# Laboratory Mixture Design for Foamed Asphalt

## Rekayasa Campuran *Foamed Asphalt* di Laboratorium

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## ABSTRACT

Foamed asphalt is a green road material which normally generated using cold-mix system and frequently used in recycling technology. Due to the unique method to generate this mixture, it is very demanding to develop mixture design of foamed asphalt mixture in laboratory. This paper describes the mixture design in three points, i.e. mixture design considerations, mixture design process, and a case study. The mixture design considerations were developed based upon the results of previous researches. Whereas the mixture design process was described in step by step. The case study aplied a mixture generated using a blend of virgin crushed limestone and RAP aggregates, and bitumen pen. 50/70. The results can be deduced as follows. It should be considered several kinds for foamed asphalt mixture design, that are foamed bitumen characteristics, bitumen grade, foamed bitumen content, aggregate properties, moisture content, mixing process, compaction process, curing and temperature condition. The mixture design procedure is proposed in seven steps, i.e. (a) determine the optimum foamed bitumen properties, (b) prepare the aggregate, (c) mixing process, (d) compaction process, (e) curing process, (f) property testing, and (g) select the optimum foamed bitumen content. After running the seven steps, the case study gave the results as follows. Foams generated at a temperature of 160°C were selected as the most stable foamed bitumen. The optimum foaming water content was found to be around 1.9%. The plasticity index of the virgin crushed limestone aggregate was 2.7%. The maximum dry density was 2.2 Mg/m3 and optimum moisture content was 4.5%. All mixtures were added water at 72% OMC, mixed using the Hobart mixer, and compacted using Marshall Hammer. All specimens were oven cured at 40°C for 3 days. After ITS testing, it was decided to select foamed bitumen contents of 2.6%.
**Key words:** Mixture design, foamed asphalt, foamed bitumen, foaming water content, foamed bitumen content.

## ABSTRAK

*Foamed asphalt* adalah bahan perkerasan jalan yang ramah lingkungan, pada umumnya dibuat dengan sistem pencampuran dingin, dan sering digunakan dalam teknologi daur ulang. Sifat campuran yang unik ini menjadi alasan perlunya dikembangkan prosedur rekayasa pencampuran di laboratorium. Tulisan ini menjelaskan rekayasa pencampuran dalam tiga hal, yaitu pertimbangan rekayasa, proses rekayasa, dan sebuah studi kasus. Pertimbangan rekayasa pencampuran dikembangkan berdasarkan hasil-hasil penelitian sebelumnya. Sedangkan proses rekayasa pencampuran dijelaskan dalam langkah demi langkah. Studi kasus menggunakan campuran yang dibuat dari kombinasi agregat *limestone* dan RAP, dan aspal pen 50/70. Secara keseluruhan hasilnya dapat disimpulkan sebagai berikut. Dalam rekayasa pencampuran *foamed asphalt* perlu mempertimbangkan karakteristik *foamed bitumen*, jenis aspal, kadar *foamed bitumen*, propertis agregat, kadar air, proses pencampuran, proses pemadatan, kondisi perawatan dan suhu. Prosedur rekayasa pencampuran diusulkan dalam tujuh langkah, yaitu (a) menentukan optimum foamed bitumen properties, (b) menyiapkan agregat, (c) proses pencampuran, (d) proses pemadatan, (e) proses perawatan, (f) uji properti, dan (g) memilih kadar optimum foamed bitumen. Setelah melaksanakan 7 langkah maka dapat disimpulkan sebagai berikut. Pada saat produksi foam dipilih suhu pemanasan aspal hingga 160°C. Kadar air pembusaan optimum ditemukan sekitar 1,9%. Plasisitas indeks agregat adalah 2,7%. Maksimum kepadatan kering adalah 2,2 Mg/m3 dan kadar air optimum adalah 4.5%. Semua campuran ditambah air hingga 72% dari kadar air optimum, dicampur menggunakan Hobart mixer, dan dipadatkan menggunakan Marshall Hammer. Semua benda uji dioven pada suhu 40°C untuk 3 hari. Setelah melalui pengujian ITS, kadar foamed bitumen ditentukan pada angka 2,6%.
**Kata-kata kunci:** Rekayasa campuran, foamed asphalt, foamed bitumen, foaming water content, kadar foamed bitumen.

## INTRODUCTION

Foamed asphalt is a green road material which normally generated using cold-mix system and frequently use in recycling technology. This mixture can potentially save fresh materials, energy and fuel consumption, and also reduce greenhouse gas emission. Discussion of this material can be found in Widyatmoko and Sunarjono (2007) and Widajat (2009) in terms of considerations to implement this technology for road construction in Indonesia.

Foamed asphalt can be generated by mixing of sprayed foamed bitumen and homogenous wet aggregates at a ambient temperature. Whereas foamed bitumen can be generated by injecting pressurised air and a small quantity of cold water into a hot bitumen phase in an expansion chamber (Figure 1) which is installed in a laboratory foaming machine, e.g. the Wirtgen WLB 10 as shown in Figure 2.

In foamed asphalt production, if the predetermined aggregate moisture is incorrect and the quantity of fine particles is insufficient, the resulting mixture becomes unworkable (Brennen et al, 1983). Moreover, if both moisture and fines have been prepared correctly, but this is not accompanied by proper design of selected foamed bitumen characteristics (Muthen, 1999) and suitable mixing (Long et al, 2004); the resultant mixture will be inconsistent and hence its performance will be unpredictable.

Due to the unique method to generate this mixture, it is very demanding to develop mixture design in laboratory for foamed asphalt. This paper describes the mixture design in three points, i.e. mixture design considerations, mixture design process, and case study.

The principal objective of mix design for pavement materials is to obtain the material proportions that fulfill the structural and functional requirements of the in-service mixture. The gradation of aggregate and amount of bitumen should be combined economically to yield a mixture property. For this purpose, the Asphalt Institute (1988) suggested consideration of the following factors:

a) The amount of bitumen needed to ensure adequate fatigue cracking resistance and durability.
b) The mixture stability and stiffness to resist deformation due to traffic loading.
c) The void percentage in the mix to allow slight compaction under traffic loading without flushing, bleeding, or loss of stability.
d) Workability during mixing, placement and compaction.

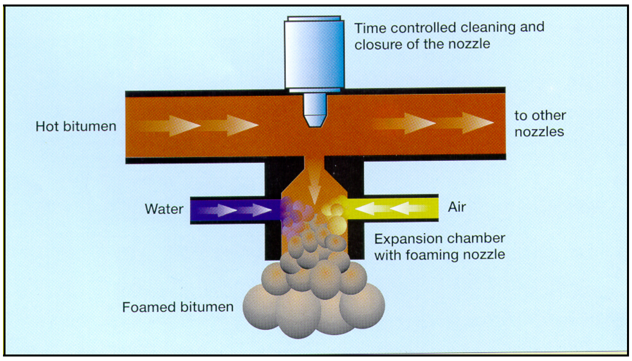

Figure 1. Foamed bitumen produced in an expansion chamber

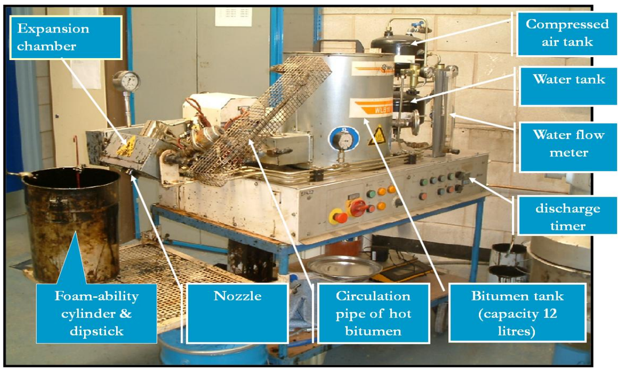

Figure 2. Laboratory Foaming Plant type Wirtgen WLB 10

## LITERATURE STUDY

### Foamed Bitumen Characteristics

Foamed bitumen is characterised in terms of maximum expansion ratio (ERm) and half-life (HL). The ratio of the maximum foam volume to the original bitumen volume is calculated as ERm, whereas the time needed by the foam to collapse to half its maximum volume is recorded as the HL.

ERm and HL are dependent parameters which are influenced by foaming water content (FWC), bitumen type and bitumen temperature (Brennen et al., 1983) and also by machine setting, i.e. water and air pressure, and nozzle size (Castedo Franco and Wood, 1983). Ruchel et al. (1982) added that the size of measuring cylinder also affected the foam parameters. Softer bitumen types and the higher bitumen temperatures generally produce better foam quality. Abel (1978) added that acceptable foaming was only achieved at temperatures above 149$^{o}$C. However, others have reported that softer and higher temperature bitumens do not always have better quality (Ruenkrairergsa et al., 2004 and He and Lu, 2004). This is because foam with lower viscosity and relatively low surface tension will be more likely to collapse prematurely before reaching its maximum volume than a higher viscosity foam (He and Wong, 2006).

Figure 3 shows typical characteristics of foamed bitumen in which foaming water content (FWC - % by bitumen mass) has the greatest effect on maximum expansion ratio and half life (Jenkins et al, 1999). It can be seen that ERm increases with increasing FWC, whilst the HL values tend to decrease.

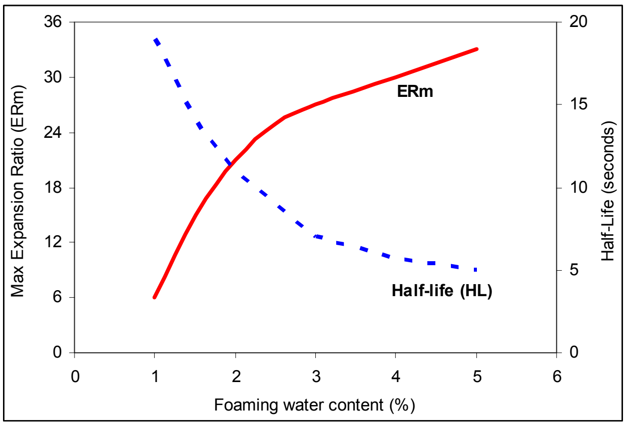

Figure 3. Characteristics of foamed bitumen in terms of maximum expansion ratio and half-life

### Determining The Best Foamed Bitumen Quality

A bitumen foam that achieves a higher ERm and a longer HL is currently understood to be of better quality and to result in better asphalt mix properties. Unfortunately, ERm and HL values show opposite trends and this makes the selection of an optimum foam difficult.

From experience, effective foam usually has a maximum expansion ratio between 10 and 15, which may be produced by injection of between 1 and 3 percent cold water. Various empirical guidance have been proposed as shown in Table 1 to limit ERm and HL and a method to select the optimum foam properties was introduced by Wirtgen (2005) as shown in Figure 4. This method is more likely to be useful for field applications. But as a research tool, selecting the best foam quality based on the mid point FWC (between minimum ERm and HL values) is not very rigorous due to these parameters not being linearly related.

Table 1. Minimum application limit of ERm and HL

| Method | Minimum ERm | Minimum HL |
|---|---|---|
| CSIR (Muthen, 1999) | 10 | 12 seconds |
| TRL Report 386 (Milton & Earland, 1999) | 10 | 10 seconds |
| Wirtgen (2005) | 8 | 6 seconds |
| Chiu and Huang (2002) | 8 | 8 seconds |

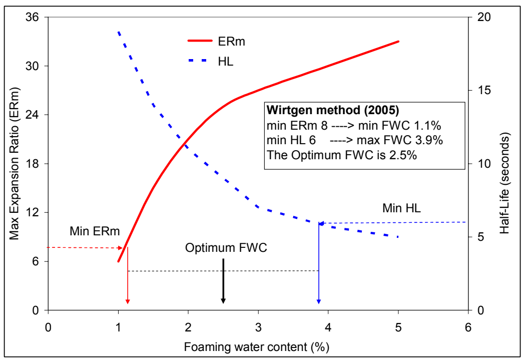

Figure 4. The Wirtgen method to select the best foam quality (Wirtgen, 2005)

It was for this reason that Jenkins et al (1999) introduced the Foam Index (FI) as a function of ERm and HL. Higher ERm and longer HL result higher FI. Foamed bitumen quality could therefore be characterised using single parameter, i.e. the FI value. Foam with higher FI was understood to have better properties. The optimum foam characteristics could therefore be obtained from the full range of FWC for any one bitumen type at one temperature (Figure 5).

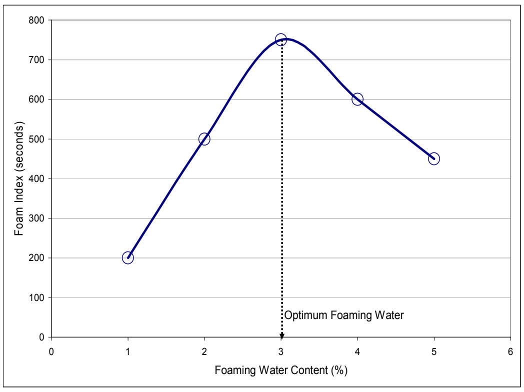


Figure 5. Optimisation of foamed bitumen characteristics using foam index (FI) concept (Jenkins, 1999).

## Foamed Asphalt Properties

For a particular mixture, there is an optimum foamed bitumen content (OFBC) at which the 'strength' of the mixture is a maximum. The associated strength has been evaluated in terms of unconfined compressive strength or UCS (Bowering, 1970), resilient modulus under the repeated load triaxial test (Shackel et al, 1974), Marshall stability and ITS (Kim and Lee, 2006) and indirect tensile stiffness modulus (Nataatmadja, 2002). However, Jenkins et al (2004) found that the OFBC can not be clearly identified in the range of bitumen content from 1.5% to 3.8% for test carried out under both dry and wet condition. The investigators gave an explanation that variation of moisture content and foam characteristics used can significantly affect the test results. The observed foaming properties (generated using 80/100 bitumen) fluctuated between 6 and 12 seconds for HL and between 15 and 24 for ERm. Unfortunately, the investigators did not report the temperature of the bitumen during the foaming process.

Shackel et al (1974) investigated the influence of bitumen grade. The use of a low bitumen grade (90pen) was found to give a material which responded better to repeated loading than using high bitumen grade (200pen), but the effect under repeated load was less than under monotonic load. In addition, He and Wong (2007) reported that mixtures (using RAP) stabilized by 100pen bitumen have better strength (ITS) and resistance to permanent deformation (RLAT) than with 60pen under both dry and soaked conditions. The effect of bitumen grade on foaming characteristics could explain the whole role of bonding mechanism in the mixture. Merill et al (2004) suggested that the choice of bitumen grade is a compromise between foaming ability and stiffness; higher grade bitumen foams easily but has lower viscosity.

Lee (1981) and Bowering & Martin (1976) have reported the effect of foamed bitumen characteristics on mixture properties. Lee (1981) has investigated the effect of ERm and HL on the characteristic of Marshall Stability and flow of foam mixture. Fine sand aggregate (nominal size 1.18mm) was mixed with 4% foamed bitumen Pen 200/300. The foams covered an ERm range of 5 to 20 and a HL range of 11 to 136 (some using anti-foam counter agent). Unfortunately, no information was given on what temperature, foaming water content and mixing protocol have been used. Figure 6 shows the data resulting from Lee's investigation. Lee stated that the data revealed no significant trends and the highest stability (after 24 hr immersion at 60$^{o}$C) was obtained at an ERm of 15 or HL of 18 seconds. However, it is noted that two samples with ERm of 15 (see points circled in figure) resulted lower stability. When these points are ignored, it seems possible to state that the optimum value of ERm can be obtained at Erm = 15; more data is however required to confirm this conclusion. The effect of ERm on mixture properties is likely to be more dominant than HL. In addition, Bowering & Martin (1976) reported that foam at ERm=15 gave better properties of mixture than at ERm=3, in which the properties were evaluated using Marshall Stability, UCS, resistance value, cohesion and swelling. These findings indicate that increasing ERm results in better mixture properties, but they did not test with ERm higher than 15.

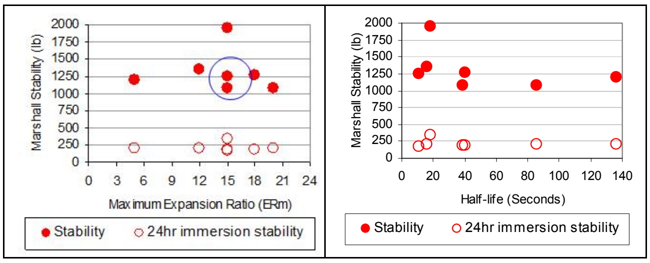


Figure 6. Effect of foamed bitumen characteristics on Marshall Stability (data from Lee 1981)

Bissada (1987) found that the poor stability of mixtures with lower penetration is due to deficiencies in their foam characteristics and hence their mixing properties. It is noted that the lack of mixing properties was not accompanied by any lack of compaction since their air voids were not too different.

The end product performance of foamed asphalt mixtures has been evaluated by many investigators. Nunn and Thom (2002) suggested that a long-term equilibrium stiffness of 2500 MPa (at 20$^{o}$C) is achievable after an intensively observed pilot scale trial in which many aggregates types such as basalt, limestone, asphalt planings/ RAP, blast furnace slag and crushed concrete, including additives (e.g. cement, fly ash), were stabilized using foaming bitumen. It was found that the mixtures having high moisture content and high air voids content (low density) performed poorly. Table 2 provides minimum acceptable values for foamed asphalt materials from various researchers.

Table 0. Minimum acceptable criteria for foamed asphalt materials.

| Minimum acceptable value | Property | Reference |
|---|---|---|
| 2500 MPa | ITSM (rise time 124ms, at 20$^{o}$C) | Nunn and Thom (2002) |
| 6000 MPa (dry condition)<br>1500 MPa (wet condition) | ITSM (rise time 50ms, at 25$^{o}$C) | Lancaster et al (1994) |
| 0.5 MPa (4 days soaked)<br>0.7 MPa (3 days cured at 60$^{o}$C) | UCS | Bowering (1970) |
| 200 kPa (dry condition) | ITS | Bowering and Martin(1976) |
| 100 kPa (wet condition) | ITS | Maccarone et al (1995) |
| 3.5 kN<br>1.5 kN/mm | Marshal stab<br>Marshal Quot | Akeroyd (1989) |

## RESEARCH METHOD

This paper describes the mixture design in three points, i.e. mixture design considerations, mixture design process, and a case study. The mixture design considerations were developed based upon the results of previous researches, e.g. Muthen (1999), Bissada (1987), and Ruchel et al (1982). Whereas the mixture design process was described in step by step based upon the mixture design proposed by Muthen (1999), Lee and Kim (2003), and Wirtgen (2005). The case study aplied a mixture generated using a blend of virgin crushed limestone and RAP aggregates with composition of 50:50, and bitumen pen. 50/70.

## DISCUSSION

### Mix Design Considerations

#### *Foamed bitumen characteristics*

Muthen (1999) stated that foamed bitumen characteristics play an important role during the mixing stage of foamed asphalt production. High expansion foamed bitumen is reported to have resulted in improved aggregate coating (Maccarone et.al., 1994) and high cohesion and compressive strength of mixture (Bowering and Martin, 1976). Understanding of foamed bitumen properties is aimed at enabling selection of the best foam quality – from the many variants - in which 3 important matters are addressed:

- good distribution in the mix - to ensure mixture homogeneity and flexibility,
- good coating of the aggregate – to ensure mixture stability and durability,
- long life time – to ensure workability during mixing and compaction.

#### *Bitumen Grade*

Bitumen grade should be an important parameter for foamed asphalt mixture performance. However, understanding of the effect of bitumen grade on the mixture properties is still unclear due to lack of understanding of bitumen grade effect on foam characteristics. Foamed asphalt mixtures are definitely loading rate and temperature-dependent behaviour mixtures, indicative of visco-elastic binder activity (Muthen, 1999). The evidence that Lee (1981) did not find any difference between the measured properties of foamed asphalt mixtures produced with different grades of bitumen 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.

#### *Foamed Bitumen Content*

Foamed bitumen content can be evaluated by optimizing mixture properties over a chosen range of FBC. However, in foamed-asphalt mixes the optimum FBC often cannot be as clearly determined as it can in the case of hot-mix asphalt. The optimum FBC is normally selected after considering both dry and wet conditions of specimens. The ratio of binder content to fines content plays a significant role in foamed mixture stability. Table 3 is intended as a guide to select the appropriate binder content based on the fines content of the mix.

Table 3. Foamed bitumen content (Ruchel et al, 1982)

| % passing 0.075mm sieve | FBC (%) | |
|---|---|---|
| | Gravel (<50% passing 4.75mm sieve) | Sand (>50% passing 4.75mm sieve) |
| 3-5 | 3 | 4 |
| 5-7.5 | 3.5 | 4.5 |
| 7.5-10 | 4 | 5 |
| > 10 | 4.5 | 5.5 |

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% for 5% fines content to a binder content of 5% for 20% 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. In general, a foamed asphalt mixture has lower bitumen content and higher voids content than a standard asphalt mixture (Abel, 1978).

#### *Aggregate Properties*

Foamed bitumen can be used with a wide range of aggregate types from conventional high quality graded materials, reclaimed asphalt and granular materials to marginal materials such as those having a high plasticity index (Muthen, 1999). However, Little et al (1983) reported that foamed bitumen mixtures with marginal aggregates have low stabilities and poor fatigue performance in comparison with conventional hot mix paving material, although they may still be acceptable in base and sub-base layers. Table 4 shows the many types of aggregates used for foamed asphalt and range of binder content adopted, from Bowering and Martin (1976).

Table 4. Type of Aggregates used for Foamed Asphalt

| Material type | Binder content range (%) | Additional requirement |
|---|---|---|
| Well graded clean gravel | 2 – 2.5 | - |
| Well graded marginally clayey/ silty gravel | 2 – 4.5 | - |
| Poorly graded marginally clayey gravel | 2 - 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 | Possible lime |
| Clayey sand | 3 – 4 | Lime modification |

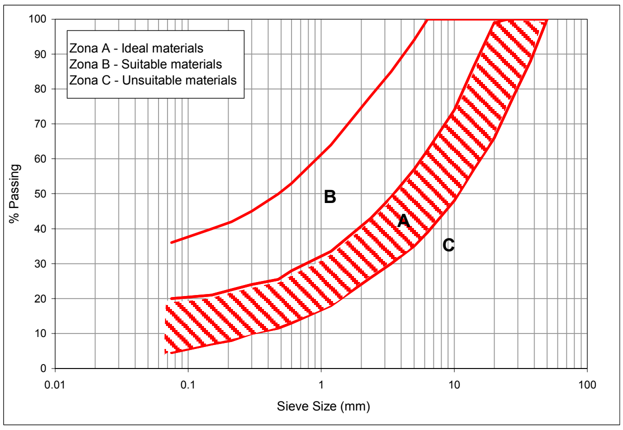


Figure 7. Aggregate grading zones for foamed asphalt (Akeroyd and Hicks ,1988)

With regard to aggregate grading, Akeroyd and Hicks (1988) introduced the Mobil foam stabilization grading chart (Figure 7) as a guidance to determine a suitable aggregate grading. The chart suggests that zones A and B are suitable for foam treatment for heavily trafficked roads and lightly trafficked roads respectively. Material that conforms to zone B will be more suitable if coarse materials are added. However, materials within zone C are very coarse and hence unsuitable for foamed asphalt materials.

A relatively large fines fraction (less than 0.075mm) with low plasticity will produce good mix characteristics because foamed bitumen tends to coat the fines and only partly coat the coarse particles (Abel, 1978). The fines content makes a dominant contribution in determining the tensile strength (Bissada, 1987), stability (Sakr and Manke, 1985) and workability of foamed asphalt mixtures (Semmelink, 2001). Ruckel et al (1982) recommended using at least 5 percent of fine aggregate (< 0.075 mm). The mixture of foamed bitumen and fine aggregate will act as a mortar between coarse aggregate particles and hence cause increased strength. The ratio of foamed bitumen to fine aggregate should be controlled because excessive foamed bitumen will tend to act as a lubricant and to cause decreasing strength and stability.

Aggregate interlock has been found to be more important than binder viscosity in building mixture stability (Sakr and Manke, 1985). This may imply that foamed asphalt mixes are not as temperature susceptible as hot mix asphalts. This can be achieved using low bitumen content in which the binder coats the fine aggregate only. This therefore suggests that coarse aggregate interlock, mortar properties, and their mixture together will mainly drive overall mixture properties.

### *Moisture Content*

Moisture content of foamed asphalt is the most important mixture design criterion due to its significant effect during mixing, compaction and during in-service life. Moisture is required to aid foamed bitumen dispersal and to coat the aggregate during mixing. Moisture also acts as a lubricant during compaction to achieve its maximum density. On the other hand, moisture is the main factor affecting lack of stiffness at early age.

Low moisture content causes inadequate foam dispersal in the mix, whereas too much water will significantly reduce the strength and extend the curing time. Therefore, moisture content should be close to the optimum moisture content for compaction. The moisture needed is dependent on compaction level used - the higher the level the lower the moisture, and filler content (Maccarone et al, 1994). The aggregate moisture content may influence the bitumen content used in the mixture. Brennen et al (1983) found that if the amount of aggregate moisture decreases the bitumen content should increase.

a) Several versions of moisture content determination method have been proposed as following.
b) **Fluff point method**. The Fluff point, developed by Mobil Oil, is the moisture content at which the aggregate has a maximum loose bulk volume. Brennen et al (1983) found that this point is close to 70-80% modified Proctor optimum moisture content (OMC).
c) Water application at 65-85 % of the modified Proctor OMC (Lee, 1981 and confirmed by Bissada, 1987).
d) **Total fluid content concept**. This concept is borrowed from emulsion mixture design in which the sum of the water and bitumen content should be close to OMC. Castedo-Franco and Wood (1983) agreed with this concept.
e) **Sakr and Manke (1985) concept**. This concept uses mixing moisture content (MMC), depending on the modified Proctor OMC, percentage of fines (PF) in the aggregate and the bitumen content (BC) as described in Eq. 2.5.

f) $$MMC=8.92+1.48OMC+0.4\,PF-0.39\,BC \quad \text{Eq. 0.1}$$

g) **High moisture content method**. Jenkins et al (2002) applied this method. Because low moisture content produces a poor quality mix, therefore the moisture content was set at a high level (around 1-2 % higher than OMC). After the mixing process the material was air dried for 30 minutes to achieve the optimum fluid content (OFC) necessary for compaction.
h) **Wirtgen concept**. This method uses optimum compaction and workability content (OCC) which is equal OMC reduced by a reduction water content ($WC_{reduc}$) that depends upon that OMC value (Eq.2.6).

$$OCC=OMC-WC_{reduc.} \quad \text{Eq. 0.2}$$

Where,
$WC_{reduc.}$ = 0 (for OMC less than 2%)
$WC_{reduc.}$ = 0.3*OMC – 0.6 (for modified Proctor OMC)
$WC_{reduc.}$ = 0.4*OMC – 0.8 (for standard Proctor OMC)

### *Mixing*

Foamed bitumen should be mixed with aggregates immediately since foam will collapse in a few seconds after spraying. Therefore the mixing method is very important to produce mixes which are both homogeneous and closely representative of those produced in the field. According to Lee and Kim (2003)'s study of the comparison between foam blending mixed in the field and the laboratory, field mixing results in better foamed asphalt properties than laboratory mixing. Therefore, Long et al (2004) recommended the use of a high-speed twin shaft pugmill mixer (developed by CSIR Transportek) to produce comparable materials with the field.

Mixing time was considered to be the approximate time needed for the foam to completely collapse after spraying. In the laboratory, this normally means about one minute (Bissada, 1987).

### *Compaction*

Two kinds of laboratory compactor are commonly used for foamed asphalt, namely:

a) Marshall hammer
b) Gyratory compactor

The Marshall hammer can be used to prepare compacted specimens for testing, not only for stability and flow tests in the Marshall apparatus, but also for indirect tensile strength, unconfined compressive strength and indirect tensile modulus tests. About 1200 grams of foam-aggregate blend is poured into the Marshall mould and then compacted for 2x75 blows.

In recent years the gyratory compactor has gained popularity for the preparation of samples. The mass of loose mixture is calculated based on its density to obtain a particular height appropriate to the height requirement of the test. The loose material is poured into the gyratory mould and set in the gyratory compactor machine. The standard Superpave protocol can be used in which compaction is set to 30-gyrations, ram pressure 600 kPa and compaction angle 1.25 degrees. Jenkins et al (2002) found that applying 150 gyrations using the Superpave protocol will produce a specimen density approaching 100% modified Proctor compaction. It is recommended to observe the number of gyrations before compaction because this is affected by material type.

In spite of the density and indirect tensile strength (ITS) of gyratory compacted specimens being slightly higher than those compacted in the Marshall compactor (Lee and Kim, 2005), the gyratory compacted specimens exhibit lower stiffness due to changes in particle rearrangement (Nataatmaja, 2001).

### *Curing and temperature condition*

One of the main differences between foamed asphalt mixture (FAM) and hot mix asphalt (HMA) is how they achieve their long-term characteristics after placement in the field. For HMA, the pavements will exhibit most of their long-term characteristics immediately after placing in the field. However, FAM needs a time period, namely the curing time, to gain its final characteristics due to the presence of water, both as aggregate moisture and foaming water.

Actually, the best way of curing in the laboratory is to cure the specimens at ambient temperature, comparable to field conditions. However, this will take a long time and is often not practical. Thus elevated temperature is usually used to accelerate the laboratory curing time, for example temperatures of 40$^o$C or 60$^o$C.

In the foamed asphalt process, some researchers have recommended to cure specimens at 60$^o$C for 3 days, being representative of a year's service after construction (Bowering, 1970; Maccarone, et al, 1995; Muthen, 1999). However, heating the specimen to 60$^o$C has an effect on binder ageing and changes its properties, so other researchers recommended applying 40$^o$C for 3 days (Jenkins, 2000) or 40$^o$C for 28 days (TRL 611, Merill et al 2004). This study selected a curing regime of 40$^o$C for 3 days in order to eliminate the effect of binder ageing and changes of specimen properties.

In determining optimum foamed bitumen content (OFBC) using ITS or UCS testing, applying curing temperatures of either 40$^o$C or 60$^o$C gives similar results (Lee and Kim, 2005). Lee and Kim also found that the loss of moisture during curing at 40$^o$C for 3 days, 60$^o$C for 2 days or 25$^o$C for 28 days is equal. It is therefore recommended to apply 40$^o$C for 3 days or 60$^o$C for 2 days in determining OFBC.

## Mix Design Process

The following are 3 of the most useful design procedures currently proposed:

1) Foamed asphalt mixes, mix design procedure – proposed by Muthen, K.M. (1999) and supported by SABITA Ltd and CSIR with the background of many South African projects.
2) Developing of a mix design process for cold-in-place rehabilitation using foamed asphalt – proposed by Lee and Kim (2003).
3) Foamed Bitumen Mix Design Procedure Using The Wirtgen WLB 10 – proposed by Wirtgen (2005).

Based on these 3 mixture design procedures, the mixture design for foamed asphalt can be described in seven steps as follow.

Step 1: Determine the optimum foamed bitumen properties

→ Investigate ERm and HL values for foams at various temperatures and foaming water contents for several chosen bitumen grades.
→ Select the best bitumen grade and temperature using the curve of ERm vs HL.
→ Select the best foaming water content using the curve of ER-HL vs foaming water content and selected foam specification (e.g. Wirtgen, 2005).

→ Step 2: Prepare the aggregate
→ Check the Plasticity Index (BS 1377-2: 1990), add lime 1% for high PI aggregate.
→ Check the gradation (BS EN 933-1:1997), ensure that gradation is within the specification envelope for foamed asphalt (e.g. Akeroyd and Hicks, 1988). Minimum filler content should be 5%.
→ Determine maximum dry density (MDD) and optimum moisture content (OMC) using a standard or a modified Proctor procedure (BS 13286-2: 2004).
→ Prepare 7.5 kg mass samples for each batch (need 3 to 5 batches), check initial moisture content (MCintial) using duplicate sample.
→ When using cement or lime, they should replace the equivalent percentage of mineral filler.

Step 3: Mixing process

→ Calculate the amount of aggregate water required (% of total aggregate mass) (see the provided equations or concepts in section 2.5.1.5).
→ Select 3 to 5 values of foamed bitumen content (FBC). Calculate the amount of foamed bitumen by % of total aggregate mass. Add 25% to calculated foam mass to cater for amount of foam lost during the mixing stage (depends on mixer agitator type). Set timer of foaming machine appropriate to foam mass required.
→ Add water to the aggregates first and mix for about 30-60 seconds. Introduce the foam and continue mixing for a further 1 minute.
→ Complete mixing the samples with selected FBCs.

Step 4: Compaction process

→ Compact the foamed blends using Marshall hammer or Gyratory compactor.
→ When using Marshall hammer, compact specimens 2x50 or 2x75 blows.
→ When using the Gyratory compactor, compact specimens with the Superpave standard protocol. Investigate the number of gyrations to obtain MDD.
→ Produce a minimum of 6x 1.2 kg specimens for each FBC.

Step 5: Curing process

→ Leave specimens in the compaction mould for 1 day at ambient temperature. Do not expose the top of the specimens when using cement.
→ Oven dry specimens (recommended at 40$^o$C for 3 days).
→ Soak half the number of specimens at 25$^o$C for 24 hours.

Step 6: Property testing

→ Store the specimens in a temperature cabinet at 20$^o$C for at least 2 hours before testing.
→ Test the conditioned and unconditioned specimens using ITS test, ITSM test, Marshall test or UCS test.

Step 7: Select the Optimum Foamed Bitumen Content (OFBC)

→ Plot the data on a curve of FBC vs mechanical property.
→ Select OFBC according to the maximum values. The minimum acceptable criteria described in Table 2 can be used as guidance.

## Case Study

The following are steps to design foamed asphalt mixture using procedure recommended in this research.

Step 1: determine the optimum foamed bitumen properties.

Bitumens pen. 50/70 was selected for the production of foamed bitumen. In order to determine the temperature and foaming water content (FWC) required to produce suitable foaming characteristics, the bitumen was subjected to foam production at 140$^\circ$C, 160$^\circ$C and 180$^\circ$C and at various water contents using the Wirtgen WLB-10 laboratory foaming plant. The foamed bitumen characteristics are presented in Figure 8 and Figure 9. Foams generated at a temperature of 160$^\circ$C were selected as the most stable foamed bitumen since most of their ERm values were higher than others, although the HL values were not the longest.

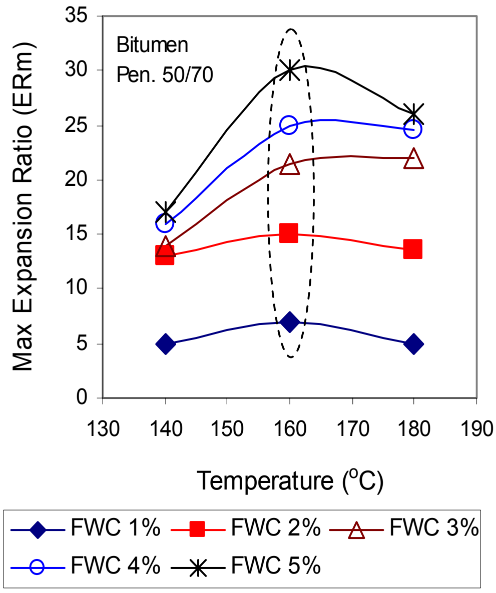


Figure 8. Foaming characteristics (ERm vs temperature) of bitumen 50/70

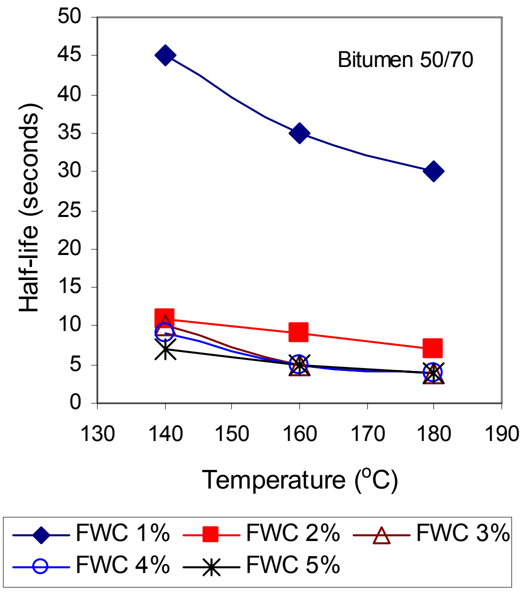


Figure 9. Foaming characteristics (half life vs temperature) of bitumen 50/70

A further step was to select the optimum foaming water content (Opt. FWC) at temperature of 160 ˚C. The Foam Index (FI) concept was initially attempted. However, as shown in Figure 10, FI values increased continually with increasing FWC and hence an optimum FWC value was impossible to locate. Therefore the Wirtgen method was used to approach the opt. FWC, although this method is not rigorous. The opt. FWC was found to be around 1.9% (Figure 10). A FWC of 2% was therefore applied.

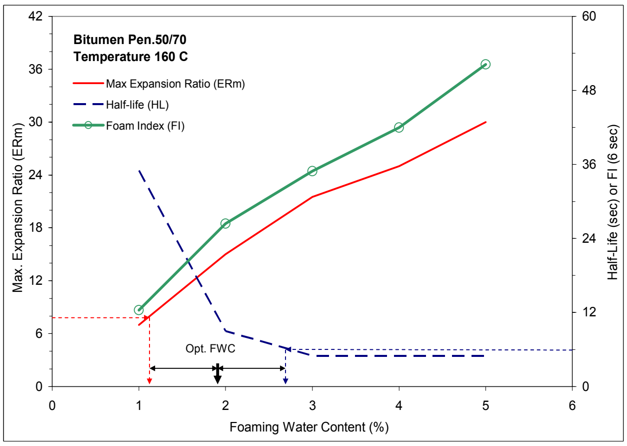


Figure 10. Determine the optimum foaming water content for foam generated using bitumen Pen. 50/70 at temperature of 160°C.

Step 2: Prepare the aggregate

Aggregates used are blend of virgin crushed limestone (VCL) and reclaimed asphalt pavement (RAP) with composition of 50:50. The Liquid Limit (LL) of VCL was determined using the cone penetrometer in accordance with BS 1377 part 2: 1990, giving 17.9% whereas the Plastic Limit obtained was 15.2%. It can be calculated that the Plasticity Index (PI), LL minus PL, was 2.7%. The gradation of the blended aggregates shown in Figure 11 which met the specification envelope. The maximum dry density (MDD) and optimum moisture content (OMC) of the aggregate was investigated using modified Proctor in accordance with BS EN 13286-2: 2004. The value of MDD is 2.2 Mg/m3 and OMC is 4.5%. It was prepared about 7.5 kg mass samples for each batch (for 6 specimens).

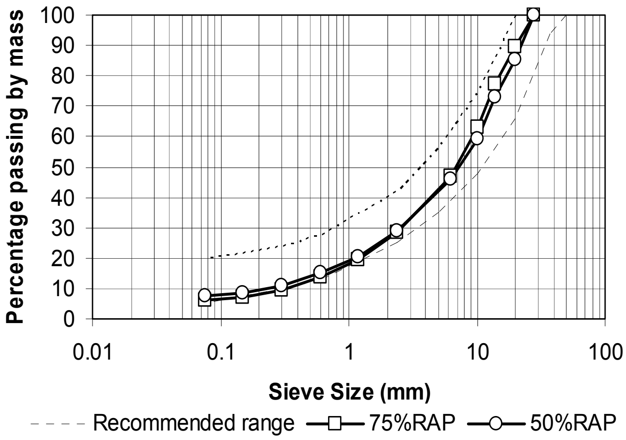


Figure 11. Gradation of blended aggregates

Step 3: Mixing process

Water was added to all mixtures at 72% OMC and mixed using the Hobart mixer for one minute before and after foam spraying. It was selected 4 values of FBC, i.e. 1%, 2%, 3%, and 4%.

Step 4: Compaction process

All mixtures were compacted using Marshall Hammer with 2x75 blows. The mass of each specimen was 1200g, giving 100 mm diameter and 63.5mm height.

Step 5: Curing process

All specimens were oven cured at 40°C for 3 days.

Step 6: Property testing

The Indirect Tensile Strength (ITS) was used to determine the optimum foamed bitumen content for 50% RAP. **Error! Reference source not found.** shows the results.

Step 7: Select the Optimum Foamed Bitumen Content (OFBC)

From curves of FBC vs ITS values shown in Figure 12, it was decided to select foamed bitumen contents of 2.6%.

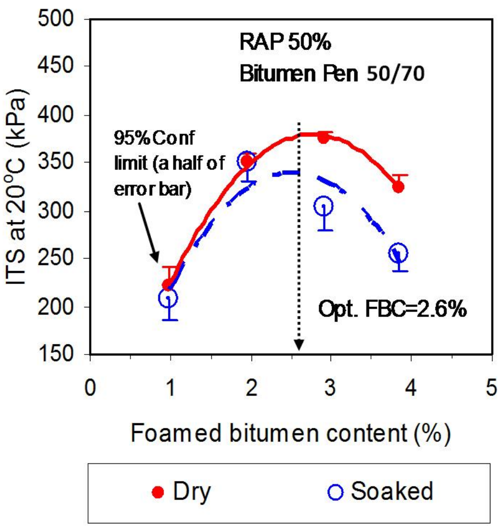


Figure 12. Determine the optimum foamed bitumen content (Opt. FBC).

The developed mixture design has been attempted in which the mixture was generated using a blend of virgin crushed limestone and RAP aggregates with composition of 50:50, and bitumen pen. 50/70. The results are as follows. Foams generated at a temperature of 160˚C were selected as the most stable foamed bitumen. The optimum FWC was found to be around 1.9% and then applied at 2%. The plasticity index of the virgin crushed limestone aggregate was 2.7%. The value of maximum dry density is 2.2 Mg/m3 and optimum moisture content is 4.5%. All mixtures were added water at 72% OMC, mixed using the Hobart mixer, and compacted using Marshall Hammer. All specimens were oven cured at 40°C for 3 days. After ITS testing, it was decided to select foamed bitumen contents of 2.6%.

## CLOSURE

Following the discussion described above, it can be deduced as follows:

1. In foamed asphalt mixture design, it should be considered several kinds, that are foamed bitumen characteristics, bitumen grade, foamed bitumen content, aggregate properties, moisture content, mixing process, compaction process, curing and temperature condition.
2. The mixture design procedure for foamed asphalt has been described based upon the mixture design proposed by Muthen (1999), Lee and Kim (2003), and Wirtgen (2005). The procedure is proposed in seven steps, i.e. (a) determine the optimum foamed bitumen properties, (b) prepare the aggregate, (c) mixing process, (d) compaction process, (e) curing process, (f) property testing, and (g) select the optimum foamed bitumen content.
3. The developed mixture design has been attempted in which the mixture was generated using a blend of virgin crushed limestone and RAP aggregates with composition of 50:50, and bitumen pen. 50/70. After running the seven steps, it was decided to select foamed bitumen contents of 2.6%.

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