Rubberised stone mastic asphalt mixtures: A performance-related evaluation

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Abstract: Incorporation of recycled tyre rubber into asphalt mixtures is an environmentally friendly practice and has also shown enhancement in the performance of the pavement. The binder content of rubberised asphalt mixtures is usually increased compared to that used in conventional asphalt. This increase is deemed important to compensate for the reduction in the actual bitumen due to the existence of rubber particles. This study presents results of performance evaluation conducted on different rubberised Stone Mastic Asphalt (SMA) mixtures produced using different types and contents of rubberised bitumen. The performance evaluation involved laboratory testing for rutting, fatigue resistance and moisture susceptibility. The energy ratio (ER) computed from Superpave Indirect Tensile (IDT) tests was used to evaluate the cracking resistance of asphalt mixtures while the rutting behaviour was evaluated using the Repeated Load Axial Test (RLAT). The indirect tensile stiffness and strength were used to evaluate the moisture susceptibility after immersion in water. The results of this study reveal that using the same binder content for rubberised SMA mixtures as used in the conventional mixtures can still give superior performance properties. The study also indicated that adding crumb rubber to softer base bitumen produced asphalt mixtures with superior cracking and rutting resistance.

Keywords: stone mastic asphalt, rubber, fatigue, rutting, moisture susceptibility

1. Introduction

The use of recycled tyre rubber in asphalt materials has gained increased interest, both in terms of research activities and application in the pavement industry. Many laboratory and field studies have shown that adding recycled tyre rubber results in enhanced engineering properties of pavements making them more resistant to traffic and climate damage [1-7]. Reused tyres in pavement applications also provides a solution to solve environmental problems associated with hazardous landfill of the end-of-life tyres. The ground tyre rubber particles are introduced into asphalt mixtures by two technologies known as the 'Wet Process' and the 'Dry Process'. In the wet process, the tyre rubber particles are mixed with the bitumen at high temperatures, the resultant product is called rubberised bitumen or crumb rubber modified bitumen (CRMB). The CRMBs are then mixed with the aggregate. In the dry process, the rubber particles are added by replacing a small part of the aggregate in the asphalt mixture. The wet process has been proven to improve the mechanical properties of materials at both laboratory and field scale [7, 8]. On the other hand, the dry process has shown inconsistency in field performance, and thus, it has been increasingly abandoned [9].

CRMBs have been successfully used in different mixture designs such as dense graded, open graded and gap graded [2, 10, 11]. In particular, the open and gap graded mixtures provide sufficient room within their aggregate skeleton which are suitable to accommodate the rubber particles and the thicker films usually associated with CRMBs. Therefore, these gradations have shown to be significantly improved when they are modified by tyre rubber [6, 12-14]. Stone Mastic Asphalt (SMA), which is a special type of gap-graded aggregate structure, was firstly developed in Germany in the 1960s to resist studded tyres damage [15]. Subsequently, many European countries and some States in the USA adopted the SMA gradation due to the considerable success in resisting the main distresses associated with flexible pavements. The SMA mixture comprises a coarse aggregate skeleton filled with a high content of bitumen/filler mortar. The stone-to-stone aggregate skeleton of the coarse aggregate provides

excellent rutting resistance while the high content of bitumen/filler mortar provides high fatigue resistance and durability. Due to the high binder content of SMA mixtures, SMA mixtures normally need to be stabilised by fibres to prevent binder drain down. On the other hand, SMA mixtures can dispense with fibres when modified bitumens are used such as CRMBs [2, 16, 17]. This added advantage provides increased motivation for the use of CRMBs in SMA mixtures. However, the main problem associated with CRMBs is the binders' high temperature viscosity which poses real challenges during production of asphalt mixtures [18]. In response to this, several research studies have considered using Warm Mix Asphalt (WMA) additives to improve the workability properties of rubberised mixtures [19-23].

Rubber particles and base bitumen physically interact with no chemical reaction where the crumb rubbers are swollen by absorbing the lighter fractions (oily compounds) available in the bitumen [18, 24, 25]. Some rubber particles may also be partly or fully digested into the bitumen when using high mixing temperatures and/or shear rates [18]. This means that CRMBs can neither be considered single homogenised binders nor totally separated phases of bitumen and crumb rubber. The interaction between rubber and bitumen should, therefore, be taken into consideration when designing the asphalt mixtures. It is well known that binder content is a key parameter in mixture design that determines the performance behaviour of asphalt mixtures. Many studies have specified the binder content of rubberised asphalt mixtures based on either Marshall tests [7, 8, 10, 13, 16, 23, 26-28] or by simply using increased rubberised binder content to that applied in the conventional mixtures to account for rubber particles [2, 6, 29-32]. However, an interaction between rubber particles and bitumen does exist [18] as well as a significant amount of rubber particles being dissolved into the bitumen by means of devulcanisation and depolymerisation [4, 33]. It should also be noted that although the fatigue resistance and durability are improved by using higher binder content [34], using excessive binder content could lead to binder drain down and also impair the rutting resistance of the asphalt mixture [12, 35].

In this study, SMA mixtures were produced using different types and contents of rubberised bitumens. The different types of rubberised bitumens were selected to investigate the effect of using softer or harder base bitumens and also to investigate the effect of incorporation WMA additives together with recycled rubbers. Three different binder contents were selected to account for the interaction state between rubber particles and base bitumen. The performance evaluation of different SMA mixtures included elemental stiffness, rutting resistance, fatigue resistance and moisture susceptibility.

2. Materials and experimental design

2.1 Aggregate

The coarse and fine aggregate fractions used in this study consisted of granite aggregate combined with limestone filler. A typical stone mastic asphalt (SMA) gradation (10mm) suitable for surface courses was selected from the British Specification BS EN 13108-5/ PD 6691:2007 for designing conventional and rubber modified mixtures. The SMA gradations used in this study are shown in Fig. 1. As the recycled tyre rubber in the modified binders can occupy some space in the mixtures, the gradations of CRMB mixtures were slightly amended to keep the same gradation for both control and modified mixtures (CRMBs at three different binder contents) as seen in Fig. 1.

2.2 Binders: selection and content

Four different binders were used to manufacture the SMA mixtures. Each binder represents a specific case in terms of bitumen modification as follows:

1. Control neat bitumen “H”: this bitumen is considered as a control and labelled “H” throughput the study. Binder H has a penetration of 40 dmm and a softening point of 51.4°C

2. Rubberised bitumen “H-R”: this rubberised bitumen was produced by adding 15.25% of recycled tyre rubber by total mass to bitumen H using the wet process. The neat bitumen H was preheated to 180^{o}C and then the required amount of recycled tyre rubber was added gradually while mixing at 180^{o}C using a Silverson L4RT high shear laboratory mixer for 120 minutes. High shear mixers have been utilised by many researchers and verified to produce rubberised bitumens with superior properties [31, 36-39]. The recycled tyre rubber used in binder H-R, was derived from discarded truck and passenger car tyres by ambient grinding. The average diameter size of the rubber particles is 300µm.

3. Rubberised bitumen “S-R”: the same recycled tyre rubber, same content and same processing conditions used with binder H-R were also used in binder S-R. The only difference is the base bitumen. A very soft bitumen with a penetration of 200 dmm and a softening point of 37°C was used to produce the rubberised bitumen S-R.

4. Rubberised bitumen “H-Rw”: the base bitumen H was modified using recycled tyre rubber that had been pre-treated with a special oil and Sasobit. The special oil reduces the migration of the lighter components of the base bitumen into the rubber and thus minimizes the effect of early ageing. The Sasobit wax allows a reduction in mixing temperature while avoiding insufficient workability and compactability. The average diameter size of the rubber particles is also 300µm. The same rubber content and processing conditions used with the above rubberised bitumens were also used with H-Rw.

The bitumen content of the control mixture is specified as 6.2% by mass of the total mixture as recommended in the British Specification. In this study, three different binder contents for the CRMBs were selected, each selected binder content represents a specific hypothesis as shown below:

a. Binder content of 6.2%; this is the same as the binder content of the control mixture. In this case, the CRMBs are considered to act as single homogenised binders and the existence of rubber particles as inert filler is ignored.
b. Binder content of 6.8%; it is assumed in this case that about 50% of the added rubber interacts and/or is dissolved into the bitumen. Therefore, the binder content is increased to compensate the reduction in the actual bitumen due to rubber particles that would keep their physical shape and are not dissolved into the bitumen.
c. Binder content of 7.4%; in this case, a similar amount of actual bitumen as in the control mixtures, is provided. All added rubber particles are treated as solid fillers. The diffusion of lighter fractions from bitumen by rubber absorption is also compensated here.

Table 1 shows a simple calculation of the amount of binder and an approximated cost at each binder content for an overlay layer of 5cm thickness, 3.5m lane width and 1 km length. The table suggests that using lower binder content can be very cost effective for large road schemes.

Table 1. Approximated cost and amount of materials needed for 1 km length x 3.5m x 5cm

Binder content	Amount of binder (ton/km)	Cost of binder (£/ton)	Total cost of binder (£/km)	Amount of crumb rubber (ton/km)
6.2%	26.50	1000	26,500	4.10
6.8%	29.00	1000	29,000	4.42
7.4%	31.50	1000	31,500	4.80

2.3 SMA mixtures production

The designed aggregate and filler proportions were placed and mixed in a mechanical asphalt mixer, as shown in Fig. 2, at the specified mixing temperature. The pre-heated binder was then added to the mixture and the mixing continued for three minutes. The mixture was then placed in a preheated slab mould (306mm x 306mm) and compacted by a smooth steel roller according to BS EN 12697-33:2003 until the desired final height of the slab (~60mm), was achieved so that 4% air voids content is ascertained. The selected mixing and compaction temperatures should correspond to binder viscosity of 170±20 mPa.s and 280±30 mPa.s respectively [40]. However, this criterion is not always possible to apply to rubberised bitumens because unreasonably high mixing and compaction temperatures are predicted with this method (~220°C). This higher temperature is not acceptable as it raises concerns about workers' health due to possible hazardous fumes. Additionally, it could cleave the polymer network in the binder and increase ageing. Therefore, the mixing and compaction temperatures were selected so that the aggregate fractions could be sufficiently coated by the binder and practically compacted to the prescribed air voids content of 4%. The mixing and compaction temperatures were specified for H-R mixtures as 190±5 ºC and 170±5 ºC respectively. For control, S-R and H-Rw mixtures, the mixing and compaction temperatures were specified as 170±5 ºC and 150±5 ºC respectively. Cellulose fibres at 0.3% of the bitumen mass were included in the control mixtures. Cellulose fibres were not included in the rubberised mixtures. Five specimens with 100 mm diameter were cored from each slab. The cores were then trimmed from each end to produce cylindrical samples of 100mm diameter and 40mm thickness suitable for RLAT tests. The experimental design of this study involved seven different asphalt mixture combinations, as shown in Table 2.

Table 2. The main parameters associated with the production of SMA mixtures

Mixture	Binder content (%)	Mixing Temperature (°C)	Compaction Temperature (°C)	Designed air voids (%)	Added cellulose fibres
Control H (6.2%)	6.2	170±5	150±5	4	0.3% of bitumen
H-R (6.2%)	6.2	190±5	170±5	4	N/A
H-R (6.8%)	6.8	190±5	170±5	4	N/A
H-R (7.4%)	7.4	190±5	170±5	4	N/A
H-Rw (6.2%)	6.2	170±5	150±5	4	N/A
H-Rw (7.4%)	7.4	170±5	150±5	4	N/A
S-R (6.2%)	6.2	170±5	150±5	4	N/A

2.4 Testing programme

Fig. 3 shows the experimental design programme considered in this study for evaluating the different rubberised mixtures.

Indirect Tensile Stiffness Modulus (ITSM) - Stiffness

The Nottingham Asphalt Tester (NAT), shown in Fig. 4, was used for testing samples in the indirect tensile mode, for stiffness determination. The test is conducted by applying a pulsating load vertically across the diameter of the cylindrical specimen, the resultant tensile horizontal deformation is measured using two linear variable differential transformers (LVDT), as seen in Fig. 4, which are fixed diametrically opposite each another in a rigid frame clamped to the sample.

The ITSM is calculated from the following equation by applying an impulse loading to induce small horizontal strains of 5 ± 2 μm.

$$ITSM = \frac{P\ (0.273+\upsilon)}{\delta\ t} \qquad (1)$$

where P = applied load; t = specimen thickness; δ =horizontal deformation and υ = Poisson's ratio. The following test parameters were applied in ITSM testing according to BS EN 12697-26:2004:

- Rise time (milliseconds): 125±10
- Deflection requirements: 5 ± 2 μm
- Pulse duration: 3s
- Number of conditioning pulses: 10
- Number of test pulses: 5
- Test temperature: 20±0.5°C
- Poisson's ratio: 0.35
- Rotation of sample: 90^o±10^o
- Time to reach temperature equilibrium: > 4hrs

The ITSM is taken as the mean of two measurements on one specimen by rotating the specimen 90^o±10^o about its horizontal axis between measurements.

The Repeated Load Axial Test (RLAT) - Rutting

The test is performed according to BS DD 226 using the NAT machine. In this test, a load pulse consisting of a square wave with a frequency of 0.5 Hz (one second loading followed by one second rest period), is applied by a pneumatic actuator. Fig. 5 shows the configuration of the RLAT inside the NAT machine. The resultant strain during the cycling load is measured along the same axis as the applied stress, using two linear variable displacement transformers (LVDTs). The following test parameters were applied in RLAT testing:

- Test temperature: 50°C
- Test duration: 7200 seconds (3600 cycles)
- Axial stress: 100 kPa
- Conditioning stress: 10 kPa for 600 seconds
- All test specimens were subjected to at least 4 hours conditioning at the test temperature prior to testing.
- Three specimens for each mixture were tested, and the average values are reported.

SuperPave Indirect Tensile Test (IDT) - Cracking

The University of Florida developed a viscoelastic fracture mechanics model to predict and control the crack initiation and crack propagation in an asphalt pavement [41]. Three types of test are performed with the Superpave IDT on each specimen: resilient modulus (non-destructive test), creep compliance (non-destructive test), and tensile strength (destructive

test). These tests were performed at 20°C using the Instron (servo-hydraulic loading frame with a maximum load capacity of 100 kN) test equipment. To obtain accurate measurements for vertical and horizontal strains, 90° 2-element cross polyester wire strain gauges were used. The vertical and horizontal strain measurements are taken from the strain gauges through a data acquisition box. The load measurements are also taken from the data acquisition box and the latter receives the load signals through the Digital Controller of the Instron, as shown in Fig. 6. Three consecutive tests are conducted as follows:

1. The resilient modulus test: The resilient modulus test was conducted in load control mode by applying a repeated haversine waveform load to the specimen for 0.1 s followed by a 0.9 s rest period. To keep the specimen undamaged and maintain the linearity of the material response, the load was selected to generate a horizontal strain between 100 and 300 microstrain during the test.
2. The creep test: After finishing the resilient modulus test, 5 minutes is given to allow the specimen to re-stabilize. Then, a static load is imposed along a diametric axis for 1000s. The creep compliance test is non-destructive; therefore, the constant load should be selected such that the generated horizontal deformation does not exceed the upper linear-elastic boundary. Also, the horizontal deformation should be high enough to minimise any noise effects in the data acquisition process. Buttlar and Roque suggested that a load that induces horizontal strains within 40 and 120 microstrain at t=30 s is appropriate, and the test should be stopped if strains exceed these limits [42].
3. The tensile strength test: The indirect tensile strength test is a destructive test and performed by applying a load at a constant deformation rate (50mm/min) with vertical ram movement until the specimens fail. The vertical and horizontal strains in addition to the load, are recorded and the maximum load is identified as the occurrence of a tensile failure.

The following steps are required to determine the Energy Ratio (ER) parameter [41, 43]:

1. Calculate the resilient modulus as follows:

$$M_R = \frac{P}{\varepsilon_x . t . D . C_{CMPL}} \qquad (2)$$

where M_R = resilient modulus; P = maximum load; ε_x = horizontal strain; t = thickness of specimen; D = diameter of specimen; and C_{CMPL} = nondimensional creep compliance factor which is calculated using Equation 3.

$$C_{CMPL} = 0.6354 \left(\frac{X}{Y}\right)^{-1} - 0.332 \qquad (3)$$

where (X/Y) = ratio of horizontal to vertical deformation.

2. Calculate the tensile strength as follows:

$$S_t = \frac{2*P}{\pi*t*D} \left(C_{SX} \right) \qquad (4)$$

where S_t = indirect tensile strength; P = maximum load; and C_{SX} = horizontal stress correction factor which is calculated using Equation 5.

$$C_{SX} = 0.948 - 0.01114 \left({}^{t}/_{D}\right) - 0.2693 \, (v) + 1.436 \left({}^{t}/_{D}\right)(v) \qquad (5)$$

where υ = Poisson's ratio and calculated as follows:

$$\upsilon = -0.10 + 1.480 \left(\frac{X}{Y}\right)^2 - 0.778 \left(\frac{t}{D}\right)^2 \left(\frac{X}{Y}\right)^2 \quad (6);$$

where *t*, *D*, and $(\frac{X}{Y})$ are as described above.

3. Calculate the $DCSE_f$ as follows:

From the tensile strength test, a typical stress-strain response of the mixture is obtained as shown in Fig. 7. The total fracture energy until failure (FE_f) is determined as the area under the stress-strain curve. The $DCSE_f$ is then determined by subtracting the elastic energy at fracture (*EE*) from the total fracture energy limit (FE_f), which can be expressed as follows:

$$DCSE_f = FE_f - \frac{{S_t}^2}{2.M_R} \quad (7)$$

4. Calculate the creep compliance $D(t)$ at time t from the creep test as follows:

$$D(t) = \frac{\varepsilon_x .t.D.C_{CMPL}}{P} \quad (8)$$

The power function parameters (D_1 and *m*) are then obtained by fitting the $D(t)$ data using the following power function:

$$D(t) = D_o + D_1\, t^m \quad (9)$$

5. Calculate the $DCSE_{min}$ as follows:

$$DCSE_{min} = \frac{m^{2.98}.D1}{A} \quad (10)$$

where the parameter A was determined as follows:

$$A = 0.0299\, \sigma_t^{-3.10} (6.36 - S_t) + 2.46x10^{-8} \quad (11)$$

where σ_t = the applied tensile stress and S_t = the tensile strength. It can be seen that the parameter A in $DCSE_{min}$ requires information about pavement structural characteristics reflected in σ_t and mixture tensile strength. However, this study has investigated the properties of different asphalt mixtures in the laboratory; therefore, it was assumed that the different mixtures are subjected to the same level of stress. Thus, σ_t is assumed to be constant and a value of 300 kPa is given as the average tensile stress for all studied mixtures.

6. Finally, the energy ratio parameter (*ER*) is defined as follows:

$$ER = \frac{DCSE_f}{DCSE_{min}} \quad (12)$$

where the $DCSE_f$ is fracture energy and computed from the area under the stress-strain curve minus the elastic energy as shown in Fig. 7.

The ER was designed as a dimensionless parameter to evaluate the cracking performance of different asphalt mixtures. Field test sections and laboratory testing have shown that the ER parameter can reliably predict and control top-down cracking performance of pavements [41, 44-46].

Water damage susceptibility

The moisture susceptibility of the control and CRMBs mixtures with different binder contents was evaluated based on determining the ratio of conditioned to unconditioned indirect tensile stiffness modulus values measured using the NAT, and the ratio of conditioned to unconditioned indirect tensile strength measured using the Instron test equipment. The following procedure has been developed specifically for the assessment of thin surfacing systems by the Highways Agency Product Approval Scheme (HAPAS) to protect against water damage. The testing procedure involves measuring the non-destructive ITSM in the dry condition, designated as $ITSM_{U,}$ and subsequently the same samples having undergone a water immersion regime as follows:

1. Three specimens were selected for each mixture
2. Saturation under a partial vacuum of 510 mm Hg at 20°C for 30 minutes
3. The samples are then transferred to a preheated water bath at 60°C under atmospheric pressure for 6 hours and moved to another water bath at atmospheric pressure at 5°C for 16 hours. The samples are finally conditioned under water at 20°C (atmospheric pressure) for 2 hours prior to stiffness testing
4. The conditioned ITSM at a test temperature of 20°C for the first conditioning cycle is determined. This is labelled as $ITSM_{c1}$
5. The steps (2) and (3) are repeated, and the conditioned ITSM of the specimen is determined for the successive conditioning cycles, these are labelled as $ITSM_{ci}$; $i = 1, 2, 3, \dots 6$
6. The ITSM ratio for each specimen is calculated for each conditioning cycle as follows:

$$ITSM_{ratio,ci} = \frac{ITSM_{ci}}{ITSM_U} \qquad (13)$$

Finally, the specimens that had undergone six water immersion cycles were tested destructively for their indirect tensile strength (ITS) values at 20°C test temperature. The ITS test is conducted by applying diametrically a load at 50 mm/min displacement speed to a cylindrical specimen until it breaks. The test is conducted in accordance with BS EN 12697-23. The ITS is calculated according to the following formula:

$$ITS = \frac{2P}{\pi.D.H} \qquad (14)$$

Where *ITS* = indirect tensile strength (MPa); *P* = peak load (N); *D* = diameter of the specimen (mm); and *H* = height of the specimen (mm).

3. Results and discussion

3.1 Indirect Tensile Stiffness Modulus (ITSM)

The stiffness modulus is an important indicator for asphalt mixtures and it is considered the main input property to determine the required layer thickness in mechanistic pavement design. The average value of 15 samples for each mixture is presented in Fig. 8, and the range bars represent the maximum and minimum values of ITSM. For asphalt mixtures produced using binders, H, H-R and H-Rw, and sharing the same binder content of 6.2%, there is no significant difference among the ITSM values of those mixtures. This indicates that the

volumetric proportion of the mineral aggregate skeleton in the mixture has a dominant effect on the ITSM. In the case where the proportion of the mineral aggregate skeleton is reduced by increasing the binder content, there is a clear reduction in the ITSM values. This is expected as part of the aggregate skeleton is replaced by highly flexible binder. On the other hand, the ITSM values of the mixture produced using the binder S-R, are considerably affected by the softer binder. The complex modulus of binders measured at approximately similar conditions (temperature and loading frequency) used for the ITSM testing are presented in Table 3. Although the complex moduli of binders H-R and H-Rw are about half of the complex modulus of binder H, these differences are not seen in the ITSM of the asphalt mixtures. However, the effect of binder in the case of S-R is substantial in the ITSM where the ITSM values of S-R mixtures are about half the ITSM values of the other mixtures. This is not surprising, as the complex modulus of binder S-R is between seven and fifteen times smaller than the value of the complex modulus among the other binders.

Table 3. The complex modulus of the control binder and RTR-MBs

Binders	|G*|, [MPa], @ 20 ℃ and 8 Hz	
	Unaged	TFOT
H	23.35	23.71
H-R	11.30	12.49
H-Rw	12.21	13.72
S-R	1.34	1.64

3.2 Rutting Resistance of Mixtures

The typical results obtained from the RLAT at a test temperature of 50ºC for the different mixtures are shown in Fig. 9, where permanent axial strain is plotted against load cycles. The cumulative axial strain at the end of the 3600 load pulses or at the initiation of the tertiary phase, and/or, the slope of the steady state phase, have been used to distinguish between better performing materials [9, 47].

The slope of the steady state phase is determined from a segment between 1500 to 3000 pulses as follows [9];

$$Minimum\ strain\ rate\ \left[{}^{\mu\varepsilon}/_{cycle}\right] = \frac{\varepsilon_{3000} - \varepsilon_{1500}}{1500}\ x\ 10^{-6} \quad (15)$$

where ε_{3000} = accumulated strain at 3000 pulses; and ε_{1500} = accumulated strain at 1500 pulses.

The permanent deformation results in terms of the total accumulated strain at the end of 3600 pulses, and in terms of the minimum strain rate, are presented in Fig. 10. The range bars represent the maximum and minimum values for replicates. The results in Fig. 10 clearly confirm the enhanced rutting performance of rubberised mixtures in comparison to the base bitumen H. The mixtures made with binder H-R at the three binder contents showed the best rutting properties among the other mixtures. The influence of binder content on permanent deformation performance for mixtures made with H-R binder showed an unexpected trend. It can be seen that increasing the binder content resulted in a slight reduction in the total strain and an insignificant change in the minimum strain rate for H-R mixtures. Generally, increasing the binder content can make asphalt mixtures more susceptible to permanent deformation as the binder film becomes thicker between aggregate particles [12, 35, 48, 49]. It could be that the high-performance recovery of binder H-R might have contributed to making the rutting resistance for mixtures with higher binder content less affected by the

thicker binder film. In other words, the reduction in rutting resistance for mixtures with higher binder content was probably compensated by the recovery improvement due to the relative increase of rubber content in the mixture. In contrast to the H-R groups, increasing the binder content for mixtures made with H-Rw binder led to increases of the total accumulated strain and the minimum strain rate. These findings agreed with the general effect of binder content as higher binder content can increase the plastic flow susceptibility. Despite the fact that the binder S-R and the mixtures made with this binder are much softer than the control H, the results in Fig. 10 indicated that the S-R mixture was less susceptible to high-temperature deformation than the control mixtures. This again seems to emphasise the high-performance ability of rubber modified binders to recover the induced strain in comparison to unmodified binders [1].

3.3 Superpave Indirect Tensile Test (IDT)

The fracture energy ratio (ER) is the main parameter obtained from the IDT. The ability of the ER parameter to reliably evaluate the cracking performance of different asphalt mixtures has been proven by several studies [41, 44-46]. The ER is based on the fact that each asphalt mixture has the ability to resist the initiation of cracking if its fundamental dissipated creep strain energy threshold $DCSE_f$ is larger than its minimum dissipated creep strain energy $DCSE_{min}$. Therefore, an asphalt mixture with a larger ER value is desirable and should have better fatigue performance in comparison to an asphalt mixture with a lower ER value.

The creep compliance progression with time from the IDT results are shown in Fig. 11, and the power parameters of the creep compliance curve, D_1 and m-value, in addition to the IDT strength and resilient modulus, are shown in Table 4, for each mixture. It can be seen from Fig. 11 that the modification by recycled tyre rubber has significantly decreased the increase rate of creep compliance with time. This, in turn, would lead to a retarding in the rate of damage accumulation, thereby enhancing the ability of the mixture to resist the initiation of cracking. The results of resilient modulus, presented in Table 4, are slightly different from the ITSM results, which is not surprising given that the definition of strain in the Resilient Modulus is somewhat different from that in the ITSM. The total strain is used in the calculation of the ITSM, while the recoverable or resilient strain is used in the calculation of the Resilient Modulus. However, the amount of elastic energy (EE) which is a function of the Resilient Modulus is marginal with respect to the total fracture energy (FE). Thus, these differences would not make a meaningful change in the $DCSE_f$ values.

Table 4 The IDT results for the different mixtures

Mixture	Resilient Modulus [MPa]	Creep Compliance		IDT strength [MPa]
		D_1	m-value	
H (6.2%)	6221	0.71	0.33	2.00
H-R (6.2%)	5398	0.31	0.31	1.98
H-R (6.8%)	5459	0.33	0.35	1.67
H-R (7.4%)	5330	0.68	0.25	1.70
H-Rw (6.2%)	6150	0.41	0.25	1.94
H-Rw (7.4%)	5220	0.41	0.32	1.85
S-R (6.2%)	2080	0.81	0.25	0.82

Fig. 12 depicts the stress–strain curves, from the IDT strength test, for the different mixtures. The stress-strain curves are important to evaluate the fracture resistance of materials by determining their failure parameters, including the IDT strength, the tensile failure strain ε_f,

and $DCSE_f$. It can be seen that the mixtures made with H-R and S-R binders exhibit much higher failure strains than mixtures made with binders H and H-Rw. The mixture made with the soft binder, S-R, experienced the largest failure strain; this compensates its fracture energy due to its lower IDT strength. On the other hand, the modification with crumb rubber Rw, has slightly reduced the failure strains compared to the control.

By analysing the data of creep and strength tests, the $DCSE_f$ and $DCSE_{min}$ are determined and presented in Fig. 13. The range bars represent the maximum and minimum of values for the replicates. It can be observed that the addition of crumb rubber has a clear effect on decreasing the $DCSE_{min}$ compared to the control mixture. This is beneficial for having materials with superior cracking resistance. On the other hand, the $DCSE_f$ seems to be less affected by the rubber modification than the $DCSE_{min}$. Although there is an increase in $DCSE_f$ for mixtures made with binder H-R in comparison to the control mixture, the results show a significant amount of variation that makes it difficult to draw a clear conclusion, as seen from the range bars. In terms of the effect of using different binder contents, for mixtures made with H-R and H-Rw binders, there is a different trend between the two binders. Increasing the binder content for H-R mixture led to a consistent decrease in $DCSE_{min}$ but variable and slight changes in $DCSE_f$, while there was a slight increase in the $DCSE_f$ and $DCSE_{min}$ when increasing the binder content for mixtures made with H-Rw binder. Fig. 14 shows the ER values for all mixtures. The results also demonstrate the superior cracking performance for mixtures made with CRMBs. The results in Fig. 14 indicate that increasing the binder content to 6.8%, for H-R binder, resulted in a modest change in ER, while increasing the binder content to 7.4% resulted in higher ER. Increasing the binder content from 6.2% to 7.4% for H-Rw mixtures seems to have a less pronounced effect on the ER compared to H-R group. The higher deformability of the S-R binder provided superior cracking performance and that was reflected in the ER value.

3.4 Water damage susceptibility

Because the SMA mixtures considered in this study are designed for surfacing and there is a concern about inadequate coating of aggregate with higher viscosity rubberised binders, it is important to evaluate the water sensitivity of these mixtures. Water damage generally deteriorates the structural integrity of bituminous materials through loss of cohesion within the bitumen or through the failure of the adhesive bond between the bitumen and aggregate [50-52]. Table 5 shows the ITSM values for the Control and CRMB mixtures before and after being exposed to successive water immersion cycles. The average value of ITSM for three specimens is reported in Table 5. The results in Table 5 indicate that the immersion regime after three cycles led to an increase in ITSM compared to its dry value for all mixtures, except for the S-R mixture which exhibited a slight reduction. It should be mentioned that the number of conditioning cycles is specified as three cycles in the HAPAS Certification Procedure; however, the number of conditioning cycles has been doubled to six, because the retained ITSM after three conditioning cycles had not exhibited any reduction. The increase in stiffness value after water immersion could be attributed to the binder ageing during conditioning. The effect of binder ageing on ITSM was possibly dominant over the water damage. However, all mixtures showed a reduction in the retained ITSM after six cycles of water immersion. The retained ITSM ratio versus the number of water immersion cycles is presented in Fig. 15 for the different mixtures. A minimum retained stiffness ratio of 80% has been set to safeguard against stripping [53]. It can be seen that all mixtures passed the minimum limit indicating excellent moisture damage resistance. With respect to the effect of binder content, increasing the binder content for H-R (7.4%) mixture compared to H-R (6.2%), led to a reduction in moisture damage after six cycles of water immersion. Also, the specimens made with binders H-Rw and S-R, are less susceptible to water damage in

comparison to the other mixtures. This indicates that the pre-treatment with WMA additives for H-Rw binder, and using softer base bitumen for S-R binder, resulted in better aggregate coating, and consequently less water was able to penetrate into the asphalt mixture matrix and affect the structural integrity.

Table 5. The change in stiffness of asphalt mixtures due to water conditioning

Mixture	Unconditioned stiffness [MPa]	Conditioned stiffness (MPa)					
		1st cycle	2nd cycle	3rd cycle	4th cycle	5th cycle	6th cycle
Control H (6.2%)	5576	5742	6205	5936	5591	5425	5225
H-R (6.2%)	5415	5595	5878	6114	----	----	5139
H-R (6.8%)	4621	4680	4737	5352	----	----	4243
H-R (7.4%)	4705	5189	4828	4943	----	----	4650
H-Rw (6.2%)	5936	6939	6940	6414	6820	----	6188
S-R (6.2%)	1782	1823	1822	1747.5	1859	----	1821

The average ITS value for the three conditioned samples is compared with the average ITS value for three dry samples, as shown in Fig. 16, with the range bars representing the minimum and maximum values. In most cases, the results of the conditioned ITS values, are similar or slightly lower than the unconditioned ones. It can be seen that the H-R (7.4%) mixture has a conditioned ITS value even higher than the unconditioned one. This demonstrates that a higher binder content is beneficial to the moisture resistance of asphalt mixtures.

4. Conclusions

A typical stone mastic asphalt (SMA) gradation (10mm) was selected from the British specification BS EN 13108-5/ PD 6691:2007 for manufacturing different rubberised mixtures and a control mixture. The different SMA mixtures were evaluated for their performance using the ITSM test, RLAT, and SuperPave Indirect Tensile Test (IDT). Based on the discussion and analysis described in this study, the following conclusions and findings can be drawn:

1. The mixing and compaction process for the rubberised mixtures were reasonably accomplished by considering and using higher mixing and compaction temperatures. On the other hand, the pre-treatment with WMA additive, in the case of H-Rw binder, provided an improved workability and compactability.
2. The addition of rubber can generally produce bituminous materials with enhanced rutting characteristics.
3. The rubber modification for a very soft base bitumen (200 dmm penetration), as in the case of S-R binder, can produce binder with excellent rutting and cracking properties. The excellent strain tolerance of S-R binder has been reflected in the mixture through the failure strain ε_f and subsequently through the ER parameter. Such results suggest that rubberised bitumens produced with a very soft base bitumen can be a very effective option for pavements that are prone to both low temperature cracking and to permanent deformation.
4. The results of the SuperPave IDT have shown that the addition of rubber can significantly decelerate the rate of damage accumulation which, in turn, leads to enhanced cracking resistance of mixtures. Indeed, the ER values have revealed that CRMBs mixtures have superior cracking resistance to the control mixture.

5. The tests to evaluate the water sensitivity of rubberised mixtures have revealed that these mixtures exhibit an excellent water damage resistance similar to the control mixture. It can, therefore, be concluded that the aggregate can be adequately coated by the higher viscosity CRMBs, even though the actual bitumen content is reduced.
6. The results of this study have shown that the same binder content as in the control mixtures can also be used for the rubberised asphalt mixtures. The laboratory testing results have indicated that an increase in the binder content for rubberised bitumen mixtures did not significantly enhance the performance-related properties.
7. The price of binder has increased significantly around the world due to growing demands and decreasing fossil fuel reserves. Using relatively lower binder content would considerably contribute to reduce the total cost of the pavement. This can result in a cost reduction for a rubberised bitumen alternative especially for large pavement projects.

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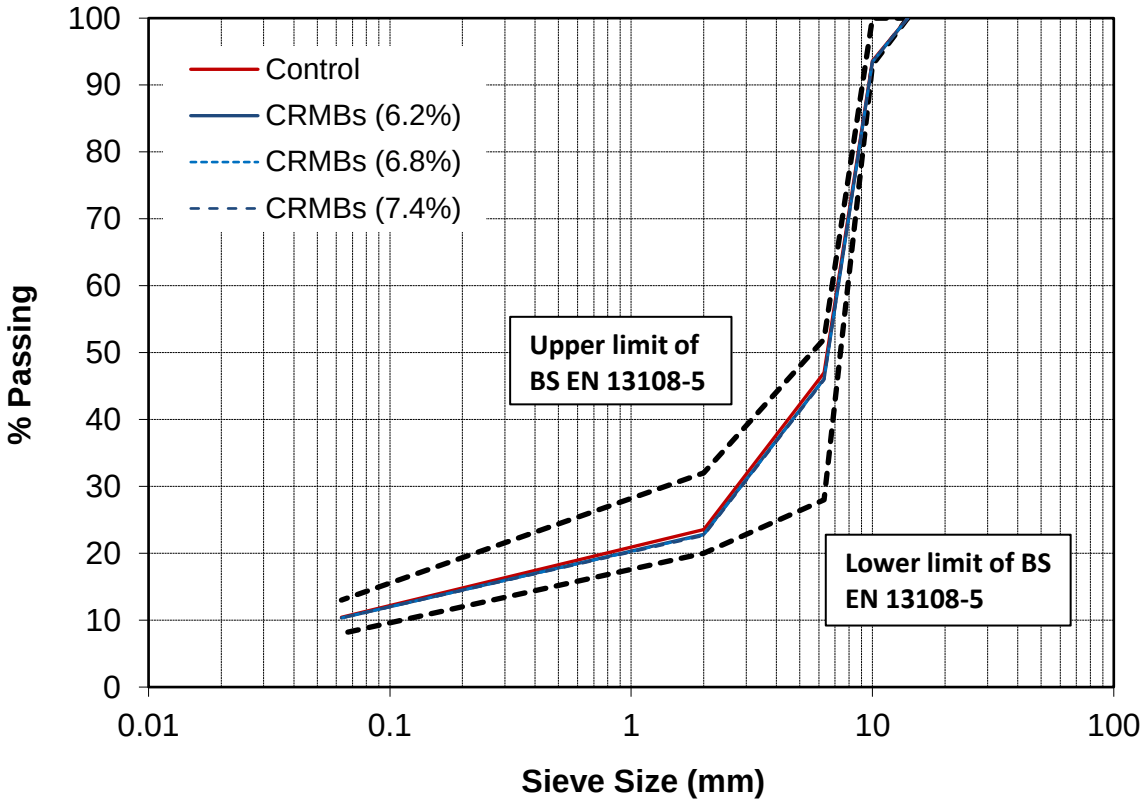

695

696 *Fig. 1. The 10mm SMA gradations according to BS EN 13108-5/ PD 6691:2007*

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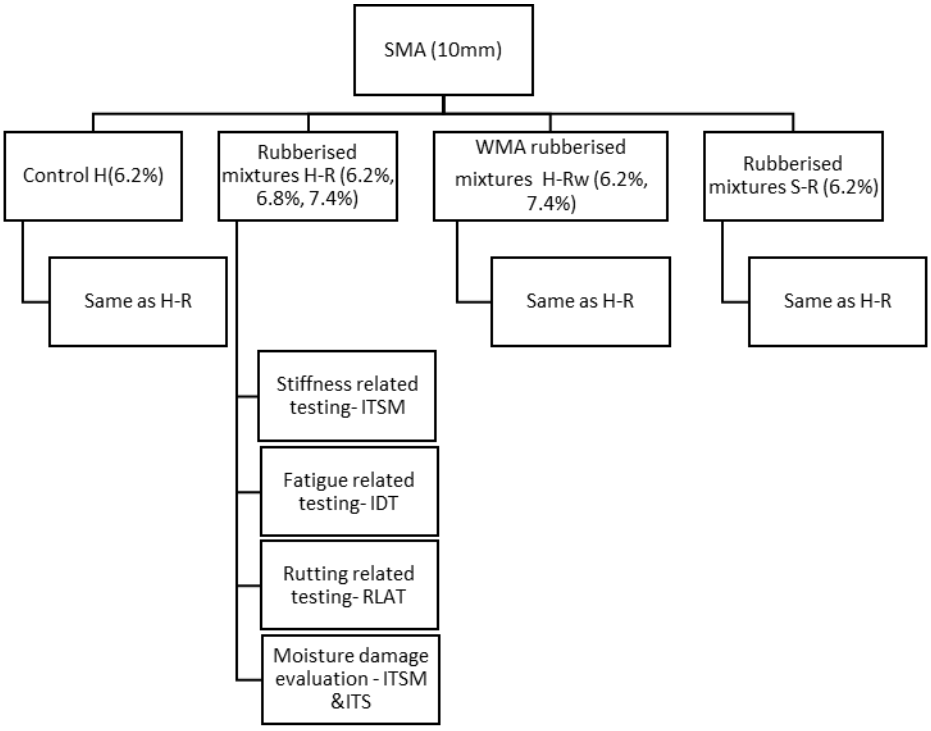
698 *Fig. 2. (a) The mechanical mixer, and (b) Steel roller, used for asphalt mixture production*



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700 *Fig. 3 Flow chart of experimental design programme undertaken in this study*

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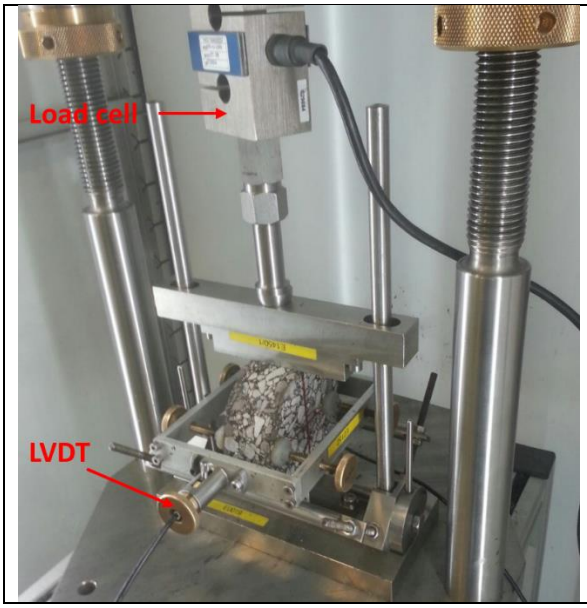

- Rise time (milliseconds) = 125±10
- Deflection requirements = 5 ± 2 μm
- Pulse duration =3s
- Number of conditioning pulses = 10
- Number of test pulses = 5
- Test temperature =20±0.5
- Poisson's ratio= 0.35
- Rotation of sample = $90^{o} \pm 10^{o}$
- Time to reach equilibrium > 4hrs

703 *Fig. 4 ITSM testing configuration in the NAT*

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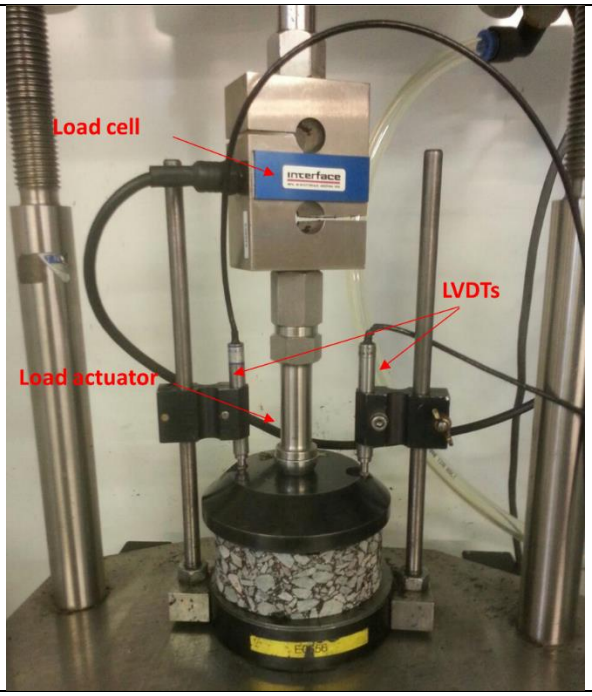

- Test temperature: 50°C
- Test duration: 7200 seconds (3600 cycles)
- Axial stress: 100 kPa
- Conditioning stress: 10 kPa for 600 seconds
- All test specimens were subjected to at least 4 hours conditioning at the test temperature prior to testing
- Three specimens for each mixture were tested, and the average values are reported.

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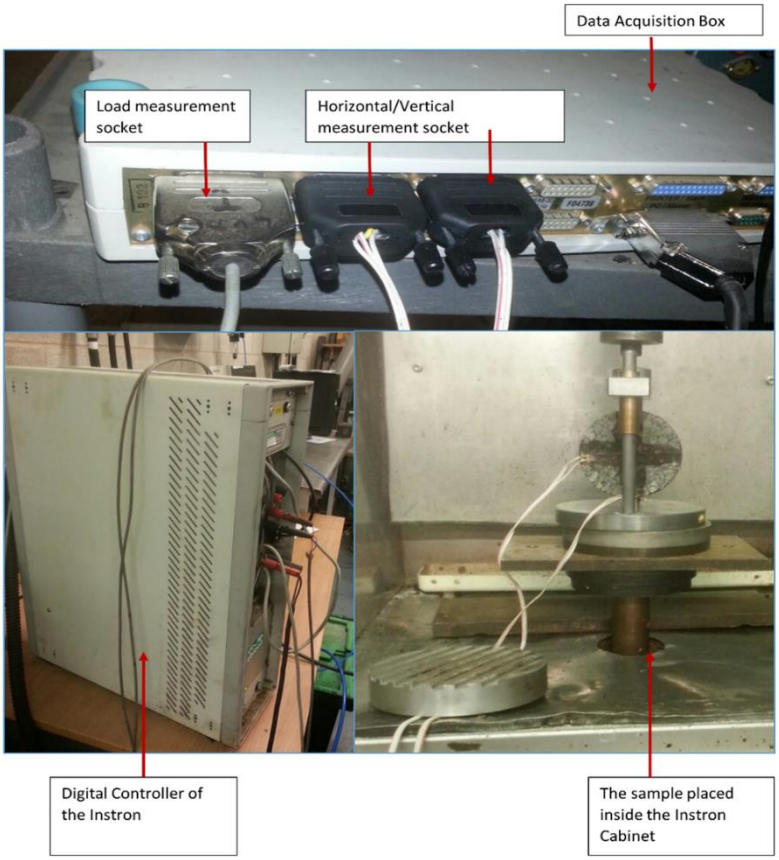
706 *Fig. 5 RLAT testing configuration in NAT*



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708 *Fig. 6. The IDT configuration in the Instron*

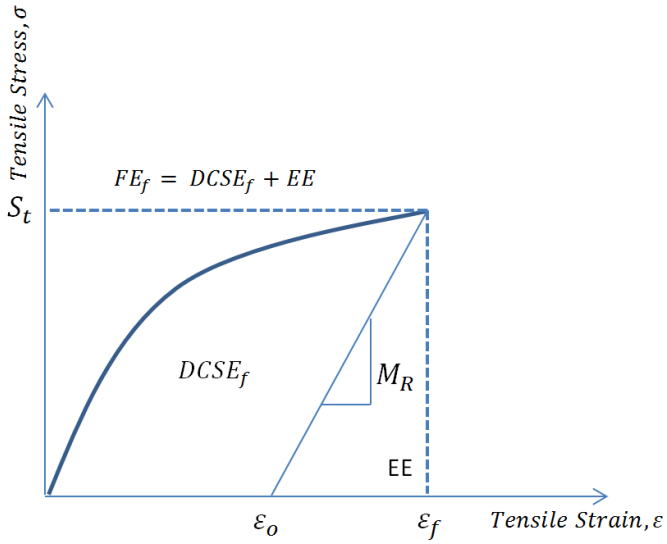


Fig. 7. Tensile strength versus tensile strain plot

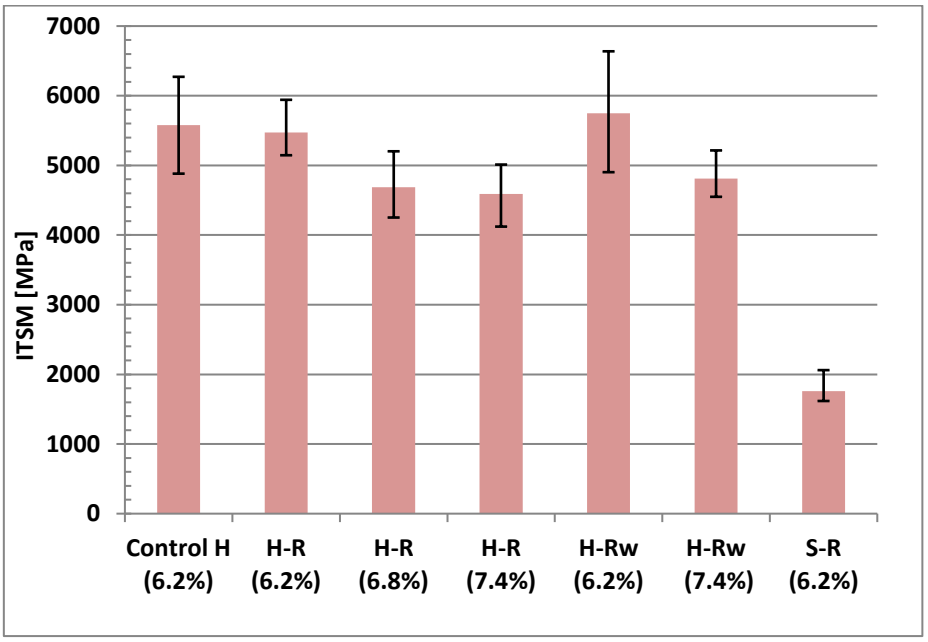
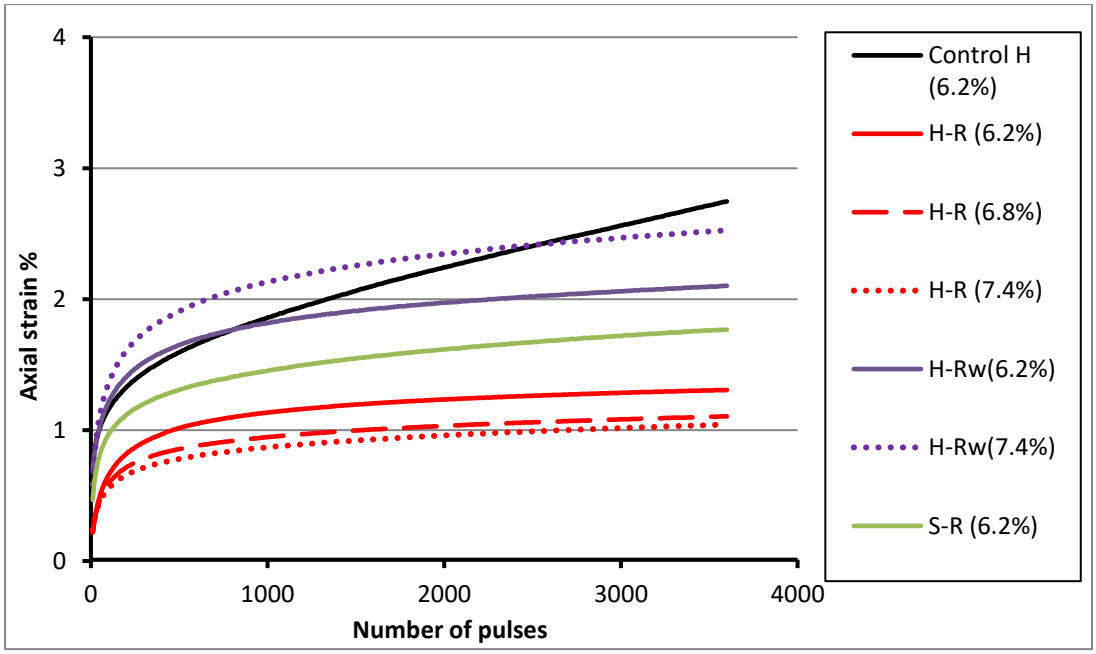


Fig. 8. ITSM results for the different mixtures



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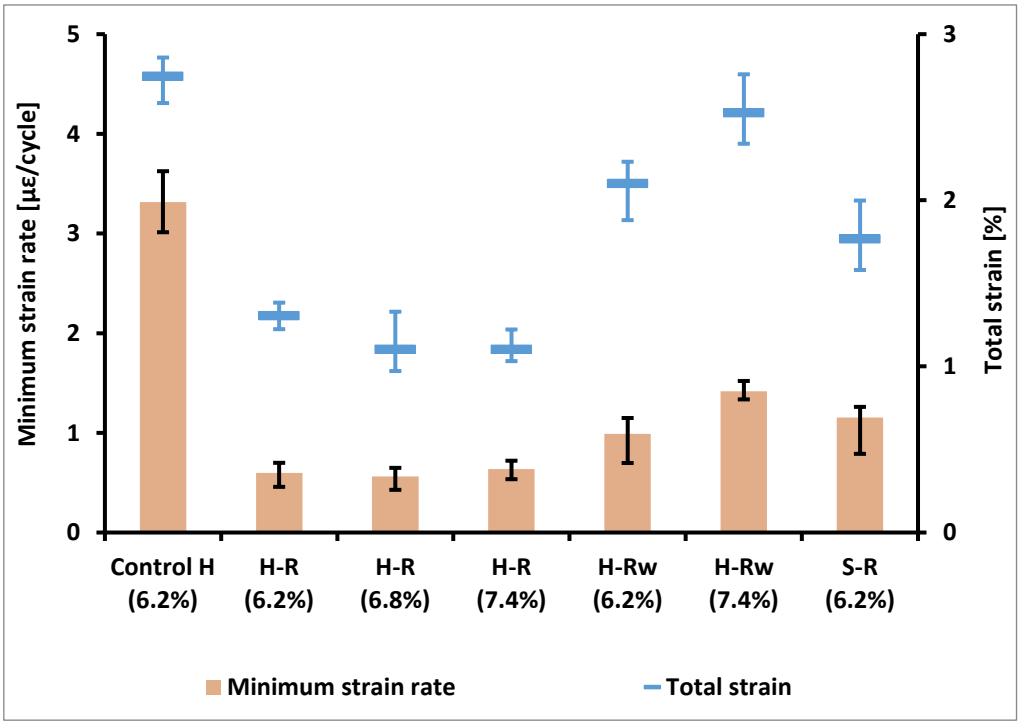
716 *Fig. 9 RLAT results of different mixtures tested at 100kPa stress and at 50°C temperature*



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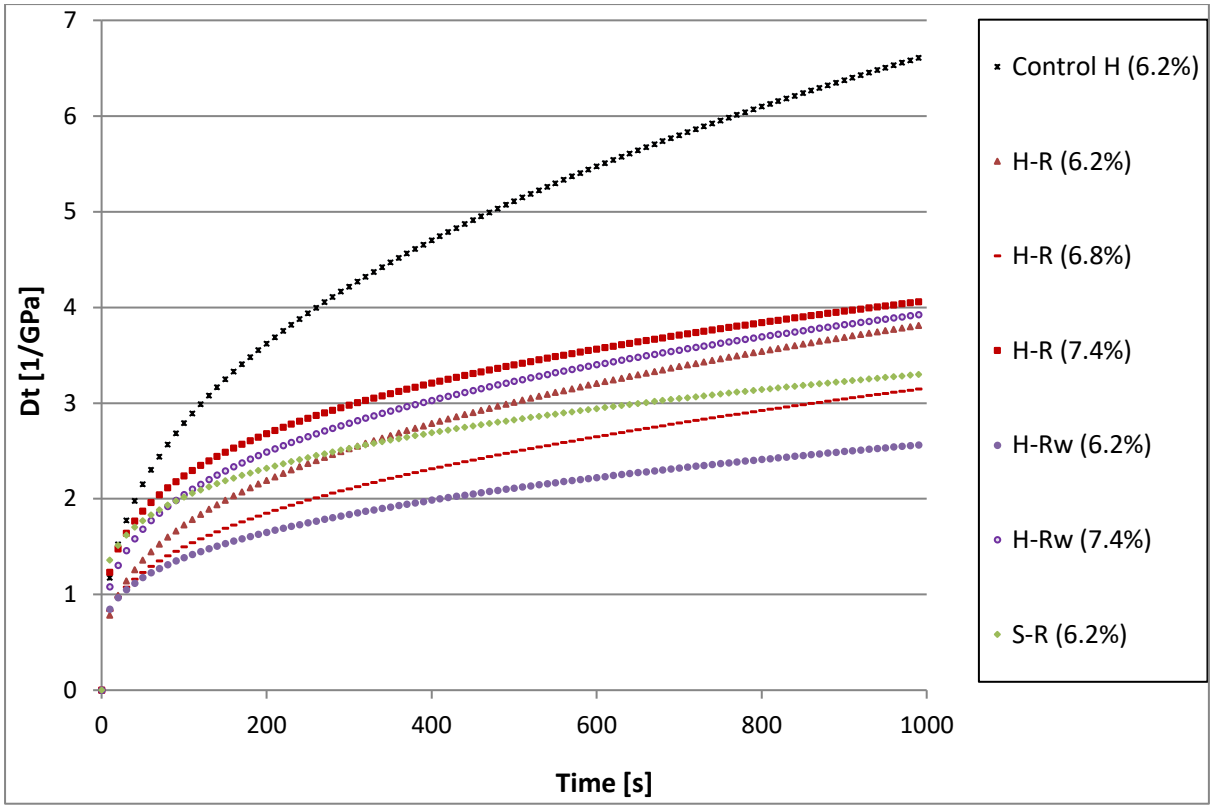
718 *Fig. 10: RLAT results in terms of the minimum strain rate and total strain*



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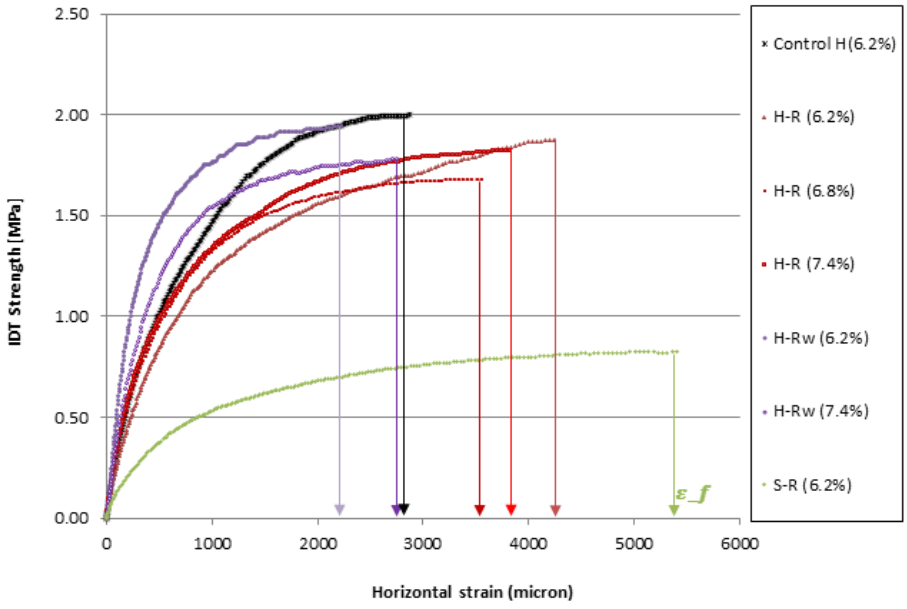
720 *Fig. 11 Creep compliance curves evolution with time for the different mixtures*



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722 *Fig. 12 Stress-Strain curve from the indirect tensile strength test for the different mixtures*

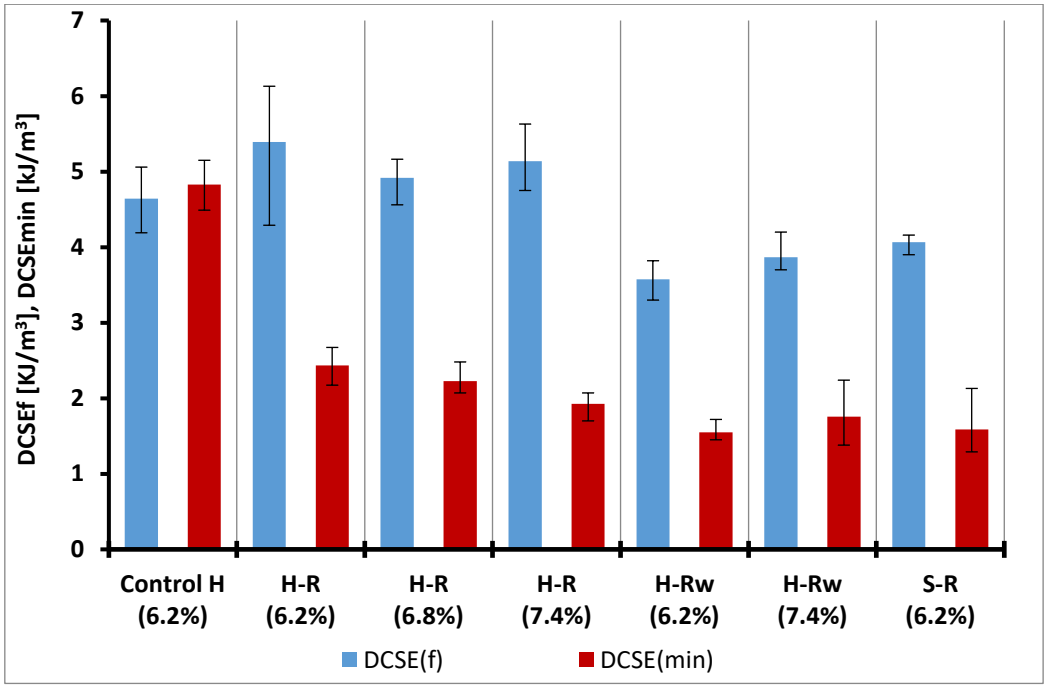


Fig. 13 $DCSE_f$ and $DCSE_{min}$ for the different mixtures

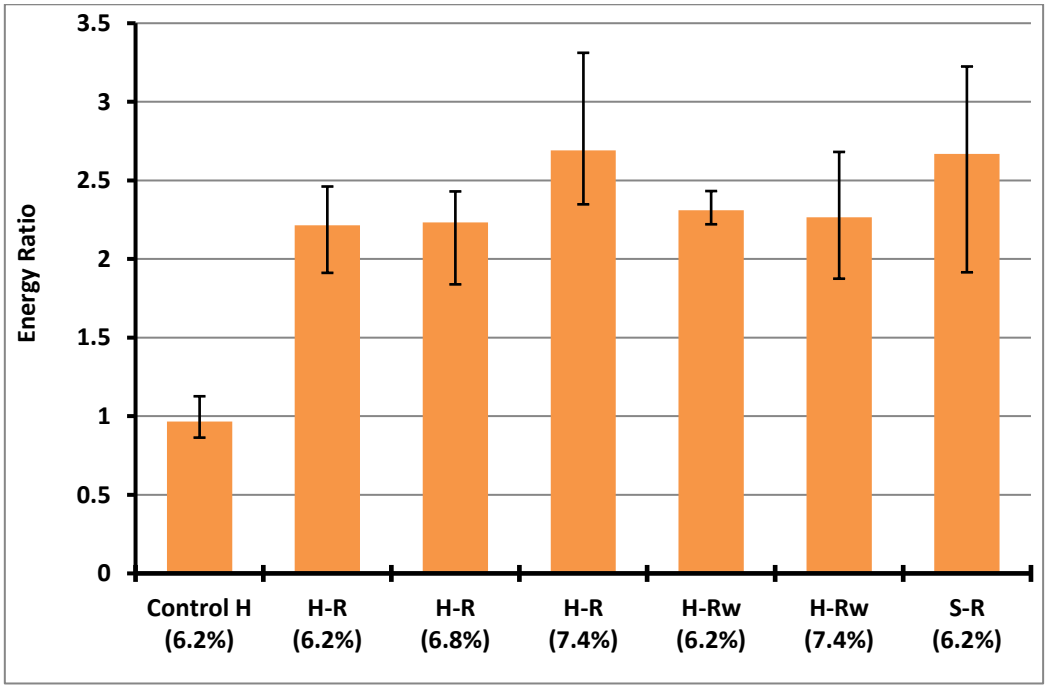
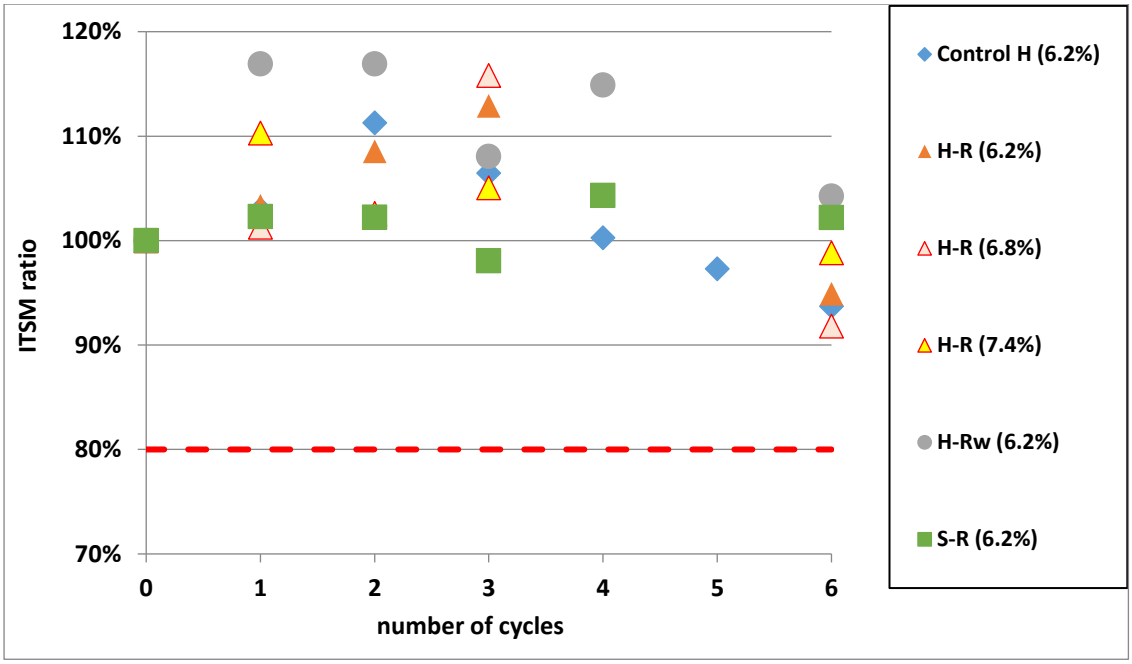


Fig. 14 ER for the different mixtures



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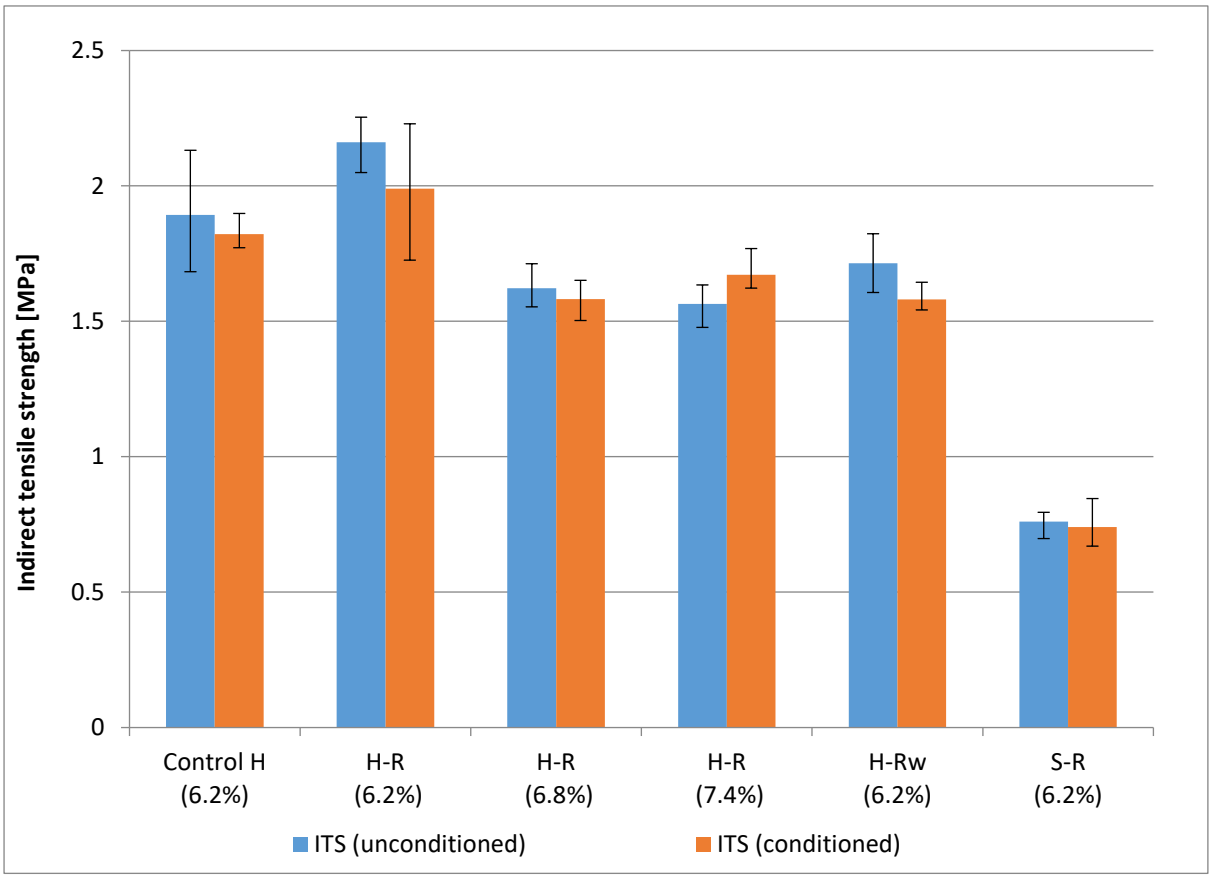
730 *Fig. 15 ITSM ratio for the mixtures after several water immersion cycles*



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732 *Fig. 16 ITS values for the conditioned and unconditioned specimens*