An investigation using idealised rubber-bitumen composite mixtures to assess the influence of short-term rubber-bitumen interaction on dry process CRM asphalt mixtures

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ABSTRACT: A laboratory study was conducted on idealised rubber-bitumen composite mixtures to study the influence of short-term, rubber-bitumen interaction on the mechanical and rheological properties of crumb rubber modified (CRM) asphalt mixtures. A series of rubber-bitumen composite mixtures using four different types of bitumen (soft to hard grade and different crude sources) and one single source of rubber (2-8 mm truck tyre crumb) were produced and their dynamic mechanical properties (complex modulus and phase angle) were evaluated. A novel technique was introduced to design the composite, which reflects the realistic proportion of rubber and bitumen in actual dry process CRM asphalt mixtures. The results indicated that the mixture stiffness is mostly influenced by the testing temperature and only marginally dependent on test frequencies. In terms of bitumen types, the stiffness reduction was significantly higher for mixtures with softer bitumens. In addition, it was found that, the stiffness for all composite mixtures decreased due to the combined effect of short-term ageing and voids content. The phase angle, on the other hand, was found to be predominantly influenced by the rubber component.

KEY WORDS: Asphalt, crumb rubber, dry process, rubber-bitumen interaction.

1 INTRODUCTION

Dry process crumb rubber modified (CRM) asphalt mixtures are composed of aggregate, large crumb rubber particles (2 to 8 mm), filler and bitumen in various proportions. In the dry process, crumb rubber is used as a partial aggregate substitute and it therefore carries loads (stresses) induced by the traffic. The mixture configuration is different from conventional asphalt mixtures as the incorporation of crumb rubber particles allows the mixture to accommodate larger strains because of the inherent resilient nature of rubber. Both rubber and aggregate are “glued” together in the mixture by the bitumen and, therefore, the performance of the mixture depends on the performance of each component as well as the composite.

However, there is an extra complication with the partial replacement of aggregate with rubber particles in that there is an interaction between the rubber and bitumen during the mixture production. Research studies on rubber-bitumen interaction using a basket drainage method have confirmed that at high temperatures, rubber absorbs the lighter fractions of bitumen through a diffusion process and as a result, residual bitumen becomes more elastic and stiffer (Airey et al. 2003, Rahman et al. 2006). These changed residual properties of the bitumen may well affect the performance of the mixture. The rubber-bitumen interaction is a diffusion process, which consists of the bitumen first entering the outer shell of the particle before eventually entering the centre until equilibrium swelling is achieved, but the shape of the cross-linked network remaining the same. The rate of swelling depends on the particle size of the rubber and the concentration of the solvent (Southern, 1967, Green and Tolonen 1977). The diffusion of solvents may also soften the rubber while at the same time increasing its elasticity (Flory and Rehner 1943). All these factors cause rubber particles to swell and ultimately for the mixture to lose effective bitumen from the system and become less workable.

To investigate the influence on the mechanical properties of the rubber-rubber composite following rubber-bitumen interaction, an attempt has been made to produce an idealized but realistic rubber-bitumen mixture to understand the affect of the short-term high temperature curing on the composite. The paper describes the development of a composite mixture that realistically simulates actual bitumen proportions in dry process asphalt mixtures. The paper then investigates the changes in mechanical properties due to short-term interaction between rubber and bitumen and the influence of other variables such as bitumen type and grade, stress level, loading frequency and test temperatures on the mechanical properties.

2 SAMPLE PRODUCTION

2.1 Materials

The experimental programme consisted of producing rubber-bitumen composite mixtures using four different bitumens and a single source of crumb rubber from recycled truck tyres. The bitumens were chosen to cover high penetration (160/220 pen) and low penetration (40/60 pen) grades from two sources (Middle East and Venezuelan). The following bitumens were used in this study:

- ME-soft – Middle East 160/220 pen bitumen,
- Ven-soft – Venezuelan 160/220 pen bitumen,
- ME-hard – Middle East 40/60 pen bitumen,
- Ven-hard – Venezuelan 40/60 pen bitumen.

The crumb rubber used in this study was 2-8 mm in size with the gradation as shown in Table 1.

Table 1. Granulated crumb rubber gradation

Sieve Size (mm)	Cumulative Percentage Passing (%)
9.5	100
6.3	70
2.36	30
1.18	0

2.2 Mixture Design

The rubber-bitumen composite mixtures were designed to have similar bitumen film thickness as would be found in a dry process CRM asphalt mixture. This was achieved by calculating the theoretical bitumen film thickness of a typical dry process CRM asphalt mixture from the whole mixture matrix that could be utilised to estimate rubber-bitumen proportions. To do that, the following assumptions were made:

- A constant bitumen film thickness (BFT) is achieved throughout the asphalt mixture matrix. In other words, there is enough bitumen in the system to cover all particles to an equal depth.
- BFT for aggregate is equal to BFT of rubber (Figure 1a)
- BFT is constant for all sizes of rubber particles (Figure 1b)

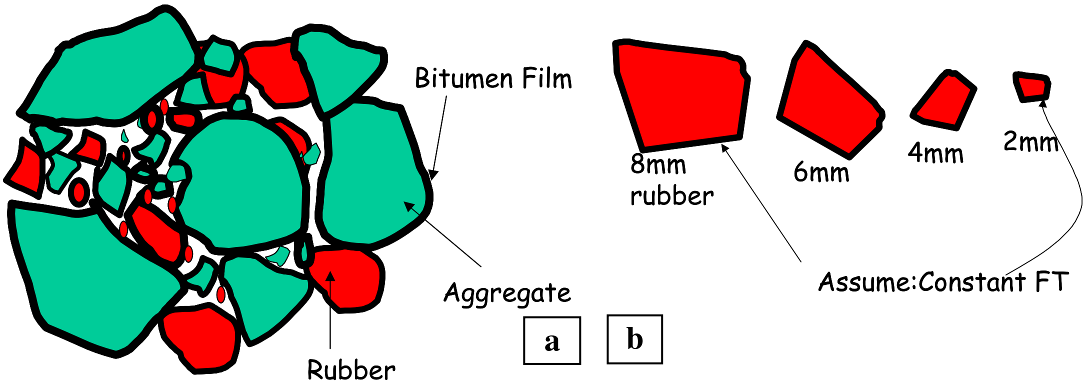


Figure 1: Schematic of bitumen film thickness in the mixture and rubber particles

BFT was calculated using the Shell formula presented in Equation 1 (Read et al. 2003) for the whole asphalt mixture matrix. This film thickness was then utilized to determine the isolated rubber-bitumen proportion compared to the actual mixture.

$$T = \frac{b}{100-b} \times \frac{1}{SG_b} \times \frac{1}{SAF} \tag{1}$$

Where T is the bitumen film thickness (µm), SG_b is the specific gravity of bitumen, b is the bitumen content (% by mass) and SAF is the surface area factor (m^2 / kg) developed by Hveem for an assumed spherical particle of aggregate and a specific gravity of 2.65 (ASTM, 1992). SAF is therefore calculated for each particle size as:

$$SAF = \frac{A}{M} \tag{2}$$

Where A is the cross-sectional area of the spherical particle (m^2) and M is the mass of the particle (kg).

The bitumen content was chosen as 6.5 % by mass of the mixture as literature suggests that bitumen content for CRM mixtures is typically 10-20% higher than conventional hot mix asphalt mixtures due to greater binder affinity of rubber at high temperature (Epps, 1994, FWHA, 1997). The specific gravity of rubber was taken as 1.1, determined from a specific gas jar protocol based on BS1377: part 2:1990:8:2. The specific gravity of bitumen, on the other hand, was supplied by the manufacturer as 1.01. Table 2 shows SAF factors for aggregate and rubber.

To calculate SAF for aggregate, it was assumed that 50% of the particles are >4.75mm and 50% are 2.36mm. On the other hand, for rubber, it was assumed that 70% of the particles are >4.75mm and 30% are 2.36mm. This assumption was found reasonable as sieve analysis of the rubber particle showed 70% of the particles are greater than 2.36mm.

After calculating *T* for the whole mixture matrix, a new *SAF* was calculated for the rubber alone using the specific gradation of rubber as presented in Table 1. Finally, Equation 1 was rearranged to calculate the bitumen content (by mass) for the rubber-bitumen composite mixture.

Table 2. Surface area factors for aggregate and rubber

Sieve size (mm)	SAF	
	Aggregate (Read et al. 2003)	Rubber (calculated)
0.075	32.77	78.95
0.15	12.29	29.61
0.3	6.14	14.79
0.6	2.87	6.91
1.18	1.64	3.95
2.36	0.82	1.98
>4.75	0.41	0.99

2.3 Pre-Compaction Short-Term Ageing

Three different batches of rubber-bitumen material were prepared using a temperature controlled sun-and-planet type mixer. Pre-heated bitumen (160°C to 170°C) and the required quantity of rubber was placed in the mixer and mixed for approximately six minutes at 160^0C. The fully coated mixture was then placed inside a thermostatically controlled oven before compaction. The mixtures were kept inside a thermostatically oven for 0, 2 and 6 hours to simulate typical durations that the mixture would be held at high temperatures during mixing, transportation and laying prior to compaction. Initially, the curing temperature was chosen at 135^0C to simulate typical short-term ageing for asphalt mixtures (Scholz, 1996), but it was found that the rubber particles stuck together and were difficult to compact. To minimise this problem, short-term ageing was conducted at 160^0C. However, ageing at 160^0C would increase the rate of reaction especially for the composite with softer bitumen. Therefore, to reduce the effect of excessive ageing, the calculated bitumen film thickness was increased by 20% during the design process. This resulted in rubber-bitumen composites consisting of 15% by mass of bitumen and a corresponding rubber mass of 85%.

2.4 Compaction

A sample geometry of 150 mm height by 75 mm diameter was chosen to suite the height to diameter ratio of 2:1 required to eliminate the instability and shear plane effects from the specimen boundaries during triaxial testing (Punmia, 1996). Specimen manufacture was achieved by compacting rubber-bitumen mixtures in a preheated (160°C) cylindrical split mould. The split mould was used as it was easier to remove the specimen after compaction without disturbing the actual mixture matrix. In addition, a non-evaporating heat resistant grease was used to lubricate the inner surface of the mould to prevent sticking of the mixture during compaction.

After filling the material in the cylindrical split mould, a wooden platen was placed on top of the specimen to provide an even surface for compaction. A steel loading head was then marked and placed on top of the wooden platen to ensure that the sample reached a target height of 150 mm at the required compaction effort. The loading head was also useful to avoid any eccentricity during compaction.

The compaction was achieved by applying a maximum static load of 15 kN. The mould was insulated during the compaction process to minimise heat lose. The procedure consisted of applying approximately 15kN load for the first 10 minutes and then turning the mould upside down to apply 15kN for a further 10 minutes on the other end. In both cases, the loading head was positioned accurately to ensure that the sample reached its target height. In addition, immediately after compaction, a dead load of 5kg was applied for a further 24 hours to provide enough time for the sample to reach room temperature. The samples were removed from the split moulds after 24 hours curing and stored at 5^0C for future testing. Examples of the compacted samples are shown in Figure 2.

Figure 2: Composite rubber-bitumen specimens

3 TESTING PROGRAMME

3.1 Test Arrangement

A triaxial testing arrangement located in a temperature controlled room was used to determine the linear stress-strain, dynamic mechanical properties of the rubber-bitumen composite mixtures following various conditioning regimes (different short-term ageing times). The axial load was applied through a piston connected to a hydraulic actuator. A load cell was located on the piston above the triaxial cell. Position control was achieved through a long range LVDT located on top of the frame, connected to the load ram to provide the feedback signal.

Lateral restraint (support) was provided to the rubber-bitumen composite sample by means of an impervious latex membrane. No extra confining stress was provided as the effect of the membrane was found to supply a confining stress of 4 to 5 kPa (Thom, 1988). This lateral support was considered sufficient to maintain the integrity of the sample during axial loading.

3.2 Test Protocol

Four different rubber-bitumen mixtures (hard and soft bitumen with one rubber type and a fixed rubber to bitumen ratio) were used to investigate the effect of bitumen crude sources and grades on the mechanical interaction. Each specimen was conditioned for at least two hours at test temperature prior to testing and then tested under sinusoidal loads (stresses) over a range of frequencies and temperatures. The resultant vertical displacement (strain) was measured using a LVDT in order to calculate complex modulus and phase angle. The detailed testing protocols are as follows:

- Pre compaction short-term ageing – 1, 2 & 6 hours,
- Test temperature – 5, 20 & 35°C,

- Stress level – 10, 20, 30, 40 & 50 kPa, and
- Testing frequency – 0.2, 0.5, 1, 2 & 5 Hz.

4 EXPERIMENTAL RESULTS AND ANALYSIS

4.1 Volumetric Consistency

Fifteen samples were produced in three series to study the consistency of the production process. Samples in each series were produced after 0, 1, 2, 4 and 6 hours of curing at 160°C using the mixture design procedure (Section 2.2), and then compacted and cured with same the procedure as outlined in Sections 2.3 and 2.4.

For each specimen, the theoretical maximum density ($\rho_{\max}$) and bulk density (ρ) was calculated using Equations 3 and 4.

$$\rho_{\max} = \frac{M_T}{\frac{M_R}{SG_R} + \frac{M_B}{SG_b}} \tag{3}$$

$$V_v = (1 - \frac{\rho}{\rho_{\max}}) \times 100 \tag{4}$$

Where, M_T: mass of total rubber plus mass of bitumen, M_R: mass of rubber, M_B: mass of bitumen, SG_R: specific gravity of rubber, SG_B: specific gravity of bitumen, V_v: voids in total mixture.

It should be noted that the bulk density of the compacted samples was calculated by measuring the dimensions of the specimens, as conventional methods to seal the specimen with self-adhesive aluminum foil was found unsuitable for rubber-bitumen composite mixtures. The average of five measurements (height and diameter) was used to calculate the volume and a high accuracy balance was used to measure the mass of the compacted specimen. Figure 3 presents the voids profile of composite samples produced using ME-hard bitumen against short-term curing period. The voids profile for all three series of tests show similar trends ensuring the consistency of the adopted sample production procedure.

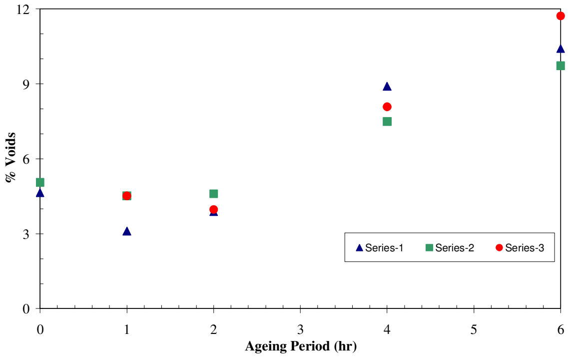


Figure 3: Voids profile of ME-hard composite mixture

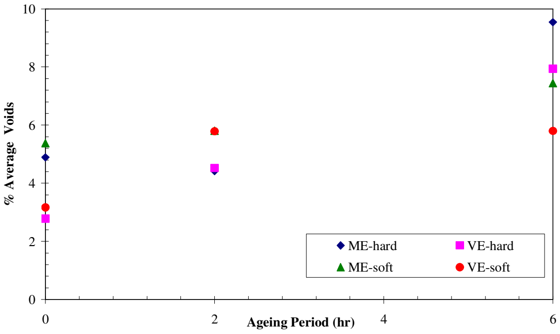


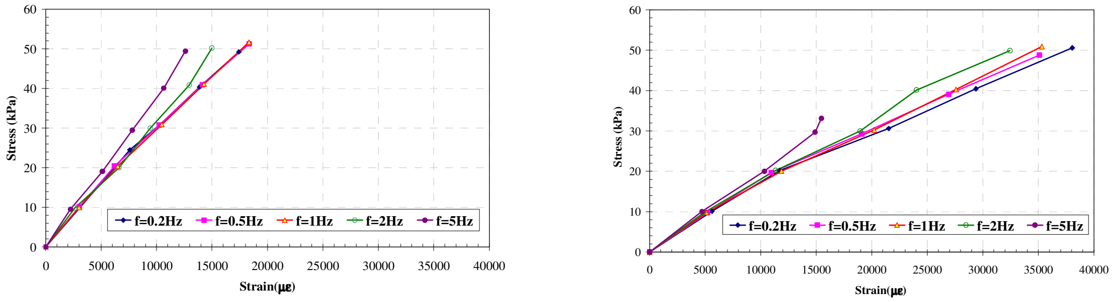
Figure 4: Voids profile of different composite mixtures

Figure 3 also demonstrates the influence of short-term high temperature curing on the loose composite mixtures. It can be seen that the percentage air voids increased due to ageing of the mixture. The results also show that the change of volumetric is slow in the first two hours but changes significantly as curing time increases. This may have an effect on the mixture performance as the conventional transportation and laying period can be up to six hours.

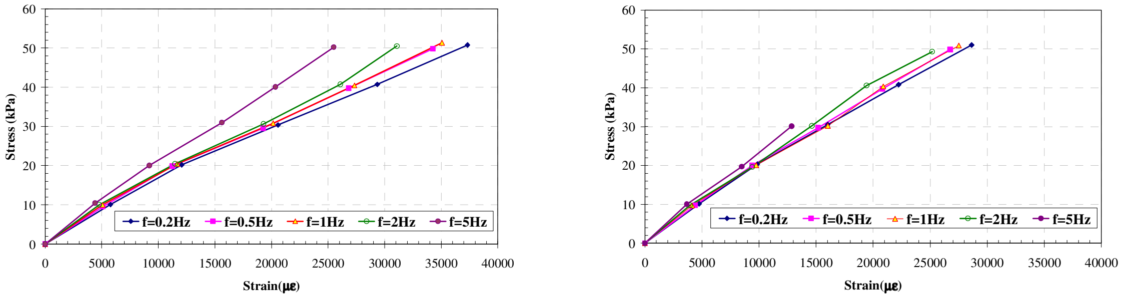
The investigation was also carried out on different composite mixtures. Two specimens for each composite mixture were produced following 0, 2 and 6 hours high temperature conditioning. The calculated average voids versus curing time for each mixture is presented in Figure 4. It can be seen that samples with harder bitumen become more voided due to curing in the loose stage compared to samples produced using softer bitumen. The result indicates that the absorption of the lighter fractions of bitumen has more effect on harder bitumen (contains more asphaltenes) compared to the softer one (contains more aromatics) and, therefore, overall workability of the mixture is reduced.

4.2 Stress-Strain Dynamic Mechanical Response

Selected stress-strain plots of the composite mixture are presented in Figure 5 for three ageing conditions tested at different temperatures. Similar relationships were plotted for all other mixtures and it showed that, in general, at low stress levels, the response of the mixture is not exactly linear with the very high degree of elasticity generating high strains. It is important to note that rubber-like material behaves as a linearly elastic substance at very small strains although there is no agreement as to how small the "small" strains may be (Sommer and Yeoh 1992). Sommer and Yeoh also reported that fitting the best straight line to experimental stress-strain data could be used to calculate stiffness for practical purposes.



a: Mixture ME-hard-0-T5 **b:** Mixture ME-soft-2-T20



c: Mixture VE-hard-6-T20 **d:** Mixture ME-hard-0-T35

Note: ME-hard-0-T5: Mixture with 40/60 grade Middle East bitumen, 0-hour high temperature conditioning at loose stage and tested at 5^0C

Figure 5: Stress-strain diagram for different mixtures

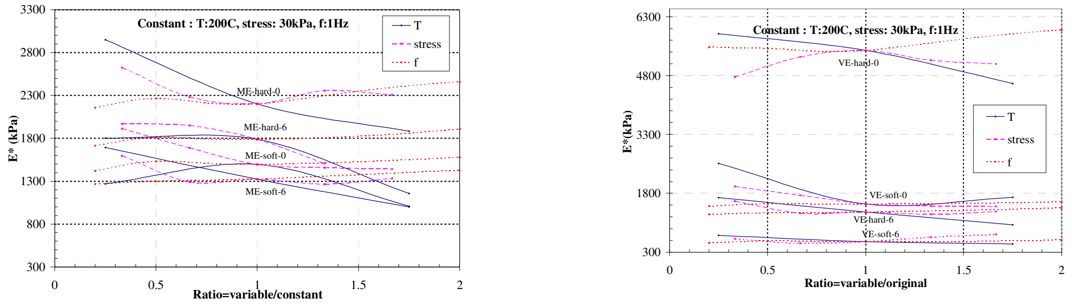
However, it is difficult to identify the influence of all the variables using this form of data presentation. Therefore, a sensitivity analysis was carried out using one set of independent test variables to predict the influence of the other variables to assess the dominant factors such as stress levels, frequencies, temperatures, and bitumen types on mechanical properties (stiffness and phase angle) of the mixtures.

4.3 Sensitivity Analysis

The sensitivity analysis was carried out with the following constants to analyse the effect of the other variables:

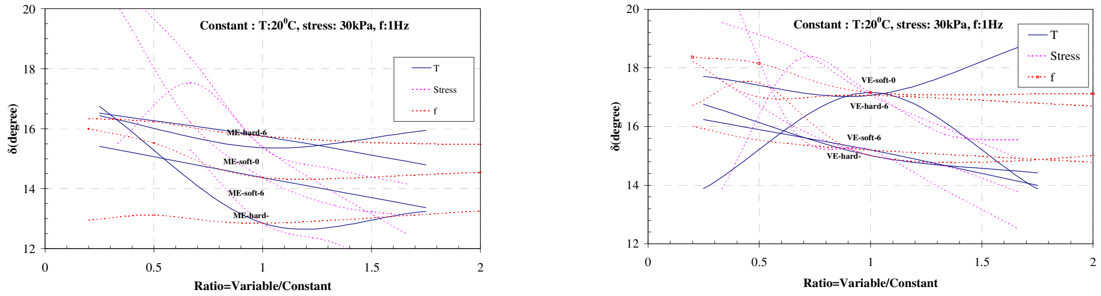
- Loading frequency - 1Hz
- Temperature - 20^0C
- Stress - 30kPa

Figure 6 presents sensitivity plots of complex modulus and phase angle versus ratio of variables and constant test parameters for zero and six hours conditioned mixtures. The results showed that overall responses at different temperatures, frequencies and stress levels are similar for all mixtures irrespective of bitumen type, grades and conditioning regimes. It also showed that increases in testing temperature significantly reduced mixture stiffness, which was only marginally influenced by loading frequency and stress level. The change in stiffness with variations in temperature is probably due to the combined influence of the more elastic response of the bitumen at low temperatures and elastic response of rubber particles at high temperatures. In addition, the results also demonstrate that the stiffness of the mixture is significantly lower for composites produced using softer bitumen compared to mixture produced using harder bitumen. As all mixtures were produced using the same percentage of rubber and bitumen using similar compaction effort and curing techniques, the softer bitumens are probably the main contributing factor for low stiffness. Another possibility is the higher percentage of bitumen absorption in softer bitumen during short-term ageing made the rubber particles softer and as the percentage of rubber particles is higher in the mixture, it is the rubber's properties that dominate the overall response of the composite mixtures.



a. Complex modulus for ME-soft and ME-hard

b. Complex modulus for VE-soft and VE-hard



c. Phase angle for ME-soft and ME-hard

d. Phase angle for VE-soft and VE-hard

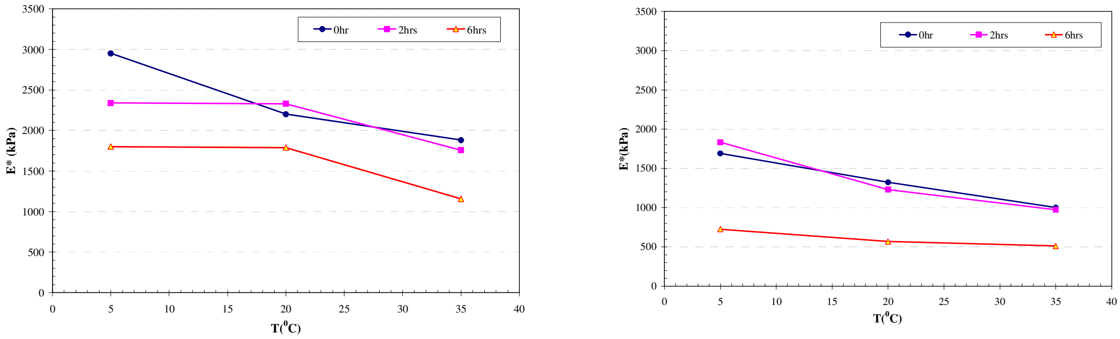
Figure 6: Sensitivity analysis on dynamic mechanical properties of composite mixtures

In terms of phase angle, in general, the results indicate that the influence of frequency on phase angle is minimal, but that the mixtures are marginally influenced by testing temperature and stress level. This may be due to the dominance of the rubber component, as it comprises a higher proportion in the mixture.

4.4 Rubber-Bitumen Interaction

Figure 7 show the influence of short term ageing and testing temperature on the stiffness for ME-hard and VE-soft composite mixtures tested at frequency 1Hz and at stress level 30kPa. The results demonstrate that the stiffness is dependent on the test temperature. It can also be seen that the high temperature ageing of the mixture prior to compaction reduced the mixture stiffness. However, the reduction in stiffness could also be attributed to the results from Figure 4, which showed, that voids content of the samples also increased with ageing and an increase in voids contents has an effect on mixture stiffness.

To identify the influence of void content on mixture performance, complex modulus versus voids content at three ageing conditions for four different mixtures tested at 20^{0}C and 1Hz were analysed and presented in Figure 8. The results show a high degree of scatter with only a 35% correlation although the stiffness of the mixture generally decreased with the increase in voids content. To review the influence of void content, the results obtained from the 20^{0}C and 1 Hz test were normalised to 6% voids and plotted in Figure 9 in terms of stiffness and conditioning periods.



a. Complex modulus versus temperature for ME-hard mixture tested at f:1Hz, Stress level :30kPa

b. Complex modulus versus temperature for VE-soft mixture tested at f:1Hz, Stress level :30kPa

Figure 7: Complex modulus of different composite mixtures

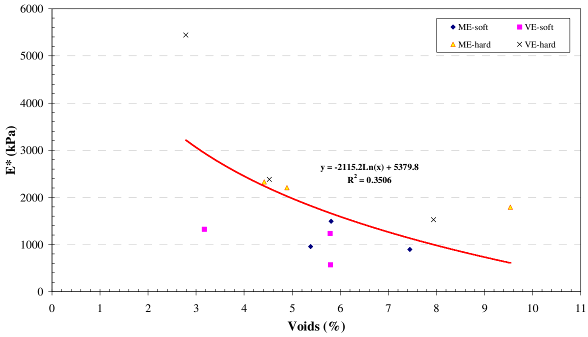


Figure 8: Complex modulus versus air voids of all composite mixtures produced after pre-compaction curing of 0, 2 & 6 hours and tested at f: 1Hz, T:20^{0}C and stress level:30kPa

The results show that the normalised stiffness for mixtures with softer bitumens decreased due to ageing although the normalised stiffness increased for both mixtures produced using the harder bitumens. This might be due to the higher percentage of asphaltenes in harder bitumen contributing to the increase in the overall stiffness of the mixture following conditioning for 6 hours at 160^{0}C. In contrast, the ageing at 160^{0}C for mixture with softer bitumen may have less effect on the bitumen because the bitumen contains higher percentages of the maltenes fractions. In terms of phase angle, Figure 10 shows results obtained from different composite mixtures aged for 0, 2 and 6 hours and tested at 20^{0}C, stress level 30kPa and frequency 1Hz. The result suggests that the composite mixtures are highly elastic and not influenced by bitumen type and grades, voids content and ageing of the mixture.

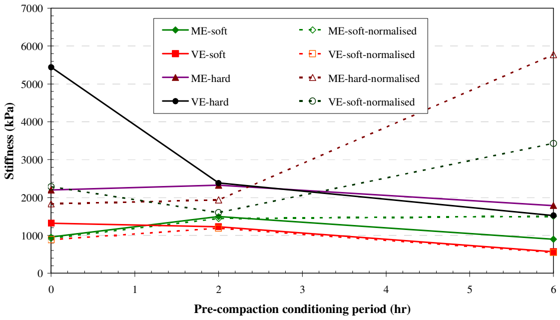


Figure 9: Complex modulus vs. conditioning period at 20^{0}C, stress level: 30kPa and f:1Hz,

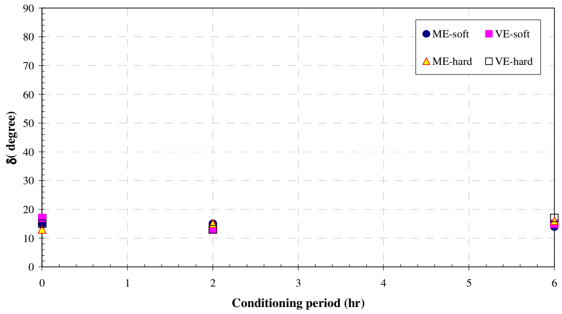


Figure 10: Phase angle vs. conditioning period at 20^{0}C, stress level: 30kPa and f:1Hz

The results also demonstrate that although the material has become more voided and less stiff with ageing, the highly elastic property of the rubber is a dominant feature in the composite mixtures with low phase angles (14^0-18^0).

5 SUMMARY AND CONCLUSIONS

An attempt has been made to study the rubber-bitumen interaction in idealised composites specimens, produced by rubber and bitumen, which simulates realistic rubber-bitumen proportions in dry process CRM asphalt mixtures. Volumetric analyses were performed to ensure the consistency of the sample production method.

The dynamic mechanical properties were determined on a range of mixtures at different conditioning and test regimes under a triaxial testing set-up. All the mixtures were tested at five stress levels (10kPa to 50kPa), five frequencies (0.1, 0.2, 1, 2, 5Hz), and three temperatures (5, 20, 35^{0}C). The resultant axial strains were measured and used to calculate complex modulus and phase angle. As the mixture is highly non-linear elastic in nature due to the high proportion of the rubber content, each test was conducted at very low stress levels to ensure that the material remains within the linear region and that the stress condition does not influence the test results.

The stress-strain response was found to be non-linear and highly elastic in nature and the strain generated under load was significantly high indicating rubber dominance in the response. A sensitivity analysis was performed to investigate the influence of the different testing variables and it was found that the mixture stiffness is mostly influenced by the testing temperature, but marginally dependent on test frequencies.

In terms of bitumen types, irrespective of crude source, the stiffness reduction is significantly higher for mixtures produced using softer bitumens than for mixtures with harder bitumens. This is probably due to the combined effect of lower bitumen stiffness and higher bitumen absorption during short-term ageing at 160^{0}C. In general, stiffness for all composite mixtures decreased due to the combined effect of short-term ageing and voids content. Phase angle on the other hand is not predominantly influenced by bitumen type and grades used, short-term ageing of the mixture, mixture volumetric, test temperature, stress level, and frequency. The overall phase angle of the mixture was within the range of 14^0-18^0 and mainly influenced by the rubber component in the mixture indicating the viscoelastic nature of the CRM asphalt mixture could be compensated by using more flexible rubber particles.

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