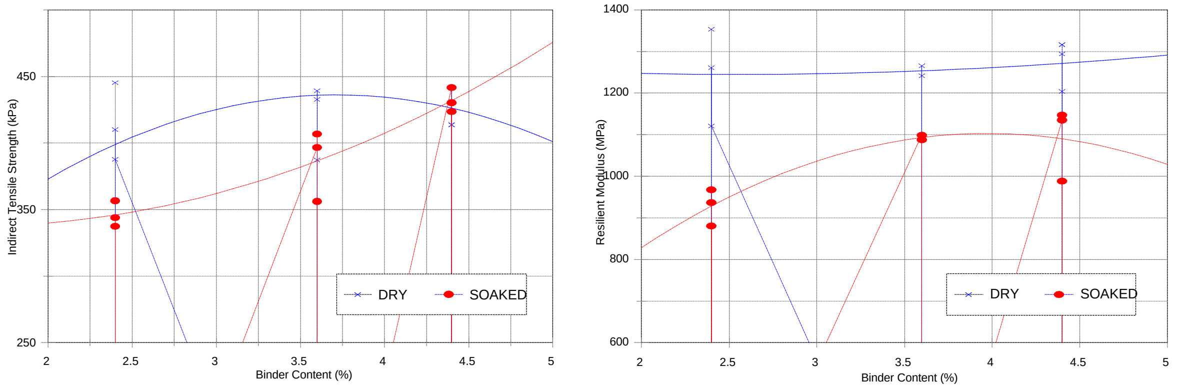

Figure 5.3 : Indirect Tensile Test - Mix B

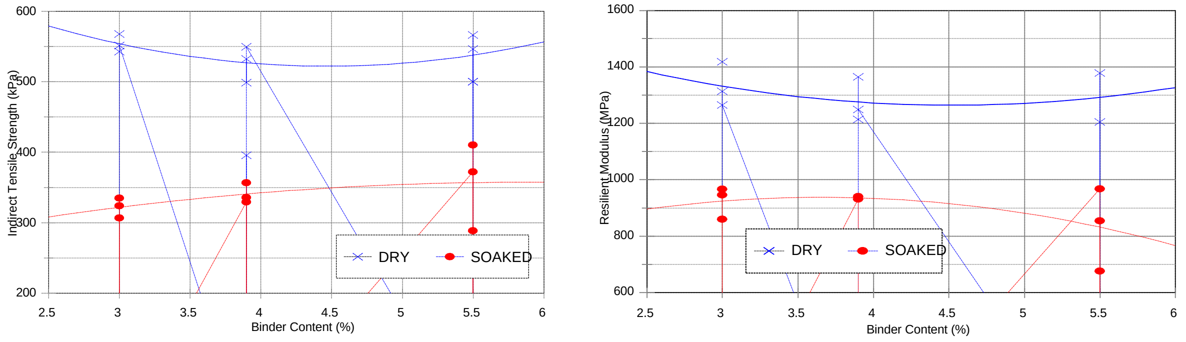

Figure 5.4 : Indirect Tensile Test - Mix C

5.4 Test results for the design mixes

Table 5.3: Tests on briquettes

Dry ITS	Wet ITS	Dry Res Mod	Wet Res Mod	Creep Mod.
Mix A: Sodwana aeolian sand (BC = 3.4%)				
113.30	132.20	571.70	456.50	early failure
Mix B: Shongweni weathered granite (BC = 3.6 %)				
529.23	197.65	1628.57	599.43	510.72
Mix C: Shongweni weathered granite (BC = 3.6 %)				
568.45	135.90	1477.80	282.20	235.79

Table 5.4: Test results from in-service pavement (extracted from Theyse,1997)

Test section	Test result			
	BC (%)	Voids (%)	ITS (dry) (kPa)	ITT (dry) (MPa)
Shongweni recycled asphalt km 3,00 - 3,20	5,9	10,7	422	1356
Shongweni weathered granite km 3,20 - 3,40	4,8	20,4	233	1261
Shongweni weathered granite km 3,40 - 3,60	4,3	10,5	287	1295
Sodwana aeolian sand	4 - 5	23,6	260	1239

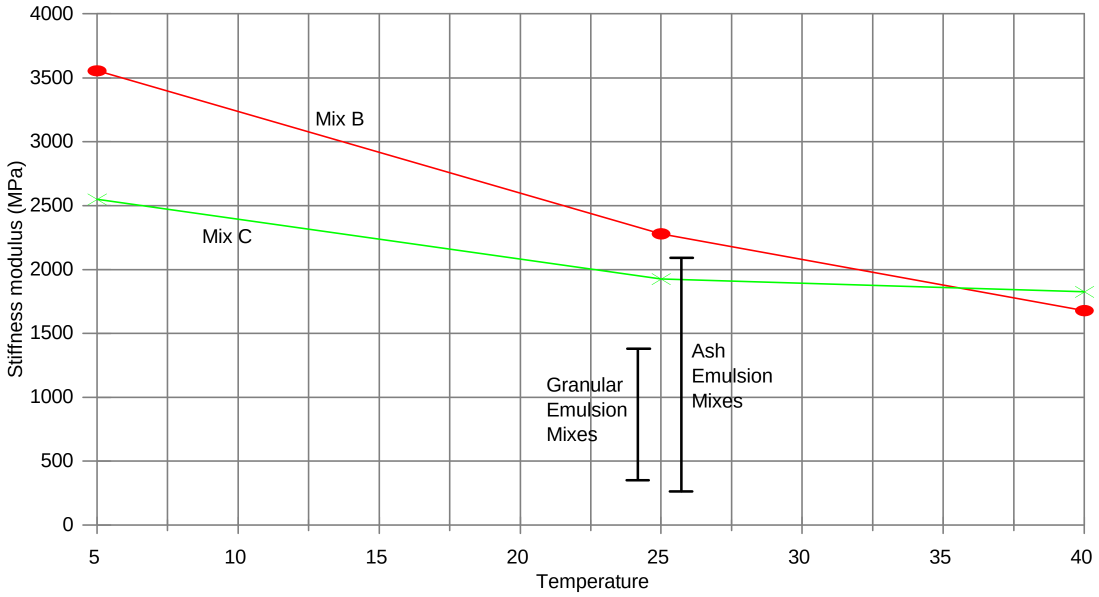

Figure 5.5 : Stiffness Moduli obtained from beam tests showing values obtained for bitumen treated granular and ash materials (at ambient temperature)

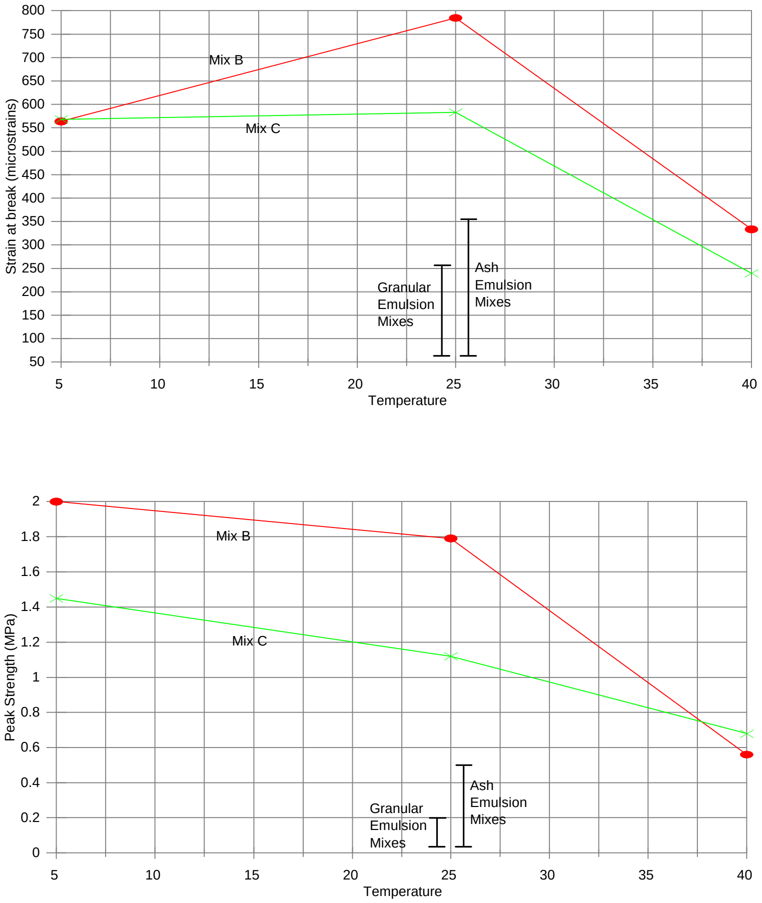

Figure 5.7: Peak stresses from the beam tests

5.5 Discussion of results

Generally the test results validate the expected decrease in strength when the materials are wet. The void contents for foamed asphalt mixes are very high (Table B1 in Appendix B) and thus highly permeable to water. The sand samples (mix A), however, show a small increase in strength when wet. It is possible that the hydration reaction of the lime+fly-ash modification contributed to this result.

It was not always possible to determine the optimum binder content solely from the soaked indirect tensile tests. In this case the other indirect tensile test results, and volumetric test results should be used to determine the design binder content. Apart from the sand mix, the foamed asphalt mixes performed relatively well, meeting the minimum criteria for both dry and wet ITS tests. This validates to some extent the grading restrictions proposed for fine, uniformly graded mixes. The sand mix was very brittle, and prone to damage on handling. However, the unconfined modes of testing may not be the best method of evaluating these mixes (uniformly graded), considering that sand mixes have been successfully used in field applications.

The beam tests were conducted at three temperatures, viz ambient (about 25°C), 5°C and 40°C. The results are shown in Figure 5.5 and Figure 5.6. As expected, the results indicate the temperature susceptibility of the material. The foamed asphalt mixes exhibited much higher stiffnesses than emulsion treated materials in the ambient temperature range and also tolerated strains 2 to 3 times larger than those tolerated by the emulsion treated materials, before failure.

It can be stated that the laboratory procedures result in mixes that are fairly representative of the field mixes, as can be seen if the results in Tables 5.3, 5.4 and B1 are compared.

6 CONCLUSION

Foamed asphalt cold mixes are gaining in popularity owing to their good performance, ease of construction and compatibility with a wide range of aggregate types. As with all bituminous mixes, it is essential to have a proper mix design procedure for foamed asphalt mixes in order to optimize the usage of available materials and to optimize mix properties. Fortunately, for foamed asphalt mixes, the mix design can be accomplished by relatively simple test procedures and by adhering to certain restrictions with respect to the materials used.

In this study, previous experience with foamed asphalt materials in other parts of the world was consolidated into a mix design guideline for use in South Africa. The mix design guideline follows a step-by-step procedure, from characterization of the raw materials through to the final testing of the compacted samples. Care was taken to ensure that the procedures adopted are compatible with standard test methods and currently accepted practice. Apart from a bitumen foaming plant, the mix design can be achieved with the standard equipment available in asphalt laboratories.

The central philosophy in the mix design is to optimize the mix strength characteristics at the worst-case operating environment, i.e.under soaked conditions. The indirect tensile strength test offers a convenient way of evaluating compacted foamed asphalt samples in this manner. Samples are compacted using standard Marshall compaction apparatus and then tested in a soaked condition. By conducting tests over a range of binder contents, the optimum binder content can be selected. Other tests, such as resilient modulus, dynamic creep and mix volumetrics, are also conducted in order to verify the selected optimum mix and to ensure adequate performance of the mix.

Many new techniques are being developed to achieve foaming of the bitumen. However, since the mix design proposed herein concentrates on optimizing the mix properties, it would work equally well with all foam asphalt mixes, irrespective of the type of apparatus used to produce the foamed bitumen.

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APPENDIX A : Laboratory Procedures for Mix Design

These procedures are mainly from the design guide provided by Tony Lewis (AA Loudon & Partners Consulting Engineers, 1998)

A.1 Apparatus

The following laboratory equipment is required to carry out the design of foamed asphalt mixes:

A laboratory foamed bitumen plant capable of producing foamed bitumen at a rate of between 50 g and 200 g per second. The method of production should closely simulate that of full-scale production of foamed bitumen. The apparatus should have a thermostatically controlled kettle capable of holding a mass of 10 kg of bitumen at between 150° C and 205° C, within a range of ± 5° C. In addition, a low-pressure compressed air supply of 0 - 500 kPa with an accuracy of ± 25 KPa should be included in the apparatus. The plant should have a system of adding cold water to the hot bitumen, variable from 0 per cent to 4 per cent by mass, with an accuracy of 0,2 per cent. The plant should be designed so that the foam can be discharged directly into the mixing bowl of an electrically driven laboratory mixer with a capacity of at least 10 kg

Marshall compaction moulds, 101,6 ± 0,5 mm in diameter and 87,3 ±1 mm high, with baseplate and extension collar to fit the moulds.
A Marshall compaction hammer with a 98,5 ± 0,5 mm diameter flat face and a 4536 ± 5 g sliding weight with a free fall of 457 ± 3 mm. The use of a mechanical hammer is optional.
A compaction pedestal consisting of a 203 x 203 x 457 mm wooden post capped with a 305 mm square steel plate. The pedestal shall be so installed that the post is plumb and the cap is level and must be provided with a rigid vertical guide for the hammer. The wooden post must be secured to a solid concrete slab.
A mould holder of suitable design to hold the mould in place during compaction.
A specimen extractor of suitable design to remove the briquette from the mould without damage.
A balance to weigh up to 5 kg accurate to 1 g.
A spatula with a blade of approximately 150 mm in length.

A compression testing machine capable of applying a load of at least 20 kN at a rate of 50,8 mm per minute, fitted with a load measuring device to measure a load of at least 15 kN and accurate to 0,1 kN.
An air cabinet capable of maintaining a temperature of 25° C ±1° C.
Two hardened steel loading strips, 13 ± 0,1 mm wide, each with a concave surface having a radius of curvature of 51 ± 1 mm and at least 70 mm long. The edges of the bearing surface should be rounded slightly to remove the sharp edge. The bearing strips should be mounted in a frame of suitable design to align the strips on the test specimen.
A steel load-transfer plate, round or square, to transfer the load from the compression testing machine to the top bearing strips without deformation. Its dimensions should be such that it will cover at least the length of the specimen to be tested on the bearing strip.
Callipers to measure the length and diameter of test specimens to the nearest 0,5 mm .
Silicone grease or oil (such as stop-cock grease)
A vacuum desiccator or other appropriate vessel and a vacuum pump capable of reducing pressure to less than 50 mm mercury, connected to a manometer.
A thermometer capable of measuring a temperature between 0° C and 50° C ± 0,2° C.

A.2 Optimization of Foamed Bitumen Properties

The objective is to determine the percentage of water which will optimize the foaming properties of a particular bitumen by maximizing the expansion ratio and half-life of the foamed bitumen.

Calibrate the bitumen and water flow rates. Regulate the bitumen discharge rate to 100 grams per second. Regulate the air supply pressure to 100 kPa. Maintain the bitumen within the temperature range of 180 - 200° C for at least 15 minutes before commencing with foam production. Five samples of foamed bitumen are required to be produced at moisture contents ranging from 1 per cent to 3 per cent in increments of 0,5 per cent.

For each sample, allow the foam to discharge for 5 seconds into a 20 litre steel drum. Mark the maximum volume to which the foam expands, using a marking pencil on the side of the drum. Using a stop watch, measure the time in seconds which the foam takes to dissipate to half of its maximum volume. This is defined as the half-life. Calculate the expansion ratio of the foamed bitumen by dividing the maximum foamed volume by the volume of bitumen in the drum after the foam has completely dissipated, after a period of at least 60 seconds. Plot the a graph of the expansion ratio and half-life versus moisture content for all the samples on the same set of axes, as shown in Figure A1. This will enable the moisture content to be optimized.

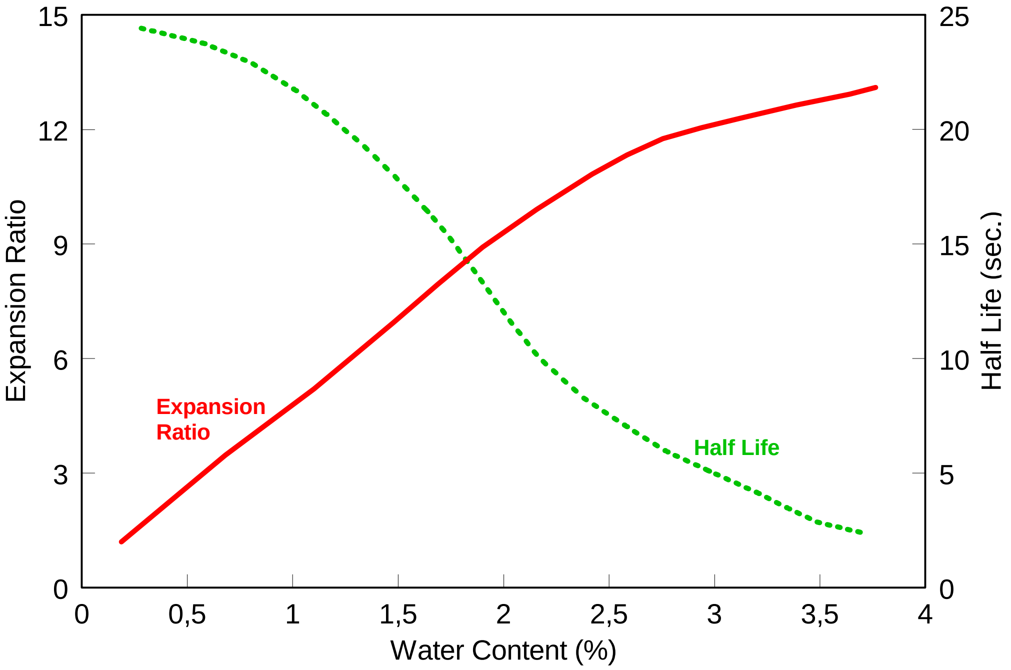

Figure A1: Optimizing foam properties.

A.3 Aggregate Preparation

Determine the gradation (refer to Method A1, TMH1) and plasticity index (refer to Method A3, TMH1) of the aggregates.

In some cases blending of more than one aggregate may be undertaken to provide the required grading (refer to section 4.2). At this stage cement, road lime or other fillers may be added if required. Lime treatment must be conducted if the PI of the aggregates is greater than 12.

Carry out a moisture/density relationship test, using the modified AASHTO method, so as to obtain the optimum moisture content (OMC) (refer to Method A7, TMH1).

The aggregate should be oven-dried to constant mass at 105° C. In the case of reclaimed bituminous materials, drying should be carried out at a lower temperature to prevent the particles from sticking together. The binder content of reclaimed bituminous materials should be determined at this stage. Once dry, the sample should be riffled and weighed into 10 kg batches.

A.4 Treatment of Aggregate Samples with Foamed Bitumen

For the mix design a total of five of the 10 kg batches, with bitumen contents 1 per cent apart, should be prepared. The laboratory foamed bitumen plant is adjusted to produce foamed bitumen with optimum properties, as determined in section A.2. An anti-stripping agent may be added to the bitumen to enhance bitumen adhesion to the aggregate.

Mix each 10 kg aggregate batch according to the following procedure:
Place the entire batch (10 kg) in the mixing bowl. Sufficient moisture should be added so that the moisture content plus the added binder content will be equal to the optimum moisture content, as determined from the moisture/density test described in section A.3. The mechanical mixer should be positioned so that the foamed bitumen can be discharged directly into the mixing bowl. Mix the aggregates and moisture in the mixer for one minute. Without stopping the mixer, discharge the required mass of foamed bitumen into the mixing bowl. Continue mixing the foamed bitumen into the moistened aggregate for a further 30 seconds. Transfer the aggregate treated with foamed bitumen to a sealed container. Repeat this procedure to obtain five samples of foamed bitumen treated material at different bitumen contents. These samples are now ready for further testing.

A.5 Moisture and Bitumen Contents

Take duplicate samples from each batch for moisture and bitumen content checks. Dry to constant mass at 105° C to 110° C and determine the moisture content of the material. Carry out a binder content determination (refer to Method C7, TMH1)

A.6 Procedure for Compaction of Foamed Asphalt Specimens

Clean the mould, collar baseplate and face of the compaction hammer. Place a plastic or paper disc at the bottom of the mould. Weigh out sufficient material to achieve a compacted height of 63,6 ±1,5 mm (usually about 1,15 kg is sufficient). Poke the mixture with a spatula 15 times around the perimeter and poke the rest of the surface 10 times leaving the surface slightly rounded.

Compact the mixture by applying 75 blows with the compaction hammer. Care should be taken to ensure that the hammer can fall freely. Remove the mould and collar from the pedestal, invert it, replace it and press it down so that it rests firmly on the baseplate. Then compact the briquette with another 75 blows.

A.7 Curing

After compaction, remove the mould from the baseplate and allow the specimen to cure for 24 hours in the mould at ambient temperature before extruding it by means of an extrusion jack or other means. Measure the height of the specimen.

The samples should then be cured for a further 72 hours at 60° C in a forced draft temperature controlled oven. The specimens should be placed on a flat smooth surface during curing as well as after curing.

A.8 Bulk Relative Density

The bulk relative density of each briquette (refer to Method C3, TMH1) should be checked after they have cooled to ambient temperature. Exclude from further testing any briquettes whose bulk relative density differs from the mean bulk density of the batch by more than 30 kg/m^3.

A.9 Determination of Indirect Tensile Strength

The standard indirect tensile strength test (refer to TMH1) is used to test compacted, cured foamed asphalt samples under dry and soaked conditions. The indirect tensile strength is determined by measuring the ultimate load to failure of a specimen which is subjected to a constant deformation rate of 50,8 mm / minute on its diametral axis.

Compact and cure test specimens as described in sections A.6 and A.7. Leave the briquettes overnight at room temperature before testing. Measure the height of each briquette at four evenly spaced places around the circumference and calculate the average height, L (m). Measure the diameter of each specimen, D (m).

Place the test briquettes in the air cabinet at 25° C ± 1° C for at least 1 hour but for not longer than 2 hours before testing. Remove a specimen from the air cabinet and place it into the loading apparatus. Position the sample such that the loading strips are parallel and centred on the vertical diametral plane. Place the transfer plate on the top bearing strip and position the assembly centrally under the loading ram of the compression testing device. Apply the load to the specimen without shock at a rate of advance of 50,8 mm per minute until the maximum load is reached. Record this load, P, accurate to 0,1 kN

In order to determine the indirect tensile strength of soaked samples, the following should be done prior to testing : Place the cured specimen in the vacuum desiccator, cover with water at 25° C ± 1° C. Apply a vacuum of 50 mm of mercury for 60 ± 1 minutes, with the timing period commencing once the required vacuum has been reached. Remove the specimen, surface dry and test for the ultimate indirect tensile load as described in the preceding paragraph.

Calculate the Indirect Tensile Strength (ITS) for each specimen to the nearest 1 kPa using the following formula:

$$\text{ITS (kPa)} = \frac{2P}{\pi LD}$$

Where :ITS = indirect tensile strength (kPa)
P = maximum applied load (kN)
L = length of specimen (m)
D = diameter of specimen (m)

A.10 Determining the Design Binder Content

Plot a graph of the measured indirect tensile strengths versus binder content for all the samples (soaked and dry tests) on the same set of axes. The binder content at which the soaked ITS is at its maximum is taken as the Design Binder Content for the foamed asphalt mix.

A.11 Determining additional mix properties at the Design Binder Content

If required, additional tests such as resilient modulus and dynamic creep tests, may be performed on samples at the design binder content. These would possibly be required for the structural design of the foamed asphalt layer. Additional samples would have to be compacted and cured for this purpose, as described in sections A.6 and A.7.

APPENDIX B : Laboratory Test Results

Table B1: Tests on briquettes

Sample number	Binder content(%)	MTRD	Wet density	Dry density	% Air Voids	ITS dry (kPa)	ITS wet (kPa)	Res. Mod dry (MPa)	Res. Mod wet (MPa)	Strain at break (%)	Creep modulus
A3-2	2.8	2.476	1.828	1.816	26.7		131.100		533.00	1.40	
A3-3	2.8	2.478	1.820	1.809	27.0		129.900		465.00	1.43	
A3-4	2.8	2.495	1.769	1.766	29.2	164.400		741.50		0.80	
A3-5	2.8	2.507	1.773	1.772	29.3	156.300		760.86		0.92	
A3-6	2.8	2.476	1.763	1.761	28.9	147.200		703.31		1.03	
A4-1	3.5	2.478	1.811	1.798	27.5		193.700		723.00	2.19	
A4-2	3.5	2.475	1.786	1.774	28.3		182.200		685.00	1.72	
A4-3	3.5	2.450	1.790	1.785	27.2		189.600		746.00	2.40	
A4-4	3.5	2.443	1.812	1.807	26.1	158.000		598.90		1.14	
A4-5	3.5	2.455	1.826	1.825	25.7	161.400		829.94		0.93	
A4-6	3.5	2.455	1.811	1.809	26.3	178.400		769.29		0.73	
A4-7	3.5	2.430	1.806	1.804	25.8	169.500				0.86	
A5-1	5.0	2.435	1.797	1.792	26.4		207.800		657.00	2.40	
A5-2	5.0	2.480	1.780	1.769	28.7		156.100		624.00	2.51	
A5-3	5.0	2.453	1.780	1.765	28.0		229.000		773.00	1.54	
A5-4	5.0	2.432	1.789	1.787	26.5	164.500		725.10		1.14	
A5-5	5.0	2.425	1.791	1.787	26.3	180.100		732.63		1.38	
A5-6	5.0	2.408	1.789	1.785	25.8	137.400		564.31		1.09	
A3	3.4	2.403	1.776	1.774	26.1	119.000				0.67	
A4	3.4	2.498	1.726	1.723	30.9	106.500		278.90		0.97	
A5	3.4	2.426	1.727	1.724	28.8	105.200		610.90		0.88	
A6	3.4	2.405	1.728	1.726	28.1	122.500		825.30		0.63	
A7	3.4						148.600			1.37	
A8	3.4						115.800		456.50	0.82	
A9	3.4										
A10	3.4										
B3-1	2.4	2.541	2.138	2.130	16.2		356.582		936.66	1.28	
B3-2	2.4	2.555	2.118	2.113	17.3		337.592		967.89	1.19	
B3-3	2.4	2.544	2.102	2.096	17.6	445.274		1353.70		0.82	
B3-4	2.4	2.547	2.112	2.105	17.4		343.919		880.85	0.92	
B3-5	2.4	2.560	2.113	2.109	17.6	410.138		1260.77		0.96	
B3-6	2.4	2.536	2.069	2.063	18.7	387.671		1120.91		0.74	
B4-1	3.6	2.513	2.118	2.110	16.0		396.592		1098.40	1.35	
B4-2	3.6	2.501	2.099	2.093	16.3		406.647		1088.14	1.38	
B4-3	3.6	2.522	2.112	2.106	16.5	387.300				0.77	
B4-4	3.6				16.4		356.225			1.28	
B4-5	3.6	2.526	2.099	2.095	17.1	439.106		1265.72		0.94	
B4-6	3.6	2.504	2.110	2.106	15.9	432.756		1241.47		0.81	
B4-7	3.6	2.498	2.097	2.091	16.3						
B5-1	4.4	2.487	2.078	2.070	16.8		441.713		1135.22	1.77	
B5-2	4.4	2.487	2.099	2.091	15.9		430.280		1147.00	1.33	
B5-3	4.4	2.473	2.064	2.058	16.8	441.831		1294.17		0.91	
B5-4	4.4	2.474	2.047	2.043	17.4		423.660		988.83	1.45	
B5-5	4.4	2.484	2.038	2.030	18.3	423.315		1203.51		0.76	
B5-6	4.4	2.486	2.051	2.048	17.6	413.755		1316.57		0.69	
B3	3.6	2.502	2.172	2.169	13.2	592.400				0.49	
B4	3.6	2.490	2.146	2.144	13.8	461.900		1531.80		1.00	
B5	3.6	2.542	2.144	2.142	15.7	561.100		1750.90		0.64	
B6	3.6	2.495	2.156	2.154	13.6	501.500		1603.00		0.49	
B7	3.6						263.200			0.72	
B8	3.6						192.300		638.60	0.97	
B9	3.6						158.800		610.10	1.87	
B10	3.6						176.300		549.60	1.36	
B1	3.6										471.43
B2	3.6										550.00
C4-1	3.0	2.504	2.058	2.050	18.1		324.025		966.84	1.16	
C4-2	3.0	2.494	2.074	2.064	17.3		307.004		860.47	0.98	
C4-3	3.0	2.505	2.032	2.024	19.2	567.614		1418.01		0.44	
C4-4	3.0	2.503	2.050	2.041	18.5		334.718		946.72	1.99	
C4-5	3.0	2.478	2.011	2.002	19.2	542.849		1314.65		0.33	
C4-6	3.0	2.474	2.108	2.099	15.1	551.513		1264.66		0.58	
Sample	Binder	MTRD	Wet	Dry	% Air	ITS	ITS	Res. Mod	Res. Mod	Strain at	Creep

number	content(%)		density	density	Voids	dry (kPa)	wet (kPa)	dry (MPa)	wet (MPa)	break (%)	modulus
C5-1	3.9	2.460	2.050	2.049	16.7		329.586		931.58	0.85	
C5-2	3.9	2.462	2.133	2.127	13.6		335.996		941.07	1.14	
C5-3	3.9	2.490	2.011	2.004	19.5	395.860				0.66	
C5-4	3.9	2.488	2.108	2.100	15.6		356.778			1.59	
C5-5	3.9	2.459	2.133	2.126	13.5	532.402		1214.32		0.50	
C5-6	3.9	2.459	2.059	2.051	16.6	498.915		1365.17		0.97	
C5-7	3.9	2.467	2.057	2.052	16.8	549.774		1249.23		0.50	
C6-1	5.5	2.446	2.037	2.029	17.0		372.221		967.70	1.16	
C6-2	5.5	2.457	2.059	2.054	16.4		288.645		675.65	1.94	
C6-3	5.5	2.387	2.020	2.018	15.4	566.404		1378.27		0.49	
C6-4	5.5	2.494	2.057	2.049	17.8		410.040		854.05	1.08	
C6-5	5.5	2.376	1.995	1.991	16.2	546.474		1205.62		0.75	
C6-6	5.5	2.433	2.007	2.003	17.7	500.287				0.77	
C3	3.6	2.419	2.080	2.078	14.0	656.400				0.41	
C4	3.6	2.338	2.076	2.074	11.2	502.200		1341.50		0.94	
C5	3.6	2.368	2.106	2.104	11.1	592.400		1610.80		0.46	
C6	3.6	2.378	2.066	2.063	13.1	522.800		1481.10		0.63	
C7	3.6						199.600			1.31	
C8	3.6						112.800		327.20	2.26	
C9	3.6								269.30		
C10	3.6						95.300		250.10	3.25	
C1											413.33
C2											58.25

Table B2: Bending Beam Tests

Sample number	Binder content(%)	Peak Stress (MPa)	Strain1 (με)	Strain2 (με)	Avg E-Mod (MPa)
b1	3.60	0.74	445.28	496.48	1569.41
b3	3.60	1.79	803.70	765.99	2283.25
b4	3.60	2.00	533.70	594.20	3544.65
b5	3.60	0.52	364.74	412.95	1339.87
b6	3.60	0.56	323.69	343.60	1684.43
c1	3.60	1.12	552.65	613.12	1914.62
c2	3.60	1.02	205.27	225.39	4755.51
c3	3.60	1.45	584.22	553.22	2553.11
c4	3.60	1.42	696.33	663.55	2086.95
c5	3.60	0.68	107.36	371.97	2837.27
c6	3.60	0.68	271.59	280.55	2448.66

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Property	**E0 - E2 Traffic**	**E3 - E4 Traffic**
Marshall Stability (25°C)	**8 kN**	**10 kN**
Retained Stability or ITS (25°C)	**60 %**	**70 %**
Indirect Tensile Strength (dry)	**100 kPa**	**150 kPa**
Resilient Modulus (25°C)	**900 MPa**	**1500 MPa**
Dynamic Creep	**10 MPa**	**15MPa**
Voids in mix	**5 - 15 %**	**5 - 15 %**