Some Aspects of Foamed Bitumen Technology

Licentiate Thesis

May Namutebi

Division of Highway and Railway Engineering
Department of Transport Science
School of Architecture and the Built Environment
Royal Institute of Technology
SE-100 44 Stockholm

TRITA-VBT 11:05
ISSN 1650-867X
ISRN KTH/VBT 11/05-SE
Stockholm 2011
Some Aspects of foamed bitumen technology

May Namutebi
PhD Student
Division of Highway and Railway Engineering
School of Architecture and the Built Environment
KTH - Royal Institute of Technology
SE- 100 44 Stockholm
may.namutebi@abe.kth.se

Abstract: Although foamed bitumen has been widely applied in pavement construction some of its aspects are still not yet understood. In this study, some of these aspects including: effects of the foaming process on binder chemistry, characterization of foamed bitumen and development of a rational method to optimize foam characteristics, evaluation of aggregate particle coating within foamed bitumen treated materials, and development of a gyratory compaction procedure for laterite gravels treated with foamed bitumen were addressed. The effects of the foaming process on bitumen chemistry were investigated using Fourier transform infrared spectroscopy techniques. Also, foam characteristics of three binders were established and a rational method to optimize foam characteristics proposed. Aggregate particle coating with foamed bitumen was studied using the concepts of surface energy and Rice density. In addition a gyratory laboratory compaction procedure for laterite gravels treated with foamed bitumen was established using the modified locking concept. Infrared techniques have shown that foaming does not cause any changes in the binder chemistry, suggesting that foaming may be a physical process. Further, foam characteristics are greatly influenced by binder viscosity. Also, the equiviscous temperature seems to produce foam with optimum foam characteristics. Rice density results showed that aggregate size fraction, binder expansion ratio and viscosity influenced aggregate particle coating. Surface energy results revealed that foamed bitumen exhibited better coating attributes than neat bitumen. A new compaction procedure for laterite gravels treated with foamed bitumen based on the modified locking point was developed.

KEY WORDS: Foamed bitumen; Aggregate coating; Rice density; Foam characteristics; Surface energy; Locking concept; Gyratory; Compaction; Optimum moisture content.
Acknowledgements

I am greatly indebted to the guidance, advice and support provided by my supervisor, Professor Björn Birgisson of Väg and Banteknik, KTH, without whom this work would not have been possible. Also, the guidance and advice by my co-supervisor Dr. Umaru Bagampadde of the department of Civil Engineering, Makerere University is highly appreciated. I am grateful to Dr. Alvaro Guarin Corbo of Väg and Banteknik, KTH, for the final editing of this thesis. The efforts by Agneta Arnious of Väg and Banteknik, Bibi and Nini of Byggvetenskap to ensure that my stay at KTH was comfortable and smooth are gratefully acknowledged.

The funding by Swedish International Development Agency (SIDA) is highly appreciated. The assistance accorded by Dr. Michael Behn of Väg and Banteknik in editing of Paper II and in carrying out the study is gratefully acknowledged. The help in characterisation of laterite gravels by Mr. Mukasa (aka mwanyinaze) of the Department of Civil Engineering, Makerere University is gratefully acknowledged, Mr. Mukasa I can never thank you enough.

Many thanks to: Dr. Denis Jelagin, Ali Butt, Ebhrahim, Anohe, Jane Salmosson of Väg and Banteknik for their assistance in carrying out the foam characterisation tests. Also, Ali and Jane’s assistance in characterising the bitumens is gratefully acknowledged. The assistance by Per Redelius, Hilde and Javid of Nynas AB of Sweden in soliciting for various types of bitumen, and help with FTIR and DSC tests is highly appreciated. Prabir’s lessons and help in using the gyratory compactor are gratefully acknowledged.

I wish to thank my family (mama, daddy, Eria, Ruth) and friends for their prayers, support and for taking care of my small apartment in Uganda while I was in Sweden. I am also grateful for the emotional support, advice, friendships accorded to me by Mrs. Munyasanga (aka mama Odette), Ingmar H., Jacob Chakuwha, Esther, Lydia, friends in our bible study group and others, thanks for carrying my burdens, God bless you big!. Mama Odette thanks for letting me stay at your home and for constantly caring about the progress of my studies, I know God brought you to Sweden for such a time as this. Finally, I wish to thank the good LORD for His faithfulness towards me, Ebenezer!
Dedication

Mukama ye musumba wange; seetaagenga...............Zabbuli ya Dawudi
Essuula 23:1
**List of Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>ER</td>
<td>Expansion ratio</td>
</tr>
<tr>
<td>FI</td>
<td>Foam index</td>
</tr>
<tr>
<td>FWC</td>
<td>Foamant water content</td>
</tr>
<tr>
<td>HL</td>
<td>Half life</td>
</tr>
<tr>
<td>HMA</td>
<td>Hot mix asphalt</td>
</tr>
<tr>
<td>OMC</td>
<td>Optimum moisture content of laterite gravels only</td>
</tr>
</tbody>
</table>
# Table of contents

ABSTRACT ........................................................................................................................................ I  
ACKNOWLEDGEMENTS ............................................................................................................. III  
DEDICATION .................................................................................................................................... V  
LIST OF SYMBOLS .......................................................................................................................... VII  
TABLE OF CONTENTS ..................................................................................................................... IX  
1.0 INTRODUCTION ......................................................................................................................... 1  
   1.1 Background .............................................................................................................................. 1  
   1.2 Objectives .............................................................................................................................. 1  
   1.3 Scope ..................................................................................................................................... 2  
2.0 LITERATURE REVIEW .................................................................................................................. 4  
   2.1 Foamed bitumen ..................................................................................................................... 4  
   2.2 Characteristics of foamed bitumen (Paper I) ....................................................................... 5  
   2.3 Factors influencing foam characteristics (Paper I) .............................................................. 7  
   2.4 Surface energy ....................................................................................................................... 10  
   2.5 Compaction of foamed bitumen mixes (Paper III) ............................................................... 12  
3.0 EXPERIMENTAL WORK ............................................................................................................... 15  
   3.1 Materials .................................................................................................................................. 15  
      3.1.1 Bitumen ............................................................................................................................ 15  
      3.1.2 Aggregates ....................................................................................................................... 15  
   3.2 Production of foamed bitumen ............................................................................................... 15  
   3.3 Production of coated aggregate fractions ............................................................................ 16  
3.4 EXPERIMENTAL METHODS ...................................................................................................... 17  
   3.4.1 Bitumen characterisation tests ............................................................................................ 17  
   3.4.2 Foamed bitumen characterisation ...................................................................................... 19  
   3.4.3 Aggregate densities ............................................................................................................ 20  
   3.4.4 Rice density tests ................................................................................................................ 20  
   3.4.5 Surface energy tests ........................................................................................................... 21  
   3.4.6 Gyratory compaction (Paper III) ...................................................................................... 22  
4.0 RESULTS, ANALYSIS AND DISCUSSIONS ................................................................................. 24  
   4.1 Foaming effects on binder chemistry (Paper II) ................................................................. 24  
   4.2 Foamed bitumen characteristics (Paper II) ......................................................................... 25  
   4.3 Aggregate coating with foamed bitumen (Paper II) ............................................................. 35  
      4.3.1 Rice density ....................................................................................................................... 35  
      4.3.2 Surface energy ................................................................................................................ 38  
   4.4 Compaction characteristics of foamed bitumen treated materials (Paper III) ..................... 40  
5.0 CONCLUSIONS AND RECOMMENDATIONS .......................................................................... 45
5.1 CONCLUSIONS ................................................................. 45
5.2 RECOMMENDATIONS ....................................................... 46
REFERENCES ........................................................................... 49
APPENDED PAPERS ................................................................. 53
List of Publications

Paper I

Paper II

Paper III
M. Namutebi, B. Birgisson, and U. Bagampadde, “Proposed gyratory compaction procedure for determining the optimal compaction characteristics of laterite gravels treated with foamed bitumen”, To be submitted to an International Journal.
1.0 INTRODUCTION

1.1 Background

Global challenges such as climate change, dwindling natural material resources, and increasing population have created a need for innovations and improved methods in construction and maintenance of pavements. Foamed bitumen is one of such innovative technologies that have been applied in pavement construction. Foamed bitumen in pavement construction accrues various advantages such as improved mix strength and durability, reduced binder contents, increased spectrum of aggregates usable, energy savings during the mix processing, environmental friendliness as no toxins are released into the environment, improved workability, propensity of using labour intensive methods, and others (Saleh, 2007; Jenkins, 2000; Muthen, 1998; Akeroyd and Hicks, 1988; Castedo et al., 1984).

Since its genesis dating back to the 1950s, foamed bitumen has been successfully applied in pavement construction by various countries such as Australia, United States, United Kingdom, South Africa and others. However, some of its aspects such as binder ageing effects during the production process, effects of binder source on foam characteristics, preferential coating of fine aggregate particles by foamed bitumen, effects of foam characteristics on the resulting mixes are still not well understood. In addition, there seems to be no rational method in establishment of optimum foam conditions. Furthermore, although a gyratory laboratory method of compaction has been recommended for foamed bitumen mixes as it best simulates the compaction conditions in the field, it is not clear how compaction conditions such as the number of gyrations can be determined. Also, limited work exists on moisture requirements at the compaction stage, although some work has been done on moisture requirements at the mixing stage. In this work, some of these aspects are addressed.

1.2 Objectives

The study was carried out with against the following objectives:

Investigation of the effects of foam production process on binder composition. Foamed bitumen is produced when small quantities of cold water and air under pressure are injected into hot bitumen. Under these production conditions, the binder is more likely to be exposed to ageing due to the presence of air and water which promote ageing.

Development of a rational method for determining optimum foam characteristics. Although, approaches to determine the optimum foam characteristics have been proposed as described in section 2.3 of this report, they seem not to be adequate to properly determine the optimum foam characteristics.

Evaluation of foam characteristics for three binders and the effects of binder source onto foam characteristics. Foamed bitumen has been characterised by various parameters such as maximum expansion ratio, half life, minimum viscosity, and coefficient of foamability. These are influenced by foamtant water content, bitumen temperature, source, type, and composition, temperature of the vessel into which foam is dispersed, water, air and bitumen pressure, additives (Lesuer et al., 2004; Wirtgen, 2004; Jenkins, 2000; Castedo et al., 1984; Brennen et al., 1983). However, limited literature exists on the effects of bitumen source on these foam characteristics.

Evaluation of aggregate particle coating within foamed bitumen treated materials. It has been observed that foamed bitumen combines with aggregate particle sizes of less than 63 μm or 75 μm (Sunarjono, 2008; Castedo et al., 1983; Csanyi and Fung, 1956) and sand aggregate fractions (between
2 mm and 63 µm) (Jenkins, 2000). This forms a mortar that binds the coarser particles into a composite mass (Jenkins, 2000). Preferential coating of the filler can possibly be attributed to a higher surface area and hence higher surface forces. However limited literature exists on the quantitative determination of proportionate preference of foamed bitumen for the fines versus the coarser particles.

Most researchers have recommended compaction of foamed bitumen mixes at the number of gyrations that yield the maximum dry density of the aggregate as determined from the Proctor method. In this work, a laboratory gyratory compaction procedure for laterite gravels treated with foamed bitumen was established.

1.3 Scope

In this study, conventional grade bitumens were used. Granite aggregates were used in evaluation of aggregate particle coating in foamed bitumen treated materials. While laterite gravels were used in the development of a gyratory compaction procedure. The effects of the foam process on bitumen chemistry were investigated using infrared spectroscopy techniques. Foam characteristics namely, expansion ratio and half life for three penetration grade bitumens from different sources were studied to gain insight into the effects of bitumen source on foam characteristics. In addition, a rational method was devised to establish optimum foam characteristics (bitumen temperature, foamant water content, expansion ratio and half life). Further, aggregate particle coating in materials treated with foamed bitumen was studied using concepts of Rice density and surface energy. Also, a gyratory compaction procedure for laterite gravels treated with foamed bitumen was developed.
2.0 LITERATURE REVIEW

2.1 Foamed bitumen

Foamed bitumen is a two phase system consisting of various bitumen bubbles enclosing steam (Jenkins, 2000; Castedo et al., 1984; Csanyi, 1957). Foamed bitumen may also be known as foam bitumen or expanded bitumen or foamed asphalt or expanded asphalt, in this work the term foamed bitumen is used. It is produced when cold water (2-3 % by weight of bitumen) and air under pressure are injected into hot bitumen (between temperatures of 150 and 180°C). The interaction of water and hot bitumen leads to heat exchange occurring between water and bitumen. As a result, water is converted into steam, which is forced into the bitumen continuum under pressure forming various bitumen bubbles enclosing steam. Figure 1 illustrates a schematic for production of foamed bitumen. However, due to drainage forces (caused by gravitational forces, Plateau border suction, coarsening/thinning) and the pressure inside the bubbles exceeding the surface tension or elongation limit of the bitumen film the foam collapses after some period of time (Sunarjono, 2008; Jenkins, 2000).

![Figure 1. Schematic of Foamed Bitumen production (Sunarjono, 2008) ](image)

In foamed bitumen the viscosity and surface tension of the binder are reduced considerably. This increases the adhesion potential of the bitumen at low temperatures since it flows easily to coat the aggregates (Csanyi, 1959). Foaming the bitumen increases its adhesive properties making it well suited for mixing with cold and moist/wet aggregates. No chemical reaction is involved since the bitumen is temporarily physically altered. Foamed bitumen may be used to stabilise a wide range of aggregates and soils such as heavy clayey sandy or granular soils, recycled aggregates (i.e. aggregates that have been used in any pavement layer before) (Csanyi, 1959 and 1957). When used as a stabiliser, it improves cohesion and resistance to moisture ingress of the resulting composite material or mixture.

When the foamed bitumen is mixed with moist aggregates, it combines with the fines fraction present in the aggregates. It also partially coats the coarse particles, this imparts to the mix a mortar and friction load carrying mechanisms, where forces in the mix are partly supported by the mortar (formed by bitumen and the fines) and partly the friction resulting from aggregate particle to particle contact. Electron microscope observations on the structure of foamed bitumen mixes, revealed that foamed bitumen droplets coated the filler fraction (fraction that passes the 75 μm sieve) first, forming mastic (Jenkins, 2000). This mastic then combines with the sand fraction (fraction that passes the 2.36 mm sieve but it is retained on the 75 μm sieve) forming mortar (mixture of mastic and sand...
fraction). The resulting mortar adheres to the coarser particles. Thus the amount of fines is an important factor in foamed bitumen mixes. However, a scientific explanation why foamed bitumen combines with the fines has not been found in the literature.

2.2 Characteristics of foamed bitumen (Paper I)

The expansion ratio and half life are the primary parameters that are used in characterising foamed bitumen. Other parameters such as foam index, minimum viscosity, coefficient of foamability have been recently devised to characterize the foam.

Expansion ratio (ER)

Expansion ratio is defined as the ratio between maximum volume of bitumen achieved in the foamed state to the volume of original bitumen (Asphalt Academy, 2009; Wirtgen, 2004; Jenkins, 2000). It is a measure of viscosity of the foam and determines how well bitumen will be dispersed in the mix. During foam formation at a given bitumen temperature and foamant water content, the expansion ratio rises to a maximum value and then reduces with time. Figure 2 shows the variation ER versus time.

![Variation of Expansion ratio versus Time](image)

**Figure 2. Variation of Expansion ratio versus Time**

Half life (HL)

The half life is the time it takes a given foamed bitumen to settle to half its maximum volume or expansion ratio attained (Asphalt Academy, 2009; Wirtgen, 2004; Jenkins, 2000). It measures the stability of any given foam and gives an indication of its rate of collapse. It also determines the length of mixing period of foamed bitumen with the moist aggregates. Short half lives may result in the bitumen reverting to a high viscosity in a short period of time before intimate mixing with a mineral aggregate. This is not favourable for mixing. On the other hand, long half-lives allow complete mixing
of foamed bitumen with the aggregate, thus giving a mix with good workability. Foamants such as lime, metallic stearates, etc may be added to enhance or increase the half life of any given bitumen.

However, the expansion ratio (ER) increases with increasing foamant water content while the half life (HL) reduces, thus both parameters cannot be optimised simultaneously. Figure 3 shows the variation of expansion ratio and half life with water content.

![Figure 3. Typical Variation of Expansion ratio and Half life with Foamant water content](image)

**Foam index (FI)**

The foam index is a measure that combines both expansion ratio and half life characteristics. It is defined as the area under the curve of expansion ratio against time (Jenkins, 2000). It is also an indicator of the energy stored in any given foam and it is expressed in units of seconds. The foam index can also be used in optimising the foamant water content and foamant dosages since it combines both the ERm and HL. However, attempts to apply the foam index in deduction of optimum foam characteristics have not been successful (Namutebi et al., 2010; Sunarjono, 2008; Saleh, 2006). As no optimum point could be deduced as the index increased with increasing foamant water content.

**Minimum viscosity**

Minimum viscosity is defined as the average viscosity of the foam within the first 60 seconds of its production (Saleh, 2006). By plotting this average viscosity against foamant water contents, a point is obtained at which the average viscosity is minimum. The foamant water content at this point gives the best foam characteristics (Saleh, 2006). Characterising the foam using the average viscosity is a good idea since viscosity is a fundamental property. However, foams keep on changing with time, measuring their viscosity by direct equipment insertion may lead to foam distortion and unreliable results.
**Coefficient of foamability**

The coefficient of foamability is defined as the ratio of maximum expansion at a given bitumen temperature to the optimum foamanant water content at that temperature, and it is expressed in units of one per percent (Lesueur et al., 2004). From a study on various foamed bitumens produced from three different penetration grade bitumens, it was deduced that this coefficient was independent of temperature and constant for given bitumen (Lesueur et al., 2004). This coefficient varied between 2 and 3, Lesueur et al. (2004) proposed it as a possible characterisation parameter for foamed bitumen.

### 2.3 Factors influencing foam characteristics (Paper I)

The above foam characteristics are influenced by foamanant water content, bitumen temperature, viscosity, type and composition as well as the temperature of the vessel in which the foam is collected. The expansion ratio increases with increasing water contents and temperature, while the half life decreases, (He and Wong, 2005; Wirtgen, 2004; Brennen et al, 1983). This can be attributed to more water being made available, and thus more steam being produced, which leads to the formation of more bubbles. This leads to increase in expansion ratio of the foam.

Reduced half lives can be attributed to increased coarsening/thinning effects and reduced viscosity as temperature increases. When small bubbles are absorbed by large ones, the bitumen film thickness surrounding the bubbles reduces causing the bubbles to collapse (Sunarjono, 2008; Wirtgen, 2004). As the viscosity decreases, the surface tension of the bitumen films decreases, and the steam pressure within the bubbles exceeds the surface tension of the bitumen and bubbles collapse (Jenkins, 2000). On the other hand, decreasing viscosity can also lead to reduction in the surface tension in the lamellae of the bubbles and thus reduce the plateau border suction which in turn leads to delay of foam collapse (Sunarjono, 2008). However, this may rarely occur since reduced viscosity will lead to reduced surface tension for both the lamellae and the Plateau border (Sunarjono, 2008).

Bitumens with lower viscosities (soft grades) foam more readily and have high values of expansion ratio and half-lives than those with higher viscosities (hard grades) (Bissada, 1987; Abel, 1978). However, studies by He and Wong (2005) on decay properties of two grades of bitumen showed that the hard bitumen grades (with higher viscosities) gave higher maximum expansion ratios compared to those given by a soft grade (with lower viscosities) at the same bitumen temperature, air pressure and water content levels. In case of half life values, a reverse trend was observed. Half lives were higher for the soft grade compared to those of a hard grade. The variation was attributed to differences in viscosities for the two grades of bitumen. This is contrary to results reported by Bissada (1987) and Abel (1978). There seems to be other factors that could influence the foaming characteristics, and bitumen composition could be one of them. In He and Wong’s work the bitumen composition was not considered.

Studies by Barinov (1990) illustrated that increasing the asphaltenes fraction of the bitumen increased the expansion ratio and half life. This can be attributed to asphaltenes acting as surfactants reducing the surface tension in the lamellae of the bubbles and therefore reducing the plateau border suction, this leads to delay of foam collapse. But from Lesueur et al (2004) work it was deduced that bitumen composition did not mainly influence the foam characteristics as compared to bitumen temperature and water content. Thus, limited literature exists on the effects of bitumen composition on the foam characteristics. This study was undertaken to establish foam characteristics of binders of
different grades and from a different source and also to gain more understanding into the foam characteristics of different grades and composition.

**Optimum foam characteristics**

Since the ER and HL vary differently with foamant water contents and bitumen temperature, there is need to determine the optimum temperature, foamant water content that would give the best foam characteristics. The following approaches have been used to determine the optimum foam characteristics.

**Wirtgen Approach**

In this approach, the average foamant water contents at which the minimum expansion ratio and half life occur is considered as the optimum foamant water content (Wirtgen, 2004), see Figure 4.

![Figure 4. Wirtgen approach to determine Optimum Foamant water content](image)

Although it easy to use, this approach is not rational. Also, there is no temperature optimisation in this method.

**Foam index approach**

This approach involves plotting the foam index versus the foamant water content, the foamant water content at which the optimum foam index occurs is taken as the optimum, see Figure 5. However, attempts to apply this concept to characterise the foam by some researchers have not been fruitful, as no optimum point could be obtained (Namutebi et al., 2010; Sunarjono, 2008; Saleh, 2006).
Figure 5. Foam index versus Foamant water content (Jenkins, 2000)

Minimum viscosity approach

The foamant water content at which the lowest value of minimum viscosity occurs is considered as the optimum foamant water content, see Figure 6. However, it is likely that the foam structure is distorted as a result of inserting testing equipment within the foam.

Figure 6. Minimum viscosity versus Foamant water content (Saleh, 2006)
2.4 Surface energy

Surface energy or surface free energy is the work done in increasing a unit area of the surface in a vacuum and is denoted by the Greek letter $\gamma$ or $\Gamma$. In this work the term surface energy represented by letter $\gamma$ is used. In terms of molecular theory the concept of surface energy can be explained as follows, molecules within the bulk of a given material experience forces of attraction from neighbouring molecules, these forces are balanced within the bulk of the material. Whilst for molecules near the surface of the material these intermolecular forces (forces acting between the molecules) are not balanced as they have fewer neighbouring molecules, Figure 7. Thus the surface molecules tend to be pulled inwards, this imparts some kind of energy onto these surface molecules, and the surface molecules tend to have some kind of excess energy and thus the concept of surface energy.

![Surface and Bulk Molecules](image)

Figure 7. Molecular interactions within the bulk and at the surface of the material

Two theories have been proposed to explain the origin of surface energy namely, Fowkes and acid-base (Good-van Oss-Chaudhury, GVOC) theories. The Fowkes theory states that surface energy is the sum of all forces acting on the surface of a given material (Fowkes, 1964). These forces include dispersive forces (non polar or van der waals forces) and forces related to specific interactions such as hydrogen bonding. While the acid-base or GVOC theory states that the surface energy is divided into three components namely, the non-polar or Lifshitz- van der Waals forces component ($\gamma_{\text{LW}}$), the Lewis acid (electron acceptor) and the Lewis base (electron donor) components (van Oss et al., 1988).

The van der Waals forces which are forces that act between molecules may consist of dipole-dipole interactions (Keesom forces), random orienting dipole-induced dipole (induction or Debye forces) and fluctuating dipole-induced dipole (dispersion forces or London forces) (van Oss et al., 1988). Generally the Lifshitz-van der Waals (dispersive component) represents the non polar interactions and the acid-base component represents the polar interactions (Hefer and Little, 2006). The van der Waals and the acid-base components represent forces that play a major role in formation of adhesive and cohesive bonds at interfaces of materials. The acid-base theory was used in this study and is expressed as shown in Equation 1.

$$\gamma = \gamma_{\text{LW}} + \gamma^*$$

[1]

Where: $\gamma$ is the total surface energy, $\gamma_{\text{LW}}$ is the Lifshitz-van der Waals component, $\gamma^*$ is the acid base component ($\gamma^* = 2\sqrt{\gamma^+\gamma^-}$), $\gamma^+$ and $\gamma^-$ are the acid and base components, respectively.
Work of Adhesion

The work of adhesion is defined as the external work required to separate two materials at their interface in a vacuum (Little and Bhasin, 2006). The work of adhesion between two materials can be expressed in terms of their surface energy components as shown in Equation 2.

\[ W_{ab} = \gamma_A + \gamma_B - \gamma_{ab} = 2\sqrt{\gamma_{ab}^{LW}} + 2\sqrt{\gamma_{ab}^w} + 2\sqrt{\gamma_{ab}^s} \]  

[2]

Where: \( W_{ab} \) is the work of adhesion between materials A and B, 
\( \gamma_A \) \( \gamma_B \) is the total surface energy for material A and B, respectively, 
\( \gamma_{ab} \) is the interfacial energy between materials A and B, 
\( \gamma_{ab}^{LW}, \gamma_{ab}^w \) are the Lifshitz-van der Waals forces components for materials A and B, respectively, 
\( \gamma_{ab}^s \) are acid components of surface energy for materials A and B, respectively, 
\( \gamma_{ab}^s \) are base components of surface energy for materials A and B, respectively.

In case of foamed bitumen, Equation 2 would need to be modified in order to take into account the water effects since the aggregate is pre-wetted prior to being mixed with foamed bitumen. Foamed bitumen has to displace water from the aggregate surface so that it adheres to the aggregate surface. Thus the interface between the aggregate and water has to be eliminated. The energy required to form these interfaces can be expressed in terms of surface energy as \( -\gamma_{aw} \). Further, interfaces between foamed bitumen and aggregates on one hand, and foamed bitumen and water on the other hand need to be formed. Therefore the work of adhesion between foamed bitumen and aggregates can be expressed as shown in Equation 3.

\[ W_{af} = \gamma_{fa} + \gamma_{aw} - \gamma_{afw} \]

\[ W_{af} = 2\gamma_f + 2\sqrt{\gamma_f^{LW}} + 2\sqrt{\gamma_f^w} - 2\sqrt{\gamma_f^{LW}} - 2\sqrt{\gamma_f^w} - 2\sqrt{\gamma_f^{LW}} - 2\sqrt{\gamma_f^w} - 2\sqrt{\gamma_f^{LW}} - 2\sqrt{\gamma_f^w} - 2\sqrt{\gamma_f^{LW}} - 2\sqrt{\gamma_f^w} + 2\sqrt{\gamma_f^s} \]

[3]

Where: subscripts f, A and w refer to foamed bitumen, aggregates and water, respectively.

The work of adhesion represents the strength of the bond formed as a result of interaction between the bitumen and the aggregate. It is indicative of the strength of adhesive bond formed, thus the term adhesive bond strength or adhesive bond energy. In bituminous mixtures, it is desired that the adhesive bond strength be as high as possible, which would imply that the bitumen and the aggregate are firmly bound together. The work of adhesion may influence mixture properties such as resistance to moisture, fatigue resistance, etc. High values of work of adhesion imply that the binder is firmly bound onto the aggregate and therefore difficult to fracture and be displaced by water.

Work of cohesion

The work of cohesion is defined as the work done in separating a liquid into two parts, it measures the strength of molecular interactions within a liquid (Little and Bhasin, 2006). Similarly the work of cohesion of a given material can be expressed in terms of surface energy as shown in Equation 4.
\[ W_\Lambda = 2\gamma_\Lambda = 2\gamma_{w} + 4\sqrt{\gamma_{\Lambda}\gamma_{w}} \]  
[4]

Where: \( W_\Lambda \) is the work of cohesion, \( \gamma_\Lambda \) is the surface energy of the material.

Similar to the case of work of adhesion, the work of cohesion influences bituminous mixture properties. A high work of cohesion indicates that more work would be required to break or fracture the binder or mastic phase of the mix, thus making the mixture resistant to fracture through cohesive failure.

**Interfacial energy/work of debonding**

Interfacial energy or work of debonding is the work done when a material \( W \) displaces another material \( B \) from its interface with material \( A \), it is expressed as shown in Equation 5 (Little and Bhasin, 2006). In bituminous mixes, the interfacial energy represents the energy released when water displaces the bitumen from the aggregate. The value of this energy depicts the potential for water to displace bitumen from the aggregate (stripping potential), (Bhasin and Little, 2007). High values of this energy indicate that water has high potential to displace the bitumen from the aggregates and low values mean that water can not easily displace the binder from the aggregate.

\[ W_{\text{hbw}} = \gamma_{\text{w}} + \gamma_{\text{bw}} - \gamma_{\text{ab}} \]  
[5]

Where: subscripts \( A, B, w \) refer to aggregates, bitumen and water respectively,

\( \gamma_{\text{w}}, \gamma_{\text{bw}}, \gamma_{\text{ab}} \) is the interfacial surface energy between materials represented by the subscripts.

The surface energy of an aggregate determines its affinity for liquids such as water, bituminous binders, etc. Similarly, the surface energy of bitumen determines its affinity to coat a surface of a given aggregate and therefore the strength and durability of resulting mixture of given bitumen and aggregate. Thus, characterising aggregates and bituminous binders in terms of their surface energy properties may lead to improved performance of a given bituminous mixture/treated material and also understanding of the bitumen-aggregate bond. Studies have shown that the surface energy concept can be applied in bituminous mixes to select bitumen and aggregates that would give rise to mixes with good engineering and performance properties (Bhasin and Little, 2007; Hefer and Little, 2005; Bhasin and Little, 2006). In this study, attempts are made to apply these concepts to foamed bitumen treated materials.

### 2.5 Compaction of foamed bitumen mixes (Paper III)

Compaction of foamed bitumen mixes or foamed bitumen treated materials requires suitable equipment that will aid in achieving a composite mass that can be able to withstand the stresses that will be applied to the pavement structure. In addition, the moisture conditions within the mix should be at optimum level to provide the required lubrication during the compaction process. Various laboratory compaction methods have been used in compaction of foamed bitumen mixes or foamed bitumen treated materials. However, of these the gyratory compaction method has been recommended.
as it best simulates the roller action in the field. However, it is not clear how the number of gyrations to compact at can be determined.

Researchers such as Sunarjono (2008) and Jenkins (2000) recommended gyratory compaction at the number of gyrations that yielded the aggregate maximum dry density as determined from the Proctor method of compaction. However, gyratory and Proctor compaction methods are different and certainly the densities achieved in either method of compaction may not be equal.

In this study, the locking concept was modified and employed to establish the gyratory compaction conditions. The locking point is the point at which maximum aggregate interlock occurs, after this locking point any additional compaction would lead to aggregate particle break down and this would compromise the resulting strength of the mix. This concept of locking point was first defined by Vavrik and Carpenter (1998) for dense graded hot mixes, as the first three gyrations that are at the same compaction height preceded by two gyrations at the same height. However, application of the compaction height as a measure of locking point in this study did not yield any definite number of gyrations for any of the mixes in this study. Instead, the rate of change of compaction was used as a measure of resistance to compaction. The number of gyrations at which the resistance to compaction increased significantly was taken as the modified locking point.

Further, moisture conditions at compaction within foamed bitumen mixes or treated materials need to be optimised so that the required mix strength after compaction is achieved. Since foamed bitumen mixes exhibit granular behaviour, as not all aggregate particles are coated with foamed bitumen, too little or much moisture would lead to low strength. Although some work has been undertaken to establish the moisture requirements at the mixing stage, limited work exists on moisture requirements at the compaction stage. In this thesis, the optimum moisture content for laterite gravels treated with foamed bitumen required to achieve maximum dry density was determined at the modified locking point.
3.0 EXPERIMENTAL WORK

3.1 Materials
The following sections describe the different materials used in the study.

3.1.1 Bitumen
Three bitumen types were employed in the study namely, 50/70, 70/100 and 80/100 penetration grades. These were obtained from Nynas AB of Sweden and were coded as B1 (50/70), B2 (70/100), and B3 (80/100). B1 and B2 were obtained from the Venezuela crude whilst the source for B3 was unknown.

3.1.2 Aggregates

a). Granite aggregates (Paper II)
Three aggregate fractions of various sizes namely, 16-2.36 mm, 2.36-63 μm and less than 63 μm were used in this study. These were coded as A1 (16-2.36 mm), A2 (2.36-63 μm), and A3 (less than 63 μm). The aggregate fractions were produced from a foliated granite rock mainly consisting of quartz, K-feldspars and plagioclase with traces of phyllosilicates, muscovite, biotite and chlorite (Ekblad and Isacsson, 2008), located in Skälund, Sweden.

b). Laterite gravels (Paper III)
Laterite gravels obtained from the tropics and classified as silty clayey sandy gravels in accordance with the British soil classification system, with a nominal size of 20 mm were used in the development of gyratory compaction procedure for foamed bitumen treated materials. Three types of laterites differing in chemical composition were used, they were coded as L1, L2 and L3.

3.2 Production of Foamed bitumen
Foamed bitumen was produced from the three penetration grade bitumens using a laboratory foam plant Wirtgen WLB 10. It consisted of:

- a bitumen tank in which bitumen is heated to the required test temperature,
- water and air tanks with pressure capacities of 0.6-0.8 MPa to store and water and air respectively,
- an insulated expansion chamber where foamed bitumen is produced with an opening made up of nozzles through which the foam is dispersed,
- a pump for circulating the bitumen through the plant,
• a control panel for general operation of the plant such as setting temperature, spray time of bitumen, pump control, etc.

Figure 8 shows the photography of the foam plant used in the study.

![Image of foam plant]

**Figure 8. Wirtgen WLB 10 laboratory Foam Plant**

Foamed bitumen was produced from 50/70, 70/100 and 80/100 penetration grade bitumens and was coded as FB1, FB2 and FB3 respectively.

### 3.3 Production of Coated aggregate fractions

Aggregate fractions of different sizes were mixed with foamed bitumen prepared from 9% bitumen content for 60 seconds. Prior to mixing with foamed bitumen, each aggregate fraction was pre-wetted with water of 75% of OMC for each aggregate fraction, this was taken as the median value of the recommended range (65-85% of OMC) for mixing moisture content (Bissada, 1987; Lee, 1981; Bowering and Martin, 1976). Aggregate fractions mixed with foamed bitumen were cured on trays at room temperature until they attained constant weight. Rice density tests were then undertaken on each of the fractions. The maximum density of each of the uncoated aggregate fraction was also determined.

Also, another set of bitumen coated aggregate fractions were prepared in the same way as above for purposes of comparison. As a reference, the aggregate fractions were heated at 150°C for three hours and mixed with conventional binder B2 (not foamed), these were coded as HMA. After cooling, these coated fractions were sealed in boxes until their Rice density was determined. Table 1 summarises the test matrix employed to study aggregate coating with foamed bitumen.
Table 1. *Test matrix for aggregate coating with foamed bitumen*

<table>
<thead>
<tr>
<th>Binder</th>
<th>Aggregate fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
</tr>
<tr>
<td>FB1</td>
<td>x</td>
</tr>
<tr>
<td>FB2</td>
<td>x</td>
</tr>
<tr>
<td>FB3</td>
<td>x</td>
</tr>
</tbody>
</table>

x: at least two replicate tests were done

3.4 Experimental Methods

These included; rheological and chemical tests on bitumen, foamed bitumen characterisation tests, Rice/maximum density tests on coated and uncoated aggregate fractions, surface energy tests, and gyratory compaction of laterite gravels and foamed bitumen mixes. The following sections briefly describe these methods.

3.4.1 Bitumen Characterisation tests

Both physical and chemical tests were employed in characterisation of the bitumens used in the study.

Physical tests

These involved undertaking traditional rheological tests on the representative bitumen specimens. The following tests were used to determine the physical properties of bitumen namely penetration at 25°C, softening point, Brookfield viscosity, specific gravity and density.

*Penetration*

This was done in accordance to EN 1426. The penetration of standard steel needle into a given representative bitumen specimen at 25°C under a load of 100g and for a period of 5 seconds was measured. The penetration was measured at three points on the surface of the specimen and the average taken.

*Softening point*

This was done in accordance to EN 1427. Two bitumen test specimens suspended in brass rings each with a steel ball onto its surface were suspended in a water bath. The temperature of the water bath was raised at a constant rate until the steel balls fell through a distance of 25 mm, the temperature at which this occurred was taken as the softening point of the bitumen.
**Brookfield viscosity**

This was done in accordance to SS-EN 13302. The dynamic viscosity of given bitumen at different temperatures (135, 140, 150, 160, 170, and 180°C) was determined using a Brookfield Viscometer. A torque was applied to a bitumen specimen at a given temperature through a rotating spindle placed within the bitumen. This torque gave a measure of the dynamic viscosity and the viscosity was read directly from the digital screen of the apparatus.

**Density and Specific gravity**

This was done in accordance to SS-EN 15236. A given bitumen sample heated in the oven was poured into a pycnometer (of mass \(m_1\) and volume, \(V_p\)) up to three-quarters of its capacity. The whole setup was left to cool for at least 40 minutes, after which the mass of pycnometer containing bitumen, \(m_2\) was measured. The pycnometer containing bitumen was then filled with distilled water and the whole set-up placed in a low form beaker containing distilled water. The low form beaker was then placed in water bath at 25°C for at least 30 minutes. The mass of pycnometer containing bitumen and water, \(m_3\) was then determined. The specific gravity and density were then computed using the masses determined and the density of water at 25°C.

**Chemical tests**

*Fourier Transform Infrared spectroscopy (FTIR)*

This was used to investigate the binder functional group composition before and after foaming, thus deducing whether foaming induces any ageing of the binder. The Fourier transform spectrometer was used to analyse the composition of the samples. Two penetration grade bitumens, B2 and B3, of the same grade but sourced from different sources were analysed. For bitumen B2, solutions (5% by weight) were prepared in carbon disulphide and injected into a zinc selenide cell. The zinc selenide cell consisted of two mirrors, 1mm distance apart, the cell was placed into the spectrometer (Infinity 60AR Mattson) and scanning undertaken.

Prior to scanning with bitumen specimens, background scans using carbon disulphide only were done in order to eliminate the effects of carbon disulphide. For bitumen B3, scanning was done using a Nicolet 380 FTIR. B3 samples were heated to 180°C for 15 minutes, hot bitumen was then poured into a diamond cell and pressed with a diamond surface. Specimens for a second and third replicates were taken after 15 minutes interval. For both binders scanning was done at a resolution of 4, wave numbers of 4000 up to 400 cm\(^{-1}\) and 32 scans. Table 2 summarises the test matrix followed.

<table>
<thead>
<tr>
<th>Bitumen</th>
<th>Neat</th>
<th>Foamed</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2</td>
<td>(x)</td>
<td>(x)</td>
</tr>
<tr>
<td>B3</td>
<td>(x)</td>
<td>(x)</td>
</tr>
</tbody>
</table>

\(x\): represents at least two replicates
Acid number determination

This was done in accordance to ASTM D 664:95. It involved determination of the amount of potassium hydroxide solution at a given concentration required to neutralise the acids within a given bitumen sample dissolved in a solvent (consisting of propanol, toluene and water). This amount of potassium hydroxide was taken as the indicator of the acid number.

Differential Scanning Calorimetry (DSC)

This test was undertaken on bitumens B2 and B3. Approximately 15 mg of bitumen specimen was weighed in an open pan and placed in the calorimeter cell under the nitrogen blanket. The specimen together with a reference empty pan were heated to 120°C and then cooled at a rate of 10°C/min to -120°C. The changes in heat energy in the bitumen specimen with respect to the reference pan were determined at different temperatures and thermographs plotted. From these thermographs the wax content was deduced.

3.4.2 Foamed bitumen characterisation

Expansion ratio and half life

Foamed bitumen characterisation was done through the use of expansion ratio and half life parameters. 500 g of bitumen at a given temperature were mixed with a given quantity of foamant water under an air pressure in an expansion chamber of the foam plant. The foam produced was collected in a warm 270 mm diameter steel container. The steel container was heated in an oven at the bitumen temperature for at least 30 minutes prior to use. The bitumen temperature was varied from 150°C up to 180°C in steps of 10°C. The foamant water content (FWC) was varied from 1% up to 5% in steps of 1%. Air and water pressures were maintained at 0.5 and 0.6 bars respectively.

A dipstick with five marks each mark representing an expansion ratio was placed in the foam immediately after foam dissipation. Using a digital camera, video clips of the produced foam were recorded and analysed in order to deduce the maximum expansion and half life. For each foamant water content (FWC) and bitumen temperature at least three replicates of the foam were produced and analysed. For a given bitumen, temperature and water content, the expansion ratio increased up to a maximum value and then reduced with time. Maximum expansion ratio (ER) and half life (HL) values were deduced from plots of expansion versus time as shown in Figure 9.
ERm and HL at a given bitumen temperature were in turn plotted against FWCs, in order to obtain the optimum foam conditions. The results obtained are summarised in graphs shown in Figure 11 of ERm and HL against foamant water content for different temperatures.

### 3.4.3 Aggregate densities

Aggregate densities for fractions A1 and A2 were determined in accordance to SS-EN 1097-6. For each representative aggregate fraction the saturated surface dried mass in water, saturated surface dried mass in air and the oven dried mass were determined. For fraction A3 (filler), the density was determined using the method of density determination for fine soils. The densities were then computed from the determined masses.

### 3.4.4 Rice density tests

These were undertaken on both uncoated and coated aggregate fractions, and were done in accordance to SS-EN 1097-6 (for uncoated fractions) and EN 12697-5 (for coated fractions). A representative specimen was obtained from any uncoated or coated fraction and placed in pycnometer of known volume \( V_p \) in cm\(^3 \) and weight \( M_1 \). The weight of pycnometer containing the specimen was determined as \( M_2 \). The pycnometer with specimen was filled with water up to two-thirds of pycnometer height and a vacuum of 4 kPa applied for 15 minutes (for A1 and A1+A2+A3), 30 minutes (for A2) and 40 minutes (for A3) to remove the air from the specimen. After air removal, the pycnometer with specimen was filled with water ensuring that no air was trapped and placed in a water bath at 25°C for at least 30 minutes (for coated fractions) and two hours (for uncoated fractions). After which, the pycnometer containing the specimen and water was removed from the water bath, it’s
outside dried and the weight $M_3$ determined. The Rice or maximum density was computed using Equation 6.

$$\rho_{mm} (\text{kg/m}^3) = \frac{\frac{M_3 - M_1}{V_p} \cdot \frac{M_1 - M_2}{1000 \rho_w}}{\rho_w}$$  \[\text{[6]}\]

Where: $\rho_{mm}$ is the Rice density, $\rho_w$ is water density at test temperature in kg/m$^3$

All weights were determined in grammes.

Table 3 summarises the test matrix employed in determination of Rice densities for both uncoated and coated aggregate fractions.

<table>
<thead>
<tr>
<th>Binder</th>
<th>Aggregate fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
</tr>
<tr>
<td>None</td>
<td>x</td>
</tr>
<tr>
<td>FB1</td>
<td>x</td>
</tr>
<tr>
<td>FB2</td>
<td>x</td>
</tr>
<tr>
<td>FB3</td>
<td>x</td>
</tr>
<tr>
<td>HMA</td>
<td>x</td>
</tr>
</tbody>
</table>

x: at least two replicates

### 3.4.5 Surface energy tests

The Wilhelmy Plate method was employed to determine the contact angle and thus the surface energy of foamed bitumen. Foamed bitumen was produced from bitumen B2 at 4.5% bitumen content and 2% foamtant water content at 160°C. Clean glass slides (24 mm by 40 mm) were immersed in foamed bitumen and conditioned by storage in desiccators for 24 hours. After which glass slides were mounted in the Wilhelmy Plate device and the test started. Slides where immersed in a probe liquid with known surface energy properties for contact angle determination.

During the test, the coated slides were dipped 5mm into and retracted from each of the three probe liquids. Three probe liquids namely, deionised water, glycerol and diiodomethane were used. Graphs of slide mass against depth of immersion during the immersion and retraction stages of the test were plotted. Using the manual option, smooth portions of the graphs were selected to compute the contact angles. At the end of the test, the stage was lowered in order to remove the slide from the liquid and discarded. Three slides were tested with each liquid. The above procedure was repeated with slides coated with neat bitumen for comparison purposes.
3.4.6 Gyratory compaction (Paper III)

Foamed bitumen mixes consisting of laterite gravels and foamed bitumen (produced from binder B2) where prepared at 4.5% bitumen content and 75% of OMC (optimum moisture content of the gravels only) as mixing water content. Mixes were compacted at the OMC using a gyratory compactor at a vertical pressure of 600 kPa, and an angle of gyration of 1.25° up to 200 gyrations. Plots of the average compaction height versus number of gyrations were done and curves fitted using regression analysis.

Since application of the original locking point as defined by Vavrik and Carpenter (1998) did not yield any definite number of gyrations, a modified locking point was proposed. This modified locking point was defined as the point at which the resistance to compaction was greatest, and thus was used to establish the number of gyrations at which the mixes achieved maximum aggregate interlock. The rate of change of the compaction curve was used as a measure of the state of compaction. Also, gradation analysis using wet sieving was done to assess whether there were any changes in gradation of the gravels after compaction at the modified locking point and after 200 gyrations.

In addition, sensitivity analysis of compaction moisture for the different mixes at the number of gyrations that gave the modified locking point was done at 60%, 75%, 90% and 100% of OMC in order to establish the optimal moisture conditions for compaction.
4.0 RESULTS, ANALYSIS AND DISCUSSIONS

4.1 Foaming effects on binder chemistry (Paper II)

The carbonyl and sulphoxide peaks were used to assess whether any ageing had occurred in the binder after foaming. These compounds are indicative of bitumen ageing. The FTIR spectra obtained for neat and foamed bitumen coincided over the entire wave number from 4000 to 400 cm\(^{-1}\) for both binders tested. In addition, there were no differences in carbonyl and sulphoxide peaks for neat and foamed specimens for all the bitumens studied (Figure 10). This implies that there is no change in the carbonyl and sulphoxide functional groups that are responsible for ageing in bitumen. Therefore, from these results it appears that foaming the bitumen does not lead to bitumen ageing.

![Absorbance vs Wave number (cm\(^{-1}\)) for Neat and Foamed Bitumen for B2](image)

**Figure 10. FTIR Spectra for Neat and Foamed Bitumen for B2**

The maximum absorbances for the binders were different (8.00 for B2 and 0.45 for B3), with bitumen B2 containing higher amounts of sulphoxide and carbonyl compounds as it exhibited higher absorbance values for peaks of these compounds than those of B3. These results imply that both binders exhibited different chemical composition although they were of the same grade. Also, it was observed that the carbonyl peak occurred at around 1729-1683 cm\(^{-1}\) wave number band for B2 and at 1705-1695 cm\(^{-1}\) band for B3, this carbonyl stretch for B3 was narrower than that for B2. While the peak for sulphoxides occurred at 1020 up to 1040 cm\(^{-1}\) wave number band for both binders.

Statistical analysis using two way ANOVA of the peak areas under the wave number bands for sulphoxides and carbonyls showed that there were no significant differences for each functional group given any bitumen after foaming (see Table 4). While significant differences occurred between B2 and B3 peaks areas for a given neat or foamed condition (see Table 4). This showed that B2 and B3 where
different since they were obtained from different crudes. In addition, thermographs from DSC showed that B3 contained wax of about 7.2% and therefore different from B2 which hardly contained any wax.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Carbonyls</th>
<th>Sulphoxides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neat and Foamed</td>
<td>0.44</td>
<td>0.99</td>
</tr>
<tr>
<td>B2 and B3</td>
<td>0.00*</td>
<td>0.03</td>
</tr>
</tbody>
</table>

NOTE:
If p>0.05, null hypothesis cannot be rejected at 5% significant level
If p<0.05, null hypothesis is rejected at 5% significant level
* Due to two significant figure limitations p value is zero.

From the foregoing, it can possibly be deduced that foaming does not lead to any chemical functional compositional changes within the binder. This may probably be explained by short time periods the bitumen is exposed to water and air in the foam plant, which may not be enough to cause ageing to occur within the binder. Hot bitumen was exposed to air and water in the expansion chamber of the foam plant for average time of 3.8 seconds. Further, the results could imply that foaming might be a physical process, involving physical forces such as surface tension and does not involve any chemical changes of the bitumen.

4.2 Foamed bitumen characteristics (Paper II)

Influence of bitumen temperature

Generally, the expansion ratio values increased while the half life values reduced for all binders as the bitumen temperature was varied from 150°C to 180°C (Figures 11a and 11b). This can be attributed to more thermal energy being made available as temperature is increased to convert water into steam. This in turn leads to production of more bubbles and thus high expansion ratio values. In addition, as the binder temperature increases the binder viscosity decreases which in turn leads to lower surface tension forces within the bitumen bubble films (Sunarjono, 2008). When these are exceeded by the internal steam pressure the bubbles collapse and thus foam collapse (Jenkins, 2000). Also due to the likelihood of many bubbles touching each other frequently, small bubbles are absorbed by the larger ones which leads to lamellae (of larger bubbles) thinning and rupture (Sunarjono, 2008). This in turn leads to foam collapse in a shorter period of time and thus reduced half life.
Binder B3 exhibited the highest ER values while B1 the highest half life values. B3 exhibited the lowest binder viscosities at all temperatures. This may suggest that lower binder viscosities enabled the steam to easily penetrate the bitumen continuum. However, B1 that exhibited the highest binder viscosities at all temperatures gave the highest half life values. High binder viscosities lead to increased surface tension within the bitumen films, which in turn balances the internal bubble pressure. These effects will lead to increased stability of the bubbles. These results agree with those by Bissada (1987) and Abel (1978) but seem to contradict those given by He and Wong (2005), where...
low viscosity binders gave low expansion ratio values, and high viscosity binders gave high expansion ratio values. This behaviour may be attributed to binder composition, B3 contained wax as shown by DSC results.

**Influence of foamant water content**

The expansion ratio values increased with increasing water contents for all bitumen temperatures for binders B2 and B3. While the half life values decreased with increasing water contents, at high foamant water contents half life values tended to be constant or increased slightly. These results agree with what other researchers have observed (Sunarjono, 2008; Brennen et al., 1983).

The foam characteristics of binder B1, exhibited a unique relation with increasing foamant water contents (FWCs). As temperature increased from 150 up to 170°C, the ER increased reaching a maximum value and then decreased. The FWC at which an optimum ER occurred increased with increasing temperature. While the half life values reduced reaching a minimum and then increased with increasing foamant water content. However, at a binder temperature of 180°C, the ER and half life values increased and decreased, respectively, with increasing foamant water contents. This behaviour may be attributed to lack of enough energy to convert a substantial amount of water into steam, it was visually observed that less steam was expelled during foam collapse at temperatures less than 180°C. Also, from this behaviour it can be deduced that there seems to be a viscosity related limit on the ERm at any given temperature for binder B1.

**Influence of binder source**

Although, B2 and B3 were obtained from different sources, they exhibited similar foam behaviour unlike B1 that was obtained from the same source as B2. This may suggest that the grade or viscosity mainly influences the foam characteristics. Also, the presence of wax within the binder seems to enhance the foam characteristics as binder B3 gave the highest ER values.

**Optimum foam conditions**

The foam index (FI) as suggested by Jenkins (2000) was computed and plotted against FWC and temperature (Figure 12). However, the FI varied differently with various temperatures and foamant water contents. No clear trends were obtained as a result it could not be used to deduce optimum foam conditions.
The Wirtgen concept was applied to deduce optimum foam conditions. After choosing the temperature that gave the highest ER and HL values, the average FWC at minimum expansion ratio and half life was taken as the optimum foamant water content. A minimum expansion ratio of 15 and half life value of 16 were considered acceptable in determination of foamant water contents, using the guidelines by Wirtgen (2004) of ER of 8 and half life of 6 seconds. Figure 13 illustrates the foamant water contents obtained at these limits for B2.
For binder B1, the highest expansion ratio and lowest half life values occurred at 180°C temperature for all foamant water contents. Since higher expansion ratios with acceptable half life values are desired, the temperature of 160°C was considered as the optimum since expansion ratio values were higher at this temperature compared to those at 150°C. While for binder B2, the highest ER (for foamant water contents above 2%) and lowest half life values for all water contents were obtained at temperatures of 160, 170 and 180°C. However, the temperature of 150°C exhibits the highest half life values for foamant water contents 2% and above, thus this was taken as the optimum temperature for B2. For binder B3, the half life values for 150°C were the highest compared to other temperatures, and the optimum foaming temperature was taken as 150°C. The optimum foamant water contents obtained using the Wirtgen approach are shown in Table 5.

**Table 5. Summary of optimum foaming conditions by Wirtgen approach**

<table>
<thead>
<tr>
<th>Bitumen</th>
<th>Temperature (°C)</th>
<th>Foamant water content (%)</th>
<th>Expansion ratio (15)</th>
<th>Half life (16 s)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>160</td>
<td>3.0</td>
<td>2.2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>150</td>
<td>1.6</td>
<td>2.3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>150</td>
<td>1.4</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

NOTE: Average foamant water contents were rounded off to the nearest whole number.
Furthermore, it can be deduced that the optimum binder temperatures (Table 5 and Figure 14) exhibit viscosities that lie within or near the recommended binder viscosity (0.15-0.19 Pas) suitable for mixing with the aggregates (ASTM D2493). This may suggest that foaming at or near the equiviscous temperatures leads to foam with optimum characteristics.

![Binder Viscosity versus Temperature](image)

**Figure 14. Binder Viscosity versus Temperature**

Therefore considering variation of foam characteristics (ER and HL) at the equiviscous temperature, the optimum foamant water content is taken at the point where the break in the ER versus FWC curve first occurs. The ER and HL values at this FWC are obtained and checked against the recommended values, see Figures 15 up to 17. The values of the foam characteristics obtained using this method are summarised in Table 6.
Figure 15. *ER and HL variation versus Foamant water content at equiviscous temperature for B1*

Figure 16. *ER and HL variation versus Foamant water content at equiviscous temperature for B2*
Figure 17. ER and HL variation versus Foamant water content at equiviscous temperature for B3

Table 6. Summary of optimum foaming conditions

<table>
<thead>
<tr>
<th>Bitumen</th>
<th>Temperature (°C)</th>
<th>Expansion ratio</th>
<th>Half life (s)</th>
<th>Foamant water content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>160</td>
<td>22</td>
<td>18</td>
<td>3</td>
</tr>
<tr>
<td>B2</td>
<td>150</td>
<td>17</td>
<td>17</td>
<td>2</td>
</tr>
<tr>
<td>B3</td>
<td>150</td>
<td>20</td>
<td>17</td>
<td>2</td>
</tr>
</tbody>
</table>

The optimum FWCs obtained for the bitumens agree with those obtained by the Wirtgen approach. Therefore determining the foam characteristics (ER and HL) at or near the equiviscous temperature could lead to foam with optimum characteristics.

Thermal aspects

The final foam system temperature, \( T_f \), was estimated using the heat balance equation. The following components of heat energy were identified:

Heat energy required raising water temperature from 20°C up to 100°C:

\[ Q_1 = M_w S_w (100-20) \]

Heat energy required to convert water into steam (latent heat of steam):

\[ Q_2 = M_s S_s \]
Heat energy required raising steam temperature from 100°C up to $T_f$;

$$Q_3 = M_S (T_f - 100)$$

Heat energy lost by bitumen;

$$Q_2 = M_b S_b (T_f - T_b)$$

Heat energy lost by can used to collect foam (foam collection vessel was heated to the same temperature as the bitumen);

$$Q_c = M_c S_c (T_f - T_c)$$

Ignoring heat losses to the surroundings;

Heat lost = Heat gained by water and steam;

$$Q_s + Q_c = Q_1 + Q_2 + Q_3$$

Making $T_f$ the subject;

$$T_f = \frac{-80M_w S_w - M_b S_b + 100M_s S_s + M_s S_b + M_s T_b}{M_s S_s + M_s S_b + M_b S_b}$$

Where: $M_w$, $M_s$, $M_c$, $M_b$ are masses of water, steam, can and bitumen respectively,
$S_w$, $S_s$, $S_c$, $S_b$ are specific heat capacities of water, steam, can and bitumen respectively,
$S_i$ is the latent heat of steam, $T_b$ is bitumen temperature.

Specific heat capacity values were obtained from Wikipedia (2010).

Note: $M_s$ was computed from the Universal gas law, and $M_w$ from the FWC.

From the plots of $T_f$ versus FWC (Figure 18), it can be deduced that the foam temperature reduces as the FWC increases. This is expected as more water is added, more heat energy is taken out of the bitumen and foam collection vessel. In case of B1, the foam temperature tends to increase at bitumen temperatures of 150°C with FWC of 5% and 160°C with FWCs of 4%, 5%. This may be due to less water being converted into steam, which tends to reduce the negative term in the $T_f$ equation, thus increasing $T_f$. This is also reinforced by computations of actual amount of water converted into steam (see Paper II).
Figure 18. Foam Temperature versus Foamant water content for B1, B2 and B3
4.3 Aggregate coating with foamed bitumen (Paper II)

4.3.1 Rice density

As expected, for all binders, the Rice densities for coated fractions were less than the maximum densities of the uncoated aggregate fractions. Statistical analysis of the differences between densities of given different coated aggregate fractions and binders using two way ANOVA at a 5% significance level revealed that the aggregate fraction strongly influenced the Rice densities. While there was no significant difference in Rice densities across the binders. Table 7 shows the Rice density results.

Table 7. Rice densities for coated aggregate fractions

<table>
<thead>
<tr>
<th>Binder</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A1 + A2 + A3</th>
</tr>
</thead>
<tbody>
<tr>
<td>No binder</td>
<td>2646</td>
<td>2672</td>
<td>2749</td>
<td>2678</td>
</tr>
<tr>
<td>FB1</td>
<td>2579</td>
<td>2372</td>
<td>2287</td>
<td>2350</td>
</tr>
<tr>
<td>FB2</td>
<td>2614</td>
<td>2386</td>
<td>2285</td>
<td>2391</td>
</tr>
<tr>
<td>FB3</td>
<td>2573</td>
<td>2369</td>
<td>2294</td>
<td>2307</td>
</tr>
<tr>
<td>HMA</td>
<td>2320</td>
<td>2319</td>
<td>2287</td>
<td>2319</td>
</tr>
</tbody>
</table>

For foamed bitumen binders, the coated aggregate filler fraction A3 gave the lowest density followed by A1 +A2 +A3 (fraction with coarse, sand and filler particles), A2 (sand) and A1 (coarser fraction) with the highest Rice density. Since the lower the Rice density the higher the amount of bitumen and the higher the Rice density the lower the amount of bitumen within a given coated fraction, this implies that most of the binder was concentrated within the filler fraction for foamed bitumen binders. Also, probably due to the differences in aggregate sizes, the smaller (filler) fraction easily attaches itself to the foamed bitumen bubbles unlike the coarse fraction. The large size of the coarse particles may cause the foamed bitumen bubbles to burst easily when they come into contact with the aggregate particles. This in turn may lead to rapid steam condensation forming water onto the aggregate surfaces, this water makes these particles hydrophobic to the binder, however this is still an hypothesis.

Also, it can be observed that when the coarser fraction A1 is heated and used in HMA, the Rice density is on average reduced by 10% compared to A1 coated with foamed bitumen. This may be explained by the temperature effect, the hot coarser aggregate fraction A1 takes more binder when heated than when at room temperature.

Statistical analysis of differences in Rice densities of aggregate fractions coated with foamed bitumen binders, showed that there were no significant differences in densities across the different foamed bitumen binders. However, significant differences occurred across the different aggregate fraction combinations. This may suggest that the aggregate fraction size mainly influenced the Rice densities and thus the aggregate coating. Also, there were no significant differences in Rice densities for A2, A3 and A1 +A2 +A3 aggregate fractions. This may suggest that when various aggregate particles are present within a given mixture, then the binder is better distributed.
In case of the hot mixed aggregate fractions (HMA), there were no significant differences in Rice densities for the different aggregate fractions. This may imply that the aggregate particle coating is similar for the different fractions coated with the HMA. Table 8 shows the output from the one way ANOVA.

**Table 8. One way ANOVA for Rice densities of HMA fractions**

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>Degrees of freedom</th>
<th>Mean square error</th>
<th>F</th>
<th>p-value</th>
<th>F critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between aggregate fractions</td>
<td>1531.92</td>
<td>3</td>
<td>510.64</td>
<td>3.22</td>
<td>0.14</td>
<td>6.59</td>
</tr>
<tr>
<td>Within aggregate fractions</td>
<td>634.68</td>
<td>4</td>
<td>158.67</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2166.59</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Theoretical binder film thickness**

From the Rice density values, the corresponding aggregate effective densities, and thus the effective volume of the binder (total volume of the binder less the amount absorbed) were computed. This effective binder volume was used to estimate the theoretical binder film thickness for each of the aggregate fractions, see Equations 7 up to 10 (Roberts et al., 1996).

Effective density, \( \rho_{se} = \frac{1 - b}{\rho_w} \frac{\rho_w - \rho_{ab}}{\rho_{mn} - \rho_{ab}} \) \[7\]

Where: \( b \) is the bitumen content by total weight of the mix, \( \rho_w, \rho_{mn} \) are water and Rice densities respectively, \( G_{bi} \) is the binder specific gravity.

Binder absorbed by aggregate weight (%), \( P_{ab} = 100 \frac{\rho_{ba} - \rho_{ab}}{\rho_{se} \rho_{ab}} \) \[8\]

Where: \( \rho_{ba}, \rho_{ab} \) are binder and aggregate bulk densities respectively.

Effective volume, \( V_{eff} = V_t - V_{abs} \) \[9\]

Where: \( V_t, V_{abs} \) are binder total and absorbed volumes respectively.

Film thickness, \( \mu m = \frac{1000V_{eff}}{SA W_{agg}} \) \[10\]

Where: \( SA \) is the aggregate surface area, \( W_{agg} \) is the aggregate weight.

The computed theoretical film thicknesses are summarised in Table 9. The coarse aggregate fraction, A1, seems to exhibit the highest film thickness followed by the sand fraction, A2, and then the filler, A3 for both foamed and hot mixed bitumens. However, these results seem to contradict those predicted by the Rice densities, which show that for foamed bitumen, the coated fraction A3 possesses a higher film thickness since most of the binder seems to be concentrated within this...
fraction. This may be explained by the smaller aggregate surface area for the coarser fractions which gives higher film thickness. While the higher aggregate surface area for the finer fraction tends to reduce the thicknesses.

Also, it is observed that the film thicknesses by the HMA fractions are higher than those exhibited by foamed bitumen binders. In addition, coated aggregate fractions A1 and A2 with foamed bitumen binders FB1 and FB3 exhibited higher film thicknesses than those with FB2. This can be explained by the high expansion ratio (for FB3) and viscosity (for B1) values, which lead to thicker film thicknesses onto the aggregate particles. Further, the film thickness of the aggregate fraction constituting all the three sizes (A1+A2+A3) meets the recommended range of 6-8μm for a hot mixture (Read and Whiteoak, 2003).

<table>
<thead>
<tr>
<th>Table 9. Summary of binder film thicknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Binder</strong></td>
</tr>
<tr>
<td>FB1</td>
</tr>
<tr>
<td>FB2</td>
</tr>
<tr>
<td>FB3</td>
</tr>
<tr>
<td>HMA</td>
</tr>
</tbody>
</table>

However, statistical analysis using two way ANOVA revealed that significant differences existed in binder film thickness across the various aggregate fractions at any given binder. However, no significant differences occurred in binder film thicknesses across the binders at any given aggregate fraction. These results are in agreement with those of Rice densities, which revealed that the aggregate fraction mainly influenced the density. Also, there were no significant differences in film thickness for the coated fine aggregate fractions A2 and A3 for all binders. These results may suggest that aggregate particle coating is mainly influenced by the aggregate particle size.

Comparing film thicknesses of coated aggregate fractions with foamed bitumens to those exhibited by the HMA, it can be deduced that on average the thickness for A1 were 50%, 90% for A2, and 100% for A3, (these percentages are expressed as a proportion of the corresponding HMA film thicknesses). This may imply that when film thickness is employed as a design criterion in foamed bitumen mix design, then only the aggregate surface area of size 2.36mm and less need to be considered in computation of the aggregate surface area, this is according to the aggregate tested.

Also, the benefit of heating aggregates seems to be significant for coarser aggregates, as the film thickness for HMA is twice thicker than for the foamed bitumen coated fraction, A1. On the other hand, for finer particles, aggregate temperature does not appear to affect the film thickness, instead for this fraction the surface area mainly influences the film thickness.
4.3.2 Surface energy

The summary of advancing contact angles obtained with three probe liquids, and the computed surface energy components for bitumen and foamed bitumen are shown in Table 10.

Table 10. Summary of Contact angles and Surface energy components

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Advancing contact angles (°)</th>
<th>Surface energy (10⁻³ N/m)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deionised water</td>
<td>Glycerol</td>
<td>Diiodomethane</td>
<td>γ&lt;sub&gt;LW&lt;/sub&gt;</td>
<td>γ</td>
</tr>
<tr>
<td>Bitumen (B2)</td>
<td>95.4</td>
<td>90.0</td>
<td>53.8</td>
<td>29.43</td>
<td>2.31</td>
</tr>
<tr>
<td>Foamed bitumen at maximum expansion</td>
<td>80.2</td>
<td>59.1</td>
<td>34.1</td>
<td>38.85</td>
<td>2.35</td>
</tr>
<tr>
<td>Foamed bitumen after collapse*</td>
<td>93.1</td>
<td>79.8</td>
<td>47.3</td>
<td>32.72</td>
<td>1.85</td>
</tr>
</tbody>
</table>

NOTE: *: slides were coated after steam expulsion

Foamed bitumen gave lower advancing contact angles and higher surface energy components compared to those obtained with neat bitumen (see Table 10). This may suggest that as bitumen is foamed its adhesive abilities are improved, since low contact angles and high surface energy components indicate good wetting. After foam collapse, contact angles increased and surface energy components reduced, tending towards those for neat bitumen. This implies that after collapse foamed bitumen tends to possess similar adhesive abilities as those of neat bitumen.

Also, an increase in the polar component is observed as the bitumen is foamed. This increase in the polar component may result from the water that is produced from steam condensation and the liquid water that still exists within the foam. This can be further supported by computation estimates of water converted into steam and moisture loss results (Paper II), not all water is converted into steam and thus some water still exists within the foam. Although there are possibilities of steam condensation occurring around the glass plate during the sampling exercise for foamed bitumen specimens, it was assumed that these were negligible. However, further research is required to quantify the effects of steam condensation on the polar component of foamed bitumen.

By combining the surface energy values obtained in Table 10 with typical surface energy values of granite aggregates, γ<sub>LW</sub><sup>W</sup> = 56.34, γ⁺ = 43.59, γ = 782.71 (10⁻³ N/m), (Masad et al., 2006), the work of cohesion, work of adhesion (in wet and dry conditions) and compatibility ratio between the bitumen or the foamed bitumen and aggregate fractions were computed (see Table 11). Equation 3 was used to compute the work of adhesion between foamed bitumen and aggregates, while Equation 5 was used to compute the work of adhesion between bitumen and aggregate fractions in wet conditions. It was assumed that the surface energy was independent of the aggregate size.
Table 11. Summary of Work of Cohesion and Adhesion, Compatibility ratio

<table>
<thead>
<tr>
<th>Binder</th>
<th>Work of cohesion (10^{-3} N/m)</th>
<th>Work of adhesion (10^{-3} N/m)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>For foamed bitumen</td>
<td>In dry conditions</td>
<td>In wet conditions</td>
<td>Compatibility ratio</td>
</tr>
<tr>
<td>Neat bitumen (B2)</td>
<td>58.86</td>
<td>101.51</td>
<td>-238.22</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>Foamed bitumen at maximum expansion</td>
<td>84.66</td>
<td>241.47</td>
<td>177.36</td>
<td>-181.52</td>
<td>0.98</td>
</tr>
<tr>
<td>Foamed bitumen after collapse</td>
<td>66.38</td>
<td>303.26</td>
<td>113.52</td>
<td>-229.10</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Note: $\gamma^{W}$, $\gamma^{*}$ and $\gamma$ for water were taken as 21.8, 25.5, 25.5 (10^{-3} N/m) respectively (Hefer et al., 2006). Negative sign indicates release of energy.

Foamed bitumen at maximum expansion gave higher values of work of cohesion and adhesion, compatibility ratio compared to those by neat bitumen (Table 11). This may suggest that foamed bitumen exhibits better coating abilities than neat bitumen. However, no statistical analysis could be made to assess whether these differences were significant, since no replicate samples of foamed bitumen were tested during surface energy measurements.

The magnitude of work of adhesion in wet conditions for the foamed bitumen at maximum expansion is less than that for bitumen and foamed bitumen at collapse. It is desired that this work of adhesion in wet conditions be as low as possible, so as to reduce the displacement of the binder from the aggregate surface (Bhasin and Little, 2007). This may suggest that foamed bitumen at maximum expansion may offer a better resistance to water displacement than neat bitumen. On the other hand, the work of adhesion in wet conditions for foamed bitumen after collapse is similar to that for neat bitumen. This implies that after foam collapse, when a greater portion of water in form of steam has escaped, the foamed bitumen tends to behave like neat bitumen.
4.4 Compaction characteristics of foamed bitumen treated materials (Paper III)

a). Locking point

Since attempts to deduce the original locking point as defined by Vavrik and Carpenter (1998) did not give any exact number of gyrations, the rate of change (gradient of slope) for the compaction curve was used instead. The locking point was then modified and defined as the first point at which two gyrations at the same gradient of slope for the compaction curve were preceded by two gyrations at same gradient of slope. The compaction curve was defined by the relation of average compaction height versus number of gyrations.

For all mixes studied, the compaction height increased rapidly during the initial number of gyrations and then became linear indicating that the rate of change compaction had decreased, Figure 19. From visual observations, it was deduced that the point at which the compaction curve became linear occurred between 25 and 50 gyrations. These points from visual observations aided in identifying the locking points for the different mixes.

The height versus number of gyrations curve for all the three foamed bitumen laterite gravel mixes could be best fitted with a logarithmic relation, Figure 19. From these relations, the gradient of slope as a second derivative was determined at each number of gyrations. The modified locking point was taken as the first point at which two gyrations at same gradient of slope were preceded with two gyrations with the same value of gradient of slope. The number of gyrations at which locking was achieved are summarised in Table 12. The number of gyrations for the mixes at which maximum interlock was achieved varied from 34 up to 44.

![Graphs of L1, L2, and L3](image)

**Figure 19.** Average compaction height versus number of gyrations for mixes
Gradation analysis using wet sieving at the number of gyrations that gave the locking point showed that there hardly any aggregate break down for L3 at 34 gyrations, Figure 20a. While aggregate break down occurred for L1 and L2 laterite gravels at 43 and 44 gyrations respectively, Figure 20a. Further, gradation analysis at 200 gyrations using wet sieving showed that there was aggregate particle break down for all the gravels studied, Figure 20b.

In addition, gradation analysis using wet sieving at 40 gyrations (the average of the modified locking point for all gravels), showed that hardly aggregate particle break down occurred for L3, Figure 20a. While for L1 and L2 aggregate particle break down still occurred, Figure 20a. Hence, even if the number of gyrations are further reduced for L1 and L2, still aggregate break down would occur. It should be noted that although aggregate particle break down occurred for L1 at the modified locking point of 43 and 40 gyrations, but this break down was 38% of that which occurred at 200 gyrations.

![Gradation for laterite gravels before and after compaction at locking point](image)

**Figure 20a.** Gradation for laterite gravels before and after compaction at locking point
Figure 20b. Gradation for laterite gravels before and after compaction at 200 gyrations

From the above, the modified locking point seems to be a suitable point at which to carry out compaction of the laterite gravels treated with foamed bitumen. The procedure for establishing the locking point involves: fitting a logarithmic curve to the compaction data obtained from the gyratory compactor, this is followed by determination of the gradient of slope of the compaction curve. The gradient of slope is obtained by taking the second derivative of the regressed curve. The locking point is identified as the first point at which two gyrations at the same gradient of slope are preceded by two gyrations at the same gradient of slope. In this work, an average of 40 gyrations is recommended as the modified locking point at which to compact laterite gravel foamed bitumen mixes.
b). Compaction optimum moisture content

The dry density increased as the moisture content increased reaching a maximum and then reduced with increasing moisture content. From the plots of dry density versus moisture content at 40 gyrations, the moisture content that gave the maximum dry density was taken as the optimum compaction moisture content for a given mix. The optimum compaction moisture content at the locking point of 40 gyrations, varied from 86% up to 94% of OMC (optimum moisture content of the gravels only) for the different mixes, Table 12. It can be observed that optimum compaction moisture content for compaction is less than the OMC for all the gravels tested, this shows that gyratory compaction of foamed bitumen mixes should be done at moisture conditions below the OMC.

Also, the maximum dry densities for the mixes are less than those for the various laterite gravels only, this can be attributed to the presence of the binder within these mixes that tends to increase the volume which in turn reduces the density. Therefore, future compaction of mixes of laterite gravels and foamed bitumen could be done at the number of gyrations that lead to locking point and optimum compaction moisture conditions.

Table 12. Gyratory compaction conditions

<table>
<thead>
<tr>
<th>Laterite gravels</th>
<th>Locking point (No. of gyrations)</th>
<th>Maximum dry density (kg/m$^3$)</th>
<th>Optimum compaction moisture content (%OMC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>43</td>
<td>1927</td>
<td>91</td>
</tr>
<tr>
<td>L2</td>
<td>44</td>
<td>1852</td>
<td>94</td>
</tr>
<tr>
<td>L3</td>
<td>34</td>
<td>1995</td>
<td>86</td>
</tr>
</tbody>
</table>
5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the findings from this study, the following conclusions were made:

Effects of foaming on bitumen chemistry

Infrared techniques revealed that there were no significant changes in carbonyl and sulphoxides functional groups of the bitumens after foaming. This suggests that foaming the bitumen does not lead to its ageing although factors conducive for ageing exist during its production. This is probably due to the short period of time the bitumen is exposed to ageing factors (water and air). In this study hot bitumen was exposed to water and air in an expansion chamber of the foam plant for a period of 3.8 seconds, which may not be long enough to induce significant ageing to the binder.

Foamed bitumen Characteristics

Foamed bitumen characteristics (ER and HL) seemed to be influenced mainly by the viscosity rather than the bitumen source. Determination of foam characteristics at or near the equiviscous temperature seems to result into optimum foam characteristics. Thus, after binder viscosity determination, the temperature whose viscosity lies within mixing range viscosity (0.15-0.19 Pas) can be taken as the optimum foam temperature. The expansion and half life versus foamanit water content plots are then established for this temperature. The optimum FWC is taken as the point where break in the ER- FWC curve first occurs. The corresponding HL value obtained is checked against the recommended values. Further, theoretical analysis of the thermal aspects of the foam system has shown that foam temperature is less than bitumen temperature, and also not all foamanit water is converted into steam.

Aggregate particle coating with foamed bitumen

Aggregate size fraction mainly influenced the Rice densities and the theoretical binder film thickness of the resulting mixes in case of foamed bitumen binders as revealed by the analysis of variance of Rice densities and thickness. When using film thickness as a criterion in foamed bitumen mix design, only the aggregate surface area for fraction of 2.36mm and less should be considered as foamed bitumen seems to be mostly concentrated in this fraction. Also, when various aggregate particle sizes exist within the aggregate, the binder is better distributed as illustrated by Rice density results and film thickness values that meet the recommended range of 6-8µm. In addition, expansion ratio and viscosity influence aggregate particle coating. Also, aggregate temperature influences the film thickness for coarser particles. While for finer particles the film thickness is mainly influenced by surface area rather than the temperature.

Foamed bitumen seems to possess better coating attributes compared to neat bitumen, as it exhibited lower contact angles and higher surface energy components compared to those of neat bitumen. The work of cohesion and adhesion in dry conditions for foamed bitumen was higher than for neat bitumen. Similarly, the work of adhesion in wet conditions for foamed bitumen was lower than for neat bitumen. This may suggest that foamed bitumen is more likely to form strong adhesive bonds with granite aggregates than neat bitumen. However, the differences were not statistically analysed as no replicate samples were tested for foamed bitumen due to resource constraints.
Gyratory compaction of foamed bitumen treated laterites

The modified locking point is proposed for use in determination of the number of gyrations at which to compact laterite gravels treated with foamed bitumen. This point is deduced from the rate of change of the compaction curve. The procedure for determining this locking point involves: fitting a logarithmic regression curve to the compaction curve, obtaining the gradient of slope for the curve, and then the modified locking point is taken as the first point at which two gyrations at the same gradient of slope are preceded by two gyrations at the same gradient of slope. In this study, the modified locking point varied from 34 to 44 number of gyrations for the mixes studied.

Gradation analysis revealed that there was hardly any aggregate particle break down for one of the laterite gravels (L3) at the modified locking point. Although, some break down occurred for L1, it was much lower than that which occurred at 200 gyrations. It is recommended to use 40 gyrations as the modified locking point and thus as the number of gyrations to compact the laterite gravel foamed bitumen mixes studied.

The optimum moisture for compaction of the mixes at the locking point of 40 gyrations was less than the optimum moisture content for the gravels only (OMC), ranging from 86% to 94% of OMC. Results have shown that gyratory compaction of foamed bitumen treated materials can be carried out at moisture conditions that are less the optimum moisture conditions of the aggregates only, as compaction of the mixes at 100% OMC led to lower densities.

5.2 Recommendations

From this study the following recommendations are made:

Effects of foaming on bitumen chemistry

Further studies should be undertaken on various bitumens that are different in order to gain more understanding of the effects of foaming on the binder, in this study only two bitumens were studied.

Foamed bitumen Characteristics

Further investigation of foam characteristics for bitumens from different sources and grades should be undertaken as only bitumens from two different sources and grades were investigated in this study. Also, the method developed for determination of optimum foam characteristics should be applied to other bitumens in order to test its validity.

Aggregate particle coating with foamed bitumen

More surface energy tests should be undertaken on foamed bitumen specimens as well as the aggregate fractions in order to gain more insight into its surface energy behaviour. Also, adhesive properties of foamed bitumen produced from different bitumens with other aggregate types should be studied. Further research is required to quantify the effects of steam condensation on the polar surface energy component of foamed bitumen, in this work these effects were ignored.
There is need to test the validity of the modified locking concept with foamed bitumen mixes laid in the field. Also, other aggregate types should be tested to validate this proposed method.
References


European Standards, “EN 1427, Bitumen and bituminous binders- Determination of the softening point- Ring and Ball method”, *European Committee for Standardization (CEN)*, 2007.


APPENDED PAPERS