Mix design considerations of foamed bitumen mixtures with reclaimed asphalt pavement material

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ABSTRACT

In the present work, a mix design parametric study was carried out with the aim of proposing a practical and consistent mix design procedure for foamed bitumen mixtures (FBMs). The mix design parameters that were adopted in the study are mixing and compaction water content (MWC), compaction effort using a gyratory compactor and aggregate temperature. This parametric study was initially carried out on FBMs with virgin limestone aggregate without reclaimed asphalt pavement (RAP) material and a mix design procedure was proposed. This proposed methodology was also found to apply to FBMs with RAP. A detailed consideration was also given to characterising the RAP material so as to understand its contribution to the mechanical properties of FBMs. Optimum MWC was achieved by optimising mechanical properties such as indirect tensile stiffness modulus and indirect tensile strength (ITS-dry and ITS-wet). A rational range of 75–85% of optimum water content obtained by the modified Proctor test was found to be the optimum range of MWC that gives optimum mechanical properties for FBMs. It was also found that the presence of RAP influenced the design foamed bitumen content, which means that treating RAP as black rock in FBM mix design is not appropriate. To study the influence of bitumen and water during compaction, modified Proctor compaction and gyratory compaction were employed on mixes with varying amounts of water and bitumen. By this, the work also evaluated the validity of the total fluid (water + bitumen) concept that is widely used in bitumen–emulsion-treated mixes, and found it not to be applicable.

Keywords: Foamed bitumen-treated mixes; mixing and compaction water content; reclaimed asphalt pavement; mechanical properties; volumetrics; water–bitumen interaction

1. Introduction

Unlike for hot-mix asphalt (HMA), there is no universally accepted mix design method for foamed bitumen mixtures (FBMs). Most of the agencies (Wirtgen 2004, Asphalt Academy 2009) which use FBMs have their own mix design procedures which are the result of numerous efforts over decades (Bowering and Martin 1976, Acott 1979, Muthen 1998, Jenkins 2000, Kim and Lee 2006, Ebels and Jenkins 2007, Ramanujam and Jones 2007). In spite of all these efforts, foamed bitumen (FB) application in cold recycling (CR) in the United Kingdom suffers from the lack of a standardised mix design procedure. As a result, the mix design parameters such as foam characteristics, mixing, compaction, curing and testing that are being adopted are far from being standardised. To overcome this, research had been undertaken at the University of Nottingham by (Sunarjono 2008) to develop a mix design procedure by identifying critical mix design parameters. The research by Sunarjono focused on the influence of the bitumen type, the foaming conditions, foam characteristics and mixer type on the mechanical properties of FBM. The major outcomes of the work were recommendations for producing an optimised FBM in terms of mixer type and usage, selection of binder type, bitumen temperature and foam characteristics. Therefore, this present study focussed on other mix design parameters such as FB content, mixing and compaction water content (MWC) and compaction effort. Thus, the primary objective of the present study is to propose a practical and consistent mix design procedure with emphasis on the use of the gyratory compactor.

The amount of water during mixing and compaction is considered as one of the most important parameters in FBM mix design (Bowering 1971, Xu et al. 2012). The MWC of FBM
is defined as the water content in the aggregate when the FB is injected. This helps in dispersion of the mastic in the mix (Brennan 1983, Jenkins 2000). However, too much water causes granular agglomerations which do not yield optimum dispersion of the mastic in the mix (Ruckel et al. 1982, Fu et al. 2010). In view of this fact, many studies have been focused on the optimisation of MWC. Lee (1981) and Bissada (1987) optimised MWC with reference to Marshall stability and found that the optimum MWC is very much dependent on other mix design variables such as the amount of fines and bitumen content. Sakr and Manke (1985) related the MWC to other mix design variables and recommended a relationship among them to obtain optimum MWC. However, this work was performed on a FB-stabilised sand mixture which did not have any coarser fractions of aggregate. Moreover, the work was based on optimising the density, without considering any mechanical properties. The concept of optimum fluid content was later borrowed from emulsion mix design in which the sum of the water and bitumen content should be close to optimum water content (OWC) (Castedo-Franco and Wood 1983, Muthen 1998) obtained by the modified Proctor test. This concept considers the lubricating action of the binder in addition to that of water. Thus, the actual water content of the mix for optimum compaction is reduced in equal measure to the amount of bitumen incorporated. However, the work of Kim and Lee (2006) and Xu et al. (2012), who optimised MWC based on both density criteria and fundamental tests (ITS and tri-axial tests) on FB Marshall specimens, calls into question the lubricating action of bitumen in the mix. Although the above-discussed works are very informative, they have their limitations and little attention has been paid to optimising MWC using gyratory compaction. Therefore, the present work was aimed at obtaining a rational range of MWC for mix design with the help of fundamental tests such as ITS (BS EN 12697-23: 2003) and indirect tensile stiffness modulus (ITSM) (DD 213: 1993) on FBM specimens. Because of the presence of the water phase, the compaction mechanism of FBMs is very different from that of HMA. Various laboratory compaction methods such as Marshall compaction (Brennan 1983, Muthen 1998, Kim and Lee 2006, Xu et al. 2012), vibratory compaction (Shackel et al. 1974, Bowering and Martin 1976, Jenkins 2000), gyratory compaction (Brennan 1983, Maccarrone et al. 1994, Jenkins et al. 2004, Saleh 2006) have been used in the past. There are very well-established guidelines for Marshall compaction (Wirtgen 2004) and vibratory compaction (Asphalt Academy 2009, Wirtgen 2010). However, there are no set guidelines for a gyratory compaction method for FBMs in terms of compaction effort (number of gyrations, gyration angle and applied pressure). Past studies have evaluated the feasibility of using laboratory gyratory compaction on FBM (Table 1). In these studies, efforts were made to obtain the design compaction effort in terms of compaction pressure, gyration angle and number of gyrations. The compaction pressures recommended by Australian guidelines (0.24 and 1.38 MPa from Table 1) were taken forward in Strategic Highway Research Program (SHRP) work on HMA, resulting in recommendations of 0.6 MPa and 1.25° angle of gyration. Jenkins et al. (2004)’s tabulated conditions were based on a single-water content and a single-FB content. From preliminary trials, it was found that the 30 gyrations recommended by Kim and Lee (2006) were too few to achieve modified Proctor densities. The ideal compaction effort has to produce mix densities that are achieved in the field. Therefore, modified Proctor density which is used worldwide to represent field compaction is used as a reference in the present study. It was understood from the past studies (Sunarjono 2008) that the permanent deformation behaviour of FBMs is sensitive to the number of gyrations, which might be attributed to the arrangement of the aggregate skeleton. Hence efforts were made to propose a design number of gyrations ($N_{\text{design}}$) and it was decided to use the SHRP recommended compaction conditions which are 600 kPa compaction pressure and 1.25° angle of gyration. During the optimisation of MWC, the compactability of these mixtures during modified Proctor compaction and gyratory compaction was also studied.

### 2. Materials

Alongside the bitumen and virgin aggregate, particular attention was given to reclaimed asphalt pavement (RAP) characterisation. This is important as RAP characteristics have considerable effect on the mix design of cold bitumen mixtures (CBM) because of the amount of variability associated with RAP in terms of source, production, storage and usage. However, it has to be noted that studies have found that RAP is less variable than virgin aggregate if its storage or stockpiling is well managed and that bituminous mixtures produced with high RAP content are actually less variable (Tebaldi et al. 2014).

It is known that in mix design of HMA containing RAP, the aged bitumen in the RAP is often considered as an active component during the mixing and the bitumen in the new bituminous mixture is adjusted using blending charts. This approach is rational as the mixing of HMA is usually carried out at temperatures above 140 °C where the aged bitumen in the RAP is less viscous. However, this is not the case in CBMs containing RAP, in which mixing and compaction is carried out at ambient temperatures which are much lower than the temperature required for softening the aged bitumen. Hence, each of the different agencies treat the RAP differently in their CBM mix design procedure. Some agencies factor the contribution of the aged bitumen present in RAP, while others do not. This conflicting consideration is due to the unknown effect of the properties of aged bitumen in the RAP on the properties of the added fresh bitumen and on the

### Table 1. Gyratory compaction effort on FBMs by different researchers.

Summary of gyratory compaction effort on FBMs by different researchers

| Number of gyrations (N) | Compaction pressure (MPa) | Gyration angle (degrees) | Reference density |
|-------------------------|---------------------------|-------------------------|------------------|
| (Brennan 1983)          | 20                        | 1.38                    | N/A              |
| (Maccarrone et al. 1994)| 85                        | 0.24                    | 2.25 kg/m³       |
| (Jenkins et al. 2004)   | 150                       | 0.6                     | 2                |
| (Kim and Lee 2006)      | 30                        | 0.6                     | 1.25 Modified proctor density |
| (Saleh 2006)            | 80                        | 0.24                    | 2                | Australian guidelines for HMA |
amount of bitumen to be added. To address these issues, research is ongoing under the initiative of the CR task group (TG6) of RILEM (TC-237 SIB). Most of the tests that were performed on RAP were part of the inter laboratory round robin testing programme on RAP characterisation as a part of TG6.

2.1. Bitumen

In HMA mix design, the expected traffic and the regional climate influence the selection of the bitumen type. However, in FBM mix design, foamability (foaming potential) of the bitumen and the mixture compactability also need to be considered during selection of the bitumen. In the present study, a 70/100 penetration grade bitumen (90 dmm penetration at 25 °C and softening point of 45 °C) was used.

2.2. Virgin aggregates

The virgin mineral aggregate used in this study was carboniferous limestone from Derbyshire, UK. The aggregates were stored separately in stockpiles of size fractions of 20, 14, 10, and 6 mm, dust (0.063 mm < dust > 6 mm) and filler (<0.063 mm). The stocks were batched to attain the design gradation for each of the mixes. Particle size distribution was determined according to BS EN 933-1: 1997. The design gradation adopted in the present study is as plotted in Figure 1.

2.3. Reclaimed asphalt pavement

The RAP material used in the present study was supplied from a UK asphalt contractor. The RAP was from a single source and from a well-managed stockpile before being delivered to the laboratory. The RAP aggregate material from the quarry was initially air dried at room temperature in the laboratory at 20 ± 2 °C for 24 h and then placed in a thermostatically controlled oven at a temperature of 40 °C for 24 h and thereafter sieved into different sizes to improve the consistency of the material and to reduce variability in the RAP. These separated fractions were stored in sealed containers for further use.

The basic properties that are recommended to be measured on RAP for use in HMA mix design are aggregate gradation before and after bitumen recovery, bitumen content, bulk specific gravity of recovered aggregates and recovered binder properties. Obtaining these properties is particularly important in the mix design of CBMs as they often contain high amounts of RAP. In addition to the above-mentioned tests, fragmentation and cohesion tests were recommended by the CR task group (TG6). These two tests are discussed in the following sections.

2.3.1. Analysis on RAP constituents

To determine mass/volume parameters such as voids in mineral aggregate (VMA), the aggregate volume properties have to be known. When RAP materials are included in the mixtures, the determination process becomes more complicated as it is necessary to calculate the bulk specific gravity of each aggregate component (virgin and RAP aggregate). Measuring specific gravity of the RAP aggregate requires extracting the aggregate, recovering the bitumen, sieving the RAP aggregate into coarse and fine fractions, and determining the specific gravity of each fraction. Before bitumen recovery, the initial gradation, which is a basic characteristic of RAP, was ascertained in accordance with BS EN 933-48 2: 2012. To evaluate constituents of the RAP,
a composition analysis was conducted in accordance with BS 598-102: 2003. The aggregates from the RAP were extracted by centrifuge using Dichloromethane as recommended by the standard. After extracting bitumen from the RAP, sieve analysis was carried out on the extracted aggregates. The gradation of the RAP including that of the recovered aggregate is shown in Figure 1.

Once the binder was extracted and recovered from the RAP materials, its properties such as penetration and softening point were determined. To determine the chemical composition of the recovered bitumen, BS 2000 Part 143: 2004 was followed in which the asphaltene contents were precipitated using heptane (C\textsubscript7H\textsubscript16). The results of asphaltene content and physical properties of recovered bitumen are presented in Table 2.

2.3.2. Homogeneity of RAP
Verifying the homogeneity of RAP properties is an important step in quality control when designing bituminous mixtures with RAP. This is particularly true in CR in which high amounts of RAP are often incorporated. Moreover, the mean values of the RAP properties are used to adjust the required grading curve and to select the virgin bitumen. Therefore, homogeneity of RAP in terms of gradation, bitumen content and the properties of recovered bitumen such as penetration, softening point and viscosity was evaluated. Figure 2 shows the gradation of different samples of the RAP before and after aggregate extraction. The figure also shows the standard deviation for each particle size for both RAP and extracted aggregates. As can be seen from the figure, the standard deviations at all sieve sizes are reasonably low (maximum standard deviation is found to be 2.2%). It should be noted that the extracted aggregates from the RAP were found to be less variable than the RAP before bitumen recovery as seen in Figure 2.

Homogeneity of RAP was also evaluated with reference to the limits suggested by NCHRP report 752 (West 2013) and guidelines for the use of RAP in Lithuania (Petrauskas 2006). The standard deviation of recovered bitumen properties and extracted aggregate properties along with homogeneity limits specified by the above-mentioned references are presented in Table 3. As can be seen from the table, the standard deviations are well below the specified maximum limits, which suggest the homogeneity of the RAP used in the study was acceptable. It has to be noted that both the references suggest testing of at least 10 samples. However, in the present study only three samples were tested for homogeneity as recommended by RILEM TG6 technical committee.

2.3.3. Fragmentation test on RAP
The fragmentation test is an impact test which involves a normalised mass falling from a height for a fixed number of times onto the surface of the RAP, and thereafter evaluating the amount of material passing the 1.6 mm sieve. The coefficient of fragmentation is the ratio of the weight of the material before impact and the weight of the material passing the 1.6 mm sieve after impact. The available guidelines for this test are from French standard P 18-574: Granulats – Essai de fragmentation dynamique. The standard requires the test to be carried out at different temperatures on the different sizes of the aggregate. As

![Figure 2. Homogeneity evaluation of RAP in terms of gradation.](image-url)
The modified Proctor compaction involves 56 blows with a standard rammer on each of five layers. The rammer and mould specification are as mentioned in BS EN 13286-2: 2004. The RAP was tested in different size fractions, 14/20 mm, 10/14 mm, and 4.5/10 mm, and at different temperatures, 5, 20, and 40 °C. The test was performed after conditioning the material for 4 h at the test temperature. The results of the tests are presented in Figure 3. As can be seen from the figure, the coefficient of fragmentation has not followed any trend, which indicates that the test results are not, as might have been expected, temperature dependent.

### 2.3.4. Cohesion test on RAP

Further to the above tests, to ascertain if the bitumen in the RAP could be classified as ‘active’ or ‘inactive’, an indicative test was conducted, which is currently under investigation by the RILEM committee. This involved conditioning a sample of RAP for 4 h at 70 °C followed by the manufacture of three 100-mm diameter by 63.5-mm high specimens using Marshall compaction with 50 blows per face. After compaction, indirect tensile strength (ITS) tests in accordance with BS EN 12697-23 were carried out at 20 °C and then in wet conditions, soaked at 20 °C for 24 h. If the soaked ITS ≤100 kPa or the specimens do not hold together after compacting at 70 °C, the RAP is considered to be inactive. For comparison, the test was also conducted with RAP conditioned using a 14-kg mass, lifted mechanically and allowed to fall under gravity on to the top surface of a RAP sample placed in a steel mould of 100-mm diameter and 50 mm height. The number of blows depends on the size of the RAP in the mould. A similar impact test is also recommended in BS EN 1097-2: 2010, which requires material to be placed in a steel cylinder and subjected to ten impacts from a hammer of mass 50 kg freely falling from 400-mm height. The amount of fragmentation caused is measured by sieving the tested material using five specified test sieves. However, in the present case modified Proctor compaction (BS EN 13286-2: 2004) which is also an impact test was employed as recommended by RILEM TG6 technical committee.

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### Table 4. Experimental design for mix design parametric study.

| Mix design parameter | Factorial levels | Remarks |
|----------------------|------------------|---------|
| Bitumen type         | 90pen (70/100 grade) Constant throughout the experiment |
| Target foam characteristics ER = 10 Asphalt Academy (2009) and Sunarjono (2008) |
| Foaming conditions HL (seconds) = 6 Constant throughout the experiment Temperature (°C): 170 Constant throughout the experiment |
| FWC (%) | 3 |
| Mixer type | Pug mill type mixer Constant throughout the experiment |
| Aggregate type | Limestone Constant throughout the experiment |
For HMA, Equation (1) can be applied as it is, as it has only two components, aggregate and bitumen. The weight and volume constituents remain constant throughout and volumetric relationships such as bulk density remain independent of time of test. However, for FBMs in addition to aggregate and bitumen, water also exists in the mixture. But these FBMs lose water with time as can be seen in Figure 5. The figure represents change in constituents (solids, bitumen, water and air) per unit weight and unit volume over time (immediately after compaction (a), after a period of time (b) and in the dry state (c)). As can be seen in the figure, neither weight nor volume constituents remain constant with time. This is because of the presence of the water phase in these mixtures. Hence, dry density ($\rho_d$) was used instead of bulk density ($\rho_b$) in Equation (1) to obtain VMA (Table 5).

$$\text{VMA}(\%) = 100 - \left( \frac{\rho_b \cdot P_s}{\rho_s} \right)$$

(1)

where $\rho_b$ is the bulk density of the specimen; $\rho_s$ is the bulk density of the aggregate (solids); $P_s$ is aggregate content by weight of mix (%).

Figure 5. Change in weight and volume constituents per unit of FBM.

Table 5. Weight and volume constituents per unit of FBM.

| Constituents per unit of FBM with MWC of 85% of OWC and bitumen content of 4% | (a) Immediately after compaction | (b) 48 h at 20 °C after compaction* | (c) dry state |
|---|---|---|---|
| | Weight (%) | Volume (%) | Weight (%) | Volume (%) | Weight (%) | Volume (%) |
| Air | 0 | 4.4 | 0 | 10.4 | 0 | 15.7 |
| Water | 5.5 | 11.3 | 2.5 | 5.3 | 0 | 0 |
| Bitumen | 4 | 8.2 | 4.1 | 8.2 | 4.2 | 8.2 |
| Solids | 90.5 | 76.1 | 93.4 | 76.1 | 95.8 | 76.1 |

*First 24 h in gyratory mould at 20 °C.

3. Methodology

A detailed experimental design was prepared for the study and is tabulated in Table 4. The factors were selected by considering the findings of previous work done at the University of Nottingham (Sunarjono 2008) and Asphalt Academy (2009). The MWC was optimised on gyratory compacted specimens that were compacted to modified Proctor densities. The role of water and bitumen during gyratory and modified Proctor compaction can be analysed by a weight–volume relationship. In the present study, VMA, which is an indicator for compactability is used to understand the role of bitumen and water during compaction. VMA of a compacted specimen can be calculated using Equation (1).

For HMA, Equation (1) can be applied as it is, as it has only two components, aggregate and bitumen. The weight and volume constituents remain constant throughout and volumetric relationships such as bulk density remain independent of time of test. However, for FBMs in addition to aggregate and bitumen, water also exists in the mixture. But these FBMs lose water with time as can be seen in Figure 5. The figure represents change in constituents (solids, bitumen, water and air) per unit weight and unit volume over time (immediately after compaction (a), after a period of time (b) and in the dry state (c)). As can be seen in the figure, neither weight nor volume constituents remain constant with time. This is because of the presence of the water phase in these mixtures. Hence, dry density ($\rho_d$) was used instead of bulk density ($\rho_b$) in Equation (1) to obtain VMA (Table 5).

3.1. Mixing

FB begins to collapse rapidly once it comes into contact with relatively cold aggregates. Therefore, the mixing process should be a dynamic one. Consequently, FB is most often applied directly from the laboratory foaming plant to the aggregate as it is being agitated in the mixer. As different mixers can produce up to a 25% difference in strength (Asphalt Academy 2009), selection of
an appropriate mixer is very important in the production of FB mix. It is always recommended to utilise a mixer that simulates site mixing. Pug mill drum mixers and milling-drum mixers are the most commonly used mixers on site for the production of FBM. These mixers provide sufficient volumes in the mixing chamber and energy of agitation to ensure better mixing (Jenkins 2000). A pug mill-type mixer is therefore recommended for production of FBM representative of the field (Long et al. 2004). Hence, a twin-shaft pug mill mixer was adopted in this work (operated at 20 ± 2 °C). Mixing time should be in accordance with the time required by the bitumen foam to collapse. In the laboratory, a mixing time of 60 s has been recommended (Bissada 1987) which is longer than in situ mixing but simulates the difference in the energy of the laboratory mixer and field plant and the same (60 s mixing time) was adopted in this study.

The optimisation of MWC was carried out on specimens compacted using the gyratory compactor to densities that were obtained by modified Proctor compaction. Targeting modified Proctor densities meant that all specimens were compacted to the same compaction effort. This approach was considered suitable as it is not appropriate to compact mixtures with different water contents to the same density as they would need very different compaction efforts. For example, mixtures with 100% of OWC (6.5% by weight of mixture) needed 200 gyrations to compact to MDD while a mixture with 65% of OWC (4.25% by weight of mixture) required around 340 gyrations. Hence, modified Proctor compaction was carried out on aggregate and water mixtures in accordance with BS EN 13286-2: 2004. The results of the modified Proctor compaction can be seen Figure 6, including results of modified Proctor compaction on mixtures with RAP. As can be seen from Figure 6, the OWC for 100% virgin limestone aggregate (VA) mixtures was found to be 6.5% and for mixtures with RAP the OWC was around 6%.

Once OWC from modified Proctor compaction had been obtained, mixing was carried out with varying water content (65, 75, 85, and 95% of OWC, which corresponds to 4.2, 4.9, 5.5, and 6.2% water content in the mixture) and varying FB content (2, 3, 4, and 5%). These mixtures were compacted using modified Proctor compaction; densities were obtained and the results for 100% VA are presented in Figure 7. After obtaining the densities, these possible combinations of mixtures were mixed and compacted using a gyratory compactor (angle of gyration...
1.25° and compaction pressure 600 kPa) using different numbers of gyrations to obtain the achieved modified Proctor densities. Gyratory compacted moulds after compaction were kept at room temperature for 24 h and then the specimens were extracted. The extracted specimens were cured at 40 °C and the water content of the specimen was monitored over time. Mechanical tests were carried out (at ambient room temperatures of 20 ± 2 °C) on the cured specimens after 3–5 days depending on the amount of water in the specimen. The tests were carried out on all specimens at approximately the same water content (between 0.6 and 0.65%) to eliminate the effect of water content on the measured mechanical properties. The effect of mixing water content on the mechanical properties can be seen in the plots in Figure 8.

The mechanical properties (ITSM, ITS-dry and ITS-wet) of gyratory-compacted and cured specimens are plotted against MWC in terms of (%) of OWC in Figure 8. Each ITSM value in the plot is an average of tests on eight specimens and ITS-dry and ITS-wet are averages of four specimens. The properties were all measured at the same water content (0.6–0.65%). As can be seen from the figures, the approximate peak ITSM values were 85% of OWC, except for 2% FBM (FBM with 2% FB content). When ITS-dry results were considered, the optimum MWC was seen at 85% of OWC for 2 and 3% FBM; and for 4 and 5% FBM the peak was at 75%. For ITS-wet values, the optimum was found at 85% except for 5% FBM. Overall, the optimum MWC for all mixtures was consistently found to lie between 75 and 85% of OWC.

### 3.1.1. Compaction effort

As discussed in the earlier sections, one of the objectives of this study was to propose a design number of gyrations ($N_{design}$) for FBM mix design. For this, aggregate mixtures with 80% of OWC (based on the 75–85% range established above) and different FB contents were prepared. Then the mixtures were compacted to 200 gyrations and densities were plotted against number of gyrations as shown in Figure 9. From the data, the number of gyrations required to reach modified Proctor density was identified as can be seen in Figure 9. To study the optimum compaction effort and to obtain the design number of gyrations ($N_{design}$), the changing height was recorded from the gyratory compactor during compaction. From the height data, density was calculated and plotted against number of gyrations (Figure 9). The marks on the curves are the target densities that were obtained from modified Proctor data. It can be seen from the plots that though the target densities were different the number of gyrations required to compact to those target densities are in a similar range. That means, a design number of gyrations required to compact to modified Proctor density can be established, independent of FB content in the mixture. $N_{design}$ for all FBMs considered was in the range of 120–160 gyrations; 140 gyrations have therefore been selected as giving an equivalence to modified Proctor.

### 3.1.2. Compactability of FBMs

The compactability of FBMs was studied on mixtures with varying amounts of bitumen and water. As discussed previously, the

**Figure 8.** Mechanical properties of 100% VA-FBM with varying FB and water content.
modified Proctor compaction and gyratory compaction methods were considered. The study enables the role of bitumen and water with these compaction methods to be understood. As seen in Figure 10, from tests on modified Proctor compacted specimens, all curves give OWC. However, that optimum differs only slightly from one bitumen content to another, implying that the bitumen hardly contributes to the 'fluid' needed for compaction. The same effect can be seen in terms of volumetrics in Figure 11, where VMA is plotted against total fluid (water + bitumen). The optimum shifts to the right in steps and the shift is around 1% for the 2, 3, 4 and 5% FB curves, again implying negligible contribution from the bitumen.

A similar picture is obtained from the volumetrics of gyratory compacted specimens. To study the gyratory compaction, the FBMs were compacted to 140 gyrations with an angle of gyration of 1.25°, compaction pressure of 600 kPa and 30 rpm. The compactability was studied using weight–volume relationships and voids in aggregate VMA as calculated by Equation (1). VMA at 140 gyrations for mixtures with different bitumen content is plotted against MWC (dashed lines) in Figure 10 (each point is an average of five data points), alongside the data from modified Proctor compaction (solid lines). As can be seen from the figure, the VMA of the specimens at
a study has been conducted on mixtures with RAP (50 and 75% RAP-FBM) to validate the proposed recommendations. To validate the MWC range proposed (75–85% of OWC), aggregates with 50 and 75% RAP and 4% FB were mixed and compacted with varying MWC (95, 85, 75, and 65% of OWC) to modified Proctor densities of similar mixtures. 4% FB was selected as it was the design FB content obtained for 100% VA mixes and it was assumed that the presence of RAP would not affect the design FB content (an assumption that was later shown to be incorrect). The specimens were cured as discussed for 100% VA-FBMs. The results of mechanical tests carried out on cured specimens are presented in Figure 12. These tests were performed at ambient room temperature of 20 ± 2 °C. ITSM values shown in figure are the average of 10 tests, while ITS-dry and ITS-wet are the average of 5 tests each. As can be seen from the figure, the optima for ITSM and ITS-dry were found at 75% of OWC and 85% of OWC, respectively. For 75% RAP-FBM, optimum ITS-dry and ITS-wet were found at 75% of OWC. Although ITS-wet for 50% RAP-FBM and ITSM for 75% RAP-FBM did not show optimum was almost the same in the two cases, very slightly greater for modified Proctor compaction, and it increased as the FB content increased. The OWC was also typically slightly higher in the case of gyratory compaction, thought to be due to the significant difference in the way the two compaction processes operate.

Overall, however, the clear implication is that the bitumen gives minimal contribution during compaction and that this phenomenon is observed for both the compaction methods that were considered. Thus, the total fluid content, which has been successfully used in bitumen–emulsion mix design (McNerney and Rioux 2000, Haas et al. 2001, Flintsch et al. 2004), is not a valid parameter in FBM mix design.

3.2. Mechanical properties of FBMs with RAP

The mix design parametric study discussed in the previous sections was done on mixtures with VA (100% VA-FBM). In this section, the tests carried out on cured specimens are presented in Figure 12. These tests were performed at ambient room temperature of 20 ± 2 °C. ITSM values shown in figure are the average of 10 tests, while ITS-dry and ITS-wet are the average of 5 tests each. As can be seen from the figure, the optima for ITSM and ITS-dry were found at 75% of OWC and 85% of OWC, respectively. For 75% RAP-FBM, optimum ITS-dry and ITS-wet were found at 75% of OWC. Although ITS-wet for 50% RAP-FBM and ITSM for 75% RAP-FBM did not show
any clear optimum, other properties of both the mixtures have their optimum in the proposed range (75–85% of OWC).

To validate the $N_{\text{design}}$, the aggregates with RAP were mixed and compacted with 0, 3 and 4% of FB and the density data is plotted in Figure 13. For clarity, the figure shows only data for 75% RAP-FBM with 0 and 3% of FB; the data for 4% FB lies in the same region on plot. It can be seen that the $N_{\text{design}}$ range is the same, i.e. between 80 and 120 gyrations. The mid-point of this range which is 100 was considered as $N_{\text{design}}$. The study conducted on 50% RAP-FBM gave $N_{\text{design}}$ as 110 gyrations.

### 3.3. FB content optimisation

The results of mechanical tests on the mixtures that were compacted at optimum MWC (80% of OWC) and to $N_{\text{design}}$, and varying FB content, are plotted in Figure 14. As can be seen in the plots, there is a clear optimum ITSM value for all mixtures. For 100% VA mixtures, the optimum was found at 4% FB content. Similarly, the optimum ITSM values for 50 and 75% RAP mixtures were found at 3.5 and 3% FB content, respectively. If ITS-dry values are considered, there was no optimum for 100% VA mixtures. ITS-dry values for these mixtures increase with increasing FB content without any optimum value. However, an optimum could be located for both the mixtures with RAP (50 and 75% RAP). The optimum values were found at 3.5 and 3% FB, respectively. When ITS-wet results are considered, the optimum ITS-wet was found only for 75% RAP mixtures, which is at 3% FB content. There was no optimum for any mixtures if indirect tensile strength ratio (ITSR) was considered. However, it can be noted that though the maximum ITSM value was higher for 100% VA than for mixes with RAP, most maximum ITS and ITSR values were found to be superior for mixes with RAP. This indicates that the mixes with RAP have better resistance against water than mixes without any RAP. This could be
attributed to the presence of fully bitumen coated RAP aggregates in the mixture. Overall, it was clear that at 4 and 3% FB contents, optimum mechanical properties were found for 100% VA and 75% RAP mixtures, respectively. However, optimum FB content was less clear for 50% RAP mixtures.

### 3.4. Effect of aggregate temperature on mechanical properties

Temperature of the aggregate during the mixing phase influences significantly the quality of FBM (Cazacliu et al. 2008). Because of this reason, it has been recommended to construct pavements with FBM only if the ambient temperature is above 10 °C (Asphalt Academy 2009, Wirtgen 2010). As was mentioned previously, the present experimental study mostly involved mixing and compaction at an ambient temperature of 20 ± 2 °C. However, this section has analysed the effect of aggregate temperature (which is also mixing temperature in the field) on the mechanical properties of FBM with 50% RAP aggregate (50% RAP-FBM). The mixing was carried out at three aggregate temperatures (5, 20, and 30 °C). Before mixing, the aggregates were conditioned at the required temperature overnight (around 18 h). The resulting temperatures of the mixtures after foaming and mixing were found to be 10, 26, and 31 °C, respectively, for aggregate temperatures of 5, 20,
and 30 °C. The mixtures were then compacted at an ambient room temperature of 20 ± 2 °C. The mechanical tests were carried out on samples that were extracted after 24 h and cured at 40 °C for 72 h (3 days). The results of the mechanical tests and volumetric properties of the cured specimens can be seen in Figures 15 and 16.

As can be seen in Figure 15, aggregate temperature has significance influence on compaction (air voids) and stiffness (ITSM) of the FBM. The lower aggregate temperatures resulted in inferior mixture properties. Though the difference is not significant from 20 to 30 °C, the aggregate temperature of 5 °C clearly resulted in higher air voids and less stiff mixtures. Similar results were also found when comparison was made in terms of strength (ITS-dry and ITS-wet) (Figure 16). Moreover, the retained strengths (ITSR) increased with increase in aggregate temperature, which reinforces the finding of poor mixing and compaction at lower aggregate temperature.

The major determinate for poor mixing at low aggregate temperature is the high temperature gradient between the aggregate and the FB which influences the rate of collapse of the foam. A high temperature gradient causes rapid collapse of the foam as the film of the bitumen bubbles is thin, which allows rapid heat transfer between FB and aggregate. Consequently, less time is available for FB to interact with the aggregate resulting in poor coating of the aggregate particles and inconsistent dispersion of the mastic in the mixture. As can be seen in Figure 15, the high temperature aggregates resulted in lower air voids in the resulting specimens. These higher densities (low air voids) could be associated with better compactability of the mixture at higher temperatures. As discussed the higher aggregate temperatures resulted in mixtures with relatively higher temperatures which help in obtaining denser specimens (Ruckel et al. 1982, Jenkins 2000). However, it has to be noted that the difference in densities between aggregate temperatures of 20 °C and 30 °C was found to be marginal.

4. Conclusions

This paper has focused on the development of a practical and consistent mix design procedure for FBM with the main focus being on the use of the gyratory compaction method in the proposed methodology. The study also evaluated the effect of the aggregate temperature on the mechanical properties of the FBM. To attain this objective, the mix design parameters such as MWC and compaction effort have been optimised. This mix design parametric study was initially carried out on FBM with VA without RAP material and a mix design procedure was proposed. The proposed methodology was later validated on FBM with RAP.

In the present study, particular attention has been given to RAP characterisation. The tests on recovered aggregate and bitumen revealed that the RAP was well within the homogeneity limits recommended by different agencies. A cohesion test revealed that the RAP used in this study can be classified as active.

A rational range of 75–85% of OWC obtained by the modified Proctor test was found to be the optimum range of MWC that gives optimum mechanical properties for FBM. As this study focused on the use of the gyratory compactor for FBM compaction, efforts were made to suggest a design number of gyrations ($N_{design}$) for optimum compaction of FBM. It was found that a unique $N_{design}$ (mixture specific) which is independent of the FB content can be established. $N_{design}$ for the virgin mixture was found to be 140, while $N_{design}$ for the mixtures with 50% of RAP and 75% of RAP was 110 and 100, respectively. It was also found that the presence of RAP influenced the design FB content, which means that treating RAP as black rock in FBM mix design is not appropriate.

This work also evaluated the validity of the total fluid (water + bitumen) concept which is widely used in bitumen–emulsion-treated mixes. It was observed that the bitumen gives minimal contribution during compaction and that this phenomenon was observed for both the compaction methods that were considered. Thus, the total fluid content, which has been successfully used in bitumen emulsion mix design is not a valid parameter in FBM mix design.

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