Rutting analysis of different rubberized stone mastic asphalt mixtures: from binders to mixtures

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Abstract: Stone Mastic Asphalt (SMA) has been broadly used on heavily trafficked roads and motorways in the UK due to its known stability and durability. In this study, several sets of SMA mixtures were produced using different rubberised bitumens, including a Fischer–Tropsch wax pre-treated rubberised bitumen. Properties associated with rutting were evaluated using both linear and nonlinear viscoelastic analyses, using different test methods such as the Strategic Highway Research Program (SHRP), Shenoy rutting parameter, zero shear viscosity (ZSV) and multiple stress creep recovery (MSCR) tests. The rutting resistance of the resulting SMA mixtures was assessed using the Repeated Load Axial Test (RLAT). The addition of rubber was expected to enhance rutting resistance of these materials. The results indicated that among the binder rutting parameters assessed, the non-recoverable creep compliance (Jnr) computed from the MSCR test, showed the best correlation with the rutting resistance of the corresponding asphalt mixtures. Finally, a more fundamental analysis was provided by assessing the conditions of binder films that would be experienced in the mixtures.

Keywords: stone mastic asphalt, crumb rubber, rutting, asphalt, Fischer–Tropsch wax

Highlights

- Rutting resistance of binders and mixtures are well correlated when the realistic strain conditions are taken into account
- SMA produced using rubberised bitumens resulted in highly rut resistant mixtures
- MSCR test can measure the rutting resistance of binders

1. Introduction

Stone Mastic Asphalt (SMA) comprises a coarse aggregate skeleton filled with a high content of bitumen/filler mortar, and a relatively high binder content. The stone-to-stone aggregate offers excellent rutting properties while the bitumen/filler mortar offers good fatigue properties. One of the known issues associated with SMA is the risk for binder drain down during production and transportation to site. Often additives such as cellulose fibres are used to stabilise the mixture and prevent binder drain down [1-5]. Inclusion of recycled tyre rubber in bituminous materials offers some advantages in terms of enhancing the pavement performance and helping solve environmental problems that are related to hazardous landfill [4, 9]. Recycled tyre rubber has been successfully used in SMA and other applications such as surface dressing (chip seal) binders and SAMIs [8-10]. The gap grading of SMA mixtures has proven to adequately accommodate the thicker film thicknesses of rubberised bitumen [12]. The high viscous nature of rubberised bitumens can also prevent the binder drain down associated with SMA mixtures [4].

The combined parameters of traffic loading and high ambient temperatures cause rutting in flexible pavements. Bituminous mixtures achieve their resistance to rutting through aggregate skeleton interlocking and the viscoelastic properties of the binder. Identifying the viscoelastic parameters of modified binders that can be used to predict the rutting resistance of mixtures is important for the asphalt industry and producers to help develop and optimise the quality of binders. The viscoelastic properties of modified binders, and particularly of rubberised binders, is fundamentally different from unmodified bitumens, and thus, more comprehensive reviews are needed to investigate them. The relationship between the linear viscous component of unmodified bitumens and the expected rutting resistance of pavement is well established in the literature [13-19]. The linear viscous parameters have, however, failed to effectively characterise modified binders. Modified binders have complex response to the different stress/strain levels and loading rates that may provide misleading correlations when tested under only linear conditions [19-22]. Thus, assessing the rutting properties of rubberised binders using different strain conditions that are associated with different damage mechanisms, is one objective of this study.

The linear and nonlinear viscoelastic properties of binders were determined and used to characterise the rutting behaviour of rubberised bitumens. The addition of a Warm Mix Asphalt (WMA) additive to rubberised asphalt mixtures provides better workability and handling during mixture production [7, 23-25]. Two base bitumens were selected with large differences in their physical and rheological properties in order to identify the effect of the base bitumen on the interaction mechanism and the final rubberised bitumen properties; a hard base bitumen with a penetration of 40 dmm and a soft bitumen with a penetration of 200 dmm were, therefore, chosen. Rubber modification for a soft base can significantly increase the performance temperature span of the resultant materials which make it a very effective option for pavements that are prone to both low temperature cracking and permanent deformation. This study also investigates the effect of combining the Warm Mix Additive (Fischer–Tropsch (F-T) wax) and crumb rubber on the rutting behaviour of binders and mixtures. The rutting resistance of binders were first assessed using the SHRP rutting parameter, Shenoy rutting parameter, zero shear viscosity (ZSV) and multiple stress creep recovery (MSCR). In order to establish a relation between the binder rutting properties with their mixtures, Repeated Load Axial Test (RLAT) was then used to assess the rutting resistance of the asphalt mixtures. The possible correlations between the rutting resistance of binders and their mixtures were, subsequently, assessed.

2. Materials and specimen production

2.1 Aggregate

Granite aggregate and limestone filler were used in this study. The design recipe of the asphalt mixtures (for the conventional and rubber modified mixtures) was selected from the

BS EN 13108-5 and BSI PD 669 standards, e.g. stone mastic gradation (10mm) suitable for surface courses. The SMA gradation is shown in Fig. 1.

2.2 Binders

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

- Control paving grade bitumen “H”: this bitumen is considered as a control and labelled “H” throughout the study. The penetration and softening point of this bitumen were 40 dmm and 51.4 °C, respectively.

- Rubberised bitumen “H-R”: this rubberised bitumen was produced by adding 15.25% of recycled rubber by total mass to bitumen H using the wet process. The neat bitumen H was preheated to 180°C and then the required amount of recycled tyre rubber was added gradually while mixing at 180°C using a Silverson L4RT high shear laboratory mixer for 120 minutes. Many researchers have recommended the use of the high shear mixers to manufacture rubberised binders with superior properties [25-29]. The recycled tyre rubber used in binder H-R, was obtained from discarded truck and passenger car tyres using ambient grinding. The average diameter size of the rubber particles is 300µm.

- Rubberised bitumen “S-R”: 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.

- Rubberised bitumen “H-Rw”: the base bitumen H was modified using recycled tyre rubber that had been pre-treated with a special oil and F-T wax. The details of pre-treatment process are not available as the recycled rubber was provided by a third-party. The F-T wax allows a reduction in compaction 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 recycled rubber used in binder H-Rw was derived from 100% recycled truck tyres using the cryogenically grinding method.

2.3 SMA mixtures production

Fig. 2 shows the mixing and compaction equipment used to produce the asphalt mixtures as follows:

1. Aggregate and filler mixed at the defined mixing temperature in mixer.
2. The required amount of binder (pre-heated at defined temperature) was then added and the mixing continued for three minutes.
3. The same binder content of 6.2% was used for all mixtures as specified in BS EN 13108-5 and BSI PD 6691.
4. Mixture then placed in a preheated slab mould.

5. Compacted using a smooth steel roller in accordance with BS EN 12697-33 to achieve the desired asphalt thickness (~60mm) which corresponds to 4% designed air voids.
6. The mixing and compaction temperatures were identified to facilitate good binder coating of the aggregates and to achieve compaction at the prescribed air voids content (4%).
7. For H-R mixtures, the mixing temperature was selected to be 190±5 °C and 170±5 °C for compaction and for control, S-R and H-Rw mixtures, 170±5 °C and 150±5 °C, respectively.
8. The cellulose fibres was only included in the control mixtures at 0.3% of the bitumen.
9. 100 mm diameter and 40mm thickness cores suitable for RLAT tests were cored and trimmed from the slabs.

3. Testing Programme

3.1 Binder Testing

All binders underwent artificial ageing using the Thin Film Oven Test (TFOT) to simulate the short-term ageing occurring during the manufacture of asphalt mixtures. The binder tests performed on TFOT residues were deemed important to establish a correlation between the rutting properties of binders and their mixtures. An isothermal high temperature of 50^{o}C was chosen as approximates the maximum pavement temperature of most UK regions. The high-temperature properties of binders were assessed using the following test methods and parameters.

SHRP Rutting Parameter

The SHRP rutting parameter (|G*|/sin δ) of the TFOT aged residues was determined at 50^{o}C and at 1.59 Hz using a Malvern DSR CVO Model. Strain control mode within the LVE region was applied on the sample sandwiched between two 25mm diameter parallel plates . The gap between the plates was 2mm for rubberised bitumens and 1mm for the neat bitumen to minimise the effect of rubber particles on the viscoelastic measurements [5, 6]

Shenoy Rutting Parameter

The Shenoy rutting parameter was also determined using the same testing conditions used with SHRP parameter but at 0.1 Hz frequency and calculated using equation 1.

$$Shenoy\ Rutting\ Parameter = {G^*}/{(1-(1/\sin\delta\tan\delta))} \quad (1)$$

Zero Shear Viscosity ZSV

The ZSV parameter was derived using the simplified Cross model to fit the data of the complex viscosity measurements. The complex viscosity measurements were obtained at test temperature of 50˚C through oscillatory sweep frequency tests (0.1 – 10 Hz) using the DSR. The Cross model shown below was used to extrapolate the complex viscosity to a very low or zero frequency.

$$\eta^* = \frac{ZSV}{1+(K\omega)^m} \quad (2)$$

where η^* is complex viscosity; ZSV is zero shear viscosity; ω is frequency (rad/s), K and m are constants.

Multiple Stress Creep and Recovery (MSCR)

The MSCR test comprised repeated creep-recovery cycles of 1 second applied creep shear stress and 9 seconds recovery period. The MSCR test was conducted in accordance with the ASTM D 7405 test method. Additional multiple stress levels (100, 400, 1600, 3200, 6400, 12800 and 25600 Pa) were considered to examine the stress sensitivity and nonlinearity of rubberised binders. 10 cycles of repeated creep-recovery were applied at each stress level. The test was conducted at a temperature of 50˚C.

3.2 Mixture Testing

The rutting resistance of mixtures was evaluated using the Repeated Load Axial Test (RLAT) in accordance with BS DD 226 using the Nottingham Asphalt Tester (NAT) equipment. The configuration of the RLAT is shown in Fig. 3 inside the NAT. The test was conducted at a temperature of 50^{o}C by applying axial stress of 100 kPa for 3600 cycles. The average value of at least three specimens were reported for each mixture.

4. Results and discussion

4.1 Rutting Resistance of Binders

It should be mentioned that the bitumen ‘H’ did not undergo the same heating history of other binders during the rubber modification, i.e. heating up at 180^{o}C and for 120 minutes. Although this may indicate a bias analysis towards the modified binders, the rubber modification (as will be seen in the next sections) changed considerably the rheological properties. For example, the SHRP rutting parameter (the least affected by rubber modification in comparison to other parameters) increased by 2 to 3 times by rubber modification. It has been shown that the SHRP rutting parameter of the control bitumen ‘H’ increased by 50% when subjected to TFOT ageing [31]. Heating up of relatively large quantity of bitumen (at least 2 kg) has far less effect than the effect of ageing thin film of bitumen (as the case under TFOT conditions). Thus, it is not anticipated that the heating up of the bitumen ‘H’ would have significant impact on the findings.

SHRP Rutting Parameter

The SHRP rutting parameter is derived from loss compliance ($J''= \sin\delta/|G^*|$) measurements of binders. The parameter indicates the binder contribution to the rutting resistance of asphalt mixtures [15]. Binders with a reduced (J''), i.e. increased SHRP rutting parameter, are preferable for controlling the rutting distress as the unrecovered strain (γ_{unr}) is minimised. The SHRP rutting parameter values for the different binders measured at a frequency of 1.59 Hz and temperature of 50 ^{o}C are shown in Fig. 4. The addition of rubber has resulted in a significant increase in the SHRP rutting parameter for binders H-R and H-Rw in comparison to their base bitumen. The binder H-Rw which was manufactured using tyre rubber pre-treated by the FT-wax, exhibited the largest SHRP rutting parameter. This indicates the positive contribution of F-T wax to the rutting resistance of binders by forming a crystal structure when the temperature drops to lower than the melting point of the F-T wax. The S-R binder which was manufactured using a very soft bitumen, e.g. 200 dmm penetration, had the smallest SHRP rutting parameter. The ranking of different binders in terms of the SHRP rutting parameter are as follows:

H-Rw > H-R> H > S-R

Shenoy Rutting Parameter

The Shenoy Rutting Parameter is considered as an improvement to the SHRP rutting parameter [16]. The main modification corresponds to the magnification of the elastic component of the binder, i.e. phase angle, making it more appreciative of the addition of polymeric modifiers to the binders. Fig. 5 shows the values of the Shenoy rutting parameter measured at a frequency of 0.1 Hz and test temperature of 50°C. The main difference shown in the Shenoy Rutting Parameter is the improvement in the binder S-R which confirms the sensitivity of this parameter to the addition of rubber. Fig. 5 also shows that the H-Rw binder exhibited a considerable increase which again reflects the increase in elastic response (reduced phase angle) of the H-Rw binder.

The ranking of different binders in terms of the Shenoy rutting parameter are as follows:

H-Rw > H-R> S-R > H

Zero Shear Viscosity ZSV

The ZSV reflects the binder's response to cyclic oscillatory loads within the linear viscoelastic regime. Fig. 6 shows the values of complex viscosities measured at 50°C and fitted using the simplified Cross Model. As expected, the base bitumen H demonstrated Newtonian fluid-like behaviour, i.e. the complex viscosity measurements are almost independent of the applied frequency. In this case, the ZSV can be easily extrapolated by the asymptote. The rubberised binders, however, exhibited Non-Newtonian behaviour (shear thinning) and they were sensitive to the frequency. The results of complex viscosity highlighted the complex response of rubberised binders to the shear rate. For example, the binder S-R is ranked below the base bitumen H at high frequencies, but it is superior to bitumen H at low frequencies.

The ranking of different binders in terms of the ZSV rutting parameter are as follows:

H-Rw > H-R> S-R > H

Multiple Stress Creep and Recovery (MSCR)

The non-recoverable creep compliance (Jnr) is highly sensitive to the stress dependency of modified binders. It is shown to accurately predict the binder rutting performance into the asphalt mixtures and it is proposed as an alternative to the SHRP rutting parameter [32]. The MSCR test enables the binder response at different stress levels to be measured, i.e. within and outside the viscoelastic region making it appropriate for specification purposes for both unmodified and modified binders [20, 33]. The binder films within the asphalt mixtures are subjected to strain levels considerably greater, e.g. 100 times, than the overall average strain of the asphalt mixtures. It is, therefore, important to measure the J_{nr} of binders at high strains.

The J_{nr} and the percentage of recovery results measured over stresses ranging from 0.1 kPa to 25.6 kPa are shown in Fig. 7 and Fig. 8, respectively. The effect of the applied shear stress on the measured J_{nr} is remarkable for all rubberised binders, i.e. shear thinning with J_{nr} increasing with the applied shear stress. The control bitumen unlike the rubberised binders exhibited Newtonian behaviour, i.e. the measured J_{nr} maintained the same measurements regardless of the stress magnitude. Different ranking for the binders was observed for the rutting parameters of binders tested using the dynamic oscillatory tests. This was expected as there are many variables associated with the oscillatory tests and creep and recovery tests. These variables include delayed elasticity, sensitivity to the level of stress and loading rate, relaxation times and nonlinearity. Fig. 8 shows that the recovery ability of rubberised binders has considerably improved in comparison to the base bitumen. Especially, the binder H-R exhibited a good recovery property even under very high stresses. The H-Rw appeared to step down a level in ranking when subjected to high stresses under the MSCR conditions. The pre-treatment by waxes (for H-Rw binder) can make the binders less flexible due to the formation of crystal lattice structure. The lattice structure of waxes makes the modified binders stiffer especially under small strains (using the dynamic oscillatory tests) but increases the stress sensitivity of the modified binders when testing under high stresses/strains (using the MSCR test).

Fig. 9 shows one cycle measurements taken from the MSCR test at a stress level of 25.6 kPa, and temperature of 50 °C for binders S-R and H. The results in Fig. 9 show that the rubberised binder S-R was able to recover significant amounts of the total strain while the control bitumen did not have this ability.

The ranking of different binders in terms of the J_{nr} rutting parameter are as follows:

H-R > H-Rw > S-R ≥ H

Based on the four different approaches (SHRP, Shenoy, ZSV and MSCR), the ranking of the different binders varies depending on the rutting parameter used.

In the next sections, the rutting resistance of mixtures manufactured using the same binders are evaluated to establish a correlation for the rutting resistance between binders and mixtures.

4.2 Rutting Resistance of SMA mixtures

Fig. 10 shows the results of axial strains development against load cycles for the different mixtures measured at a test temperature of 50 °C using the RLAT. Three characteristic phases are normally formed when plotting the axial strain against load cycles termed the primary phase, secondary phase and tertiary phase. The primary phase is generated from the rapid increase in the vertical strain caused by the combination effects of loading platens seating and material densification. The secondary phase starts when the axial strain rate gradually decreases and reaches a steady state. At this stage, the relationship between the strain and the load cycles are almost linear. The tertiary phase is the last stage and starts when the strain rate increases rapidly indicating the failure of the sample. However, the tertiary phase was not reached for any of the mixtures tested in this study. The main analysis parameters used to evaluate the rutting resistance of mixtures tested using the RLAT are (i) the cumulative axial strain at the end of the 3600 load pulses or at the initiation of the tertiary phase, and (ii) the slope of the steady state phase (minimum strain rate).

The slope of the second phase (minimum strain rate), i.e. the steady state phase, is determined from a segment between 1500 to 3000 pulses as follows;

$$Minimum\ strain\ rate\ \left[{}^{\mu\varepsilon}/_{cycle}\right] = \frac{\varepsilon_{3000} - \varepsilon_{1500}}{1500}\ x\ 10^{-6} \qquad (\mathbf{3})$$

where;

ε_{3000} = accumulated strain at 3000 pulses

ε_{1500} = accumulated strain at 1500 pulses

Fig. 11 shows the RLAT results analysed to determine the total accumulated strain at the end of 3600 pulses and the minimum strain rate. The average value of at least three replicates are reported with the range bars represent the maximum and minimum values. The improvement gained by the addition of rubber, particularly for the SMA (H-R) mixture, is clearly seen in the RLAT results of rubberised mixtures. The RLAT results for mixtures produced using the binder S-R are very interesting. The binder S-R was manufactured using very soft bitumen (penetration of 200 dmm), however, the rutting resistance at a temperature of 50 °C for the asphalt mixture made with this binder was better than the control mixtures which was made with a base bitumen with a penetration of 40 dmm. The S-R mixture also shows comparable performance to the H-Rw mixture. A t-test (two-sample assuming equal variances) was carried out between the means of the minimum strain rate for S-R and H-Rw mixtures. It was concluded that the difference between the minimum strain rate of S-R and H-Rw was not statistically significant.

Such results confirm the positive effect of rubber to enhance the high temperature properties of bituminous materials and the importance of rubber modification using soft base bitumen.

4.3 Rutting susceptibility: From binder to mixture

Correlation between binder rutting parameters and RLAT

The different analysis and test methods use to characterise the rutting resistance of binders resulted in different rankings for the binders considered in this study. Identifying the test method and parameter that can reliably reflect the binder contribution in resisting rutting distress is one of the main objectives of this study. Therefore, the different rutting parameters of the binders were correlated with the rutting parameters of the asphalt mixtures. The minimum strain rate obtained from the RLAT measurements for the asphalt mixtures was selected to establish the correlation with the binder parameters. The minimum strain rate parameter for the mixtures was selected over the total strain because the latter is largely influenced by the initial conditioning of the test, i.e. the initial seating of loading platens and the orientation of the aggregate interlock for different specimens.

The different asphalt mixtures are ranked in terms of the minimum strain rate as follows:

SMA (H-R) > SMA (H-Rw) > SMA (S-R) > SMA (H)

The binder rutting parameters obtained from the MSCR test were the only ones among the other parameters that correctly ranked the binders with respect to the mixture performance. The SHRP rutting parameter did not provide an accurate ranking with the mixtures which confirms its inappropriateness for characterising the modified binders. The ZSV and Shenoy parameters provided better ranking prediction to the rutting performance of the mixtures but was still inferior to the MSCR test parameters.

Fig. 12 (a to f) presents correlations for the rutting parameters of the binders and mixtures based on linear regression analysis. Fig. 12 (a, b, and c) showed poor correlation between the rutting parameters of the binders obtained from the dynamic oscillatory test and the minimum strain rate of the mixtures.

The correlations based on the J_{nr} parameter obtained from MSCR, shown in Fig. 12 (d and e), were significantly improved. Fig. 12 (f) shows poor correlation ($R^2 = 0.42$) for the J_{nr} tested at a high stress level of 25.6 kPa. However, a significantly improved correlation ($R^2 = 0.99$) can be obtained if the S-R point is removed, as shown in Fig. 13. The binder S-R was made using a very soft base bitumen and exhibited considerable increase in the J_{nr} at high stresses. For rubberised binders manufactured using soft base bitumens, the linkages formed between bitumen and rubber are weaker at high strains and these physical linkages cannot act as a single phase in a very soft medium [6]. This greatly affects the deformation resistance of modified binders at high stresses and this resistance would be mainly controlled by the properties of base bitumen. Moreover, the binder S-R experienced a considerably high strain value (~ 960%) when the stress level reached 25.6 kPa. This magnitude of strain is unlikely to occur under the RLAT condition, even though high strains are expected for the binder films in a mixture.

In the next section, the effect of strain levels is analysed to provide a better understanding about the rutting resistance of materials at high temperatures.

Establishing a more fundamental relationship between binders and mixtures

The binder films within asphalt mixtures when subjected to loading undergo a wide range of strain distributions. The distribution and magnitude of strains vary depending on the compositional properties of asphalt mixtures, i.e. air voids, aggregate size and grading, and the properties of the constituent materials [34, 35]. It has been shown that the strain within binder films, based on finite-element analysis, can be between 10 and 100 times the bulk strain of the mixture [34]. The approximate strains that binder films experience within the mixtures are, therefore, considered to provide a fundamental relationship between the rutting parameters of binders and asphalt mixtures. The average strains of binder films within the mixture were estimated by multiplying the total accumulated strain from RLAT results by the median value (55) and compared with the binder strains that occur in the MSCR as shown in Table 1. The average total strains of 10 cycles, obtained from the MSCR test at each stress level, are presented in Table 1 together with the estimated binder film strains. The shaded values shown in Table 1 represent the binder strains under the MSCR conditions that are close to the estimated binder strains under the RLAT conditions.

Table 1 shows that each binder needed a different stress level under the MSCR conditions to induce the same estimated strain that may occur under the RLAT conditions. For binders S-R and the base bitumen H, the MSCR stress levels needed to induce approximately the same strains under RLAT conditions, were 3.20 kPa and 6.4 kPa, respectively. Table 1 shows that for binders H-R and H-Rw, the MSCR stress levels that corresponded to the RLAT conditions had to be determined by interpolation between two stress levels.

The J_{nr} for each binder were determined at a stress level that induced approximately the same strain under RLAT conditions. Fig. 14 shows linear fitted correlation between the J_{nr} of the binders and the minimum strain rate of the mixtures. The results in Fig. 14 suggest that a good correlation can be obtained between the binder rutting parameter J_{nr} and the minimum strain rate when the strain conditions of binders and mixture testing are considered. The correlation ($R^2 = 0.97$) shown in Fig. 12 (d) is better than the correlation in Fig. 14. However, a closer look into the correlation in Fig. 12 showed that the J_{nr} at 0.1 kPa stress level did not actually differentiate between the rutting resistance of binders H-R and H-Rw although their mixtures exhibited large differences in rutting performance. On the other hand, the J_{nr} determined based on matching the same strain conditions in the binder and mixture testing was able to differentiate between the rutting resistance of those binders and reflect that correctly into the asphalt mixtures.

5. Conclusions

This study has presented the results of an assessment of the rutting performance at high temperature for different rubberised binders and a control base bitumen in addition to their asphalt mixtures. The DSR was used to measure the binder's response at high temperature when subjected to dynamic oscillatory loads or creep and recovery loads. The RLAT was used to evaluate the permanent deformation resistance at high temperatures for asphalt mixtures. The results from the binder testing were analysed to obtain different rutting parameters for the binders in order to establish a correlation with the rutting resistance of the mixtures.

The conclusions below are presented based on the analysis of this study:

1. The rutting resistance at high temperature for binders and mixtures was significantly enhanced by the addition of rubber. The addition of rubber to a very soft bitumen, e.g. S-R (200 dmm penetration), enhanced the rutting resistance of both the binder and mixture to a point that made them better than the asphalt mixture made with bitumen H (40 dmm penetration). Using a very soft bitumen is known to provide better stress relaxation and resist low temperatures cracking. Thus, the addition of rubber to a soft bitumen will produce bituminous materials suitable for resisting the defects at both low and high in-service temperatures.
2. The results have shown that the rutting parameters for binders derived from the dynamic oscillatory test failed to adequately characterise the rutting resistance of rubberised binders. On the other hand, the rutting parameters derived from the MSCR test accurately reflected the binder contribution to the rutting resistance of the asphalt mixtures.
3. Among the different binders used in this study, the rubberised binder H-R which was made using ambiently ground rubber showed the best rutting resistance followed by the binder H-Rw which was made using cryogenically ground rubber followed by S-R and H.
4. The results have shown that considering the same strain conditions that would occur for the binder films under the binder testing conditions and the mixture testing conditions, can provide a more fundamental approach to assess the rutting resistance of binders and mixtures. In this regard, the MSCR test offers the readiness to measure the binder's response at different stress levels. This enables the stress level that would induce approximately similar strains occur under the mixture conditions to be selected.
5. The correlations have been developed on only limited data set and materials. More data and different materials will be required for future researches to draw a universal relationship.

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Table 1. The estimated binder strains under the RLAT conditions and MSCR strains for the different binders

	H	**H-R**	**H-Rw**	**S-R**
Estimated strain%	**151.03**	**71.83**	**115.54**	**97.17**
Stress level [kPa]	MSCR strains %			
0.10	2.25	0.65	0.53	2.82
0.40	8.91	2.68	2.14	11.30
1.60	35.48	10.89	9.08	46.08
3.20	71.51	21.94	18.58	99.25
6.40	143.94	45.06	38.65	222.49
12.80	288.09	97.43	83.43	446.26
25.60	582.32	220.15	198.91	959.64

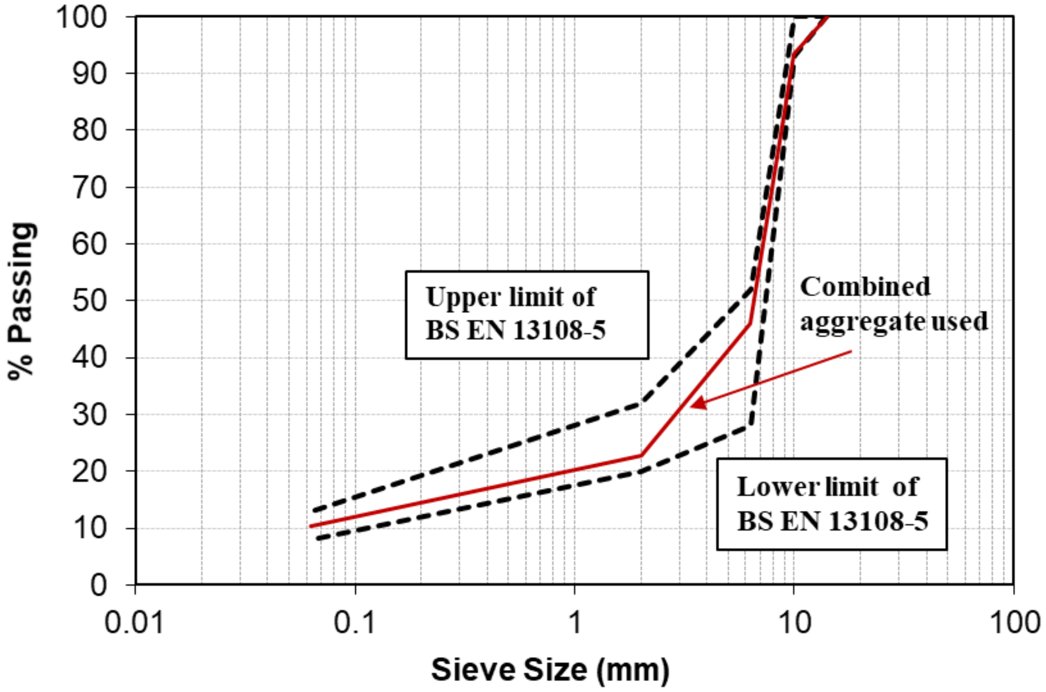


Fig. 1. The 10mm SMA gradation in accordance with BS EN 13108-5 and BSI PD 6691

Fig. 2. (a) Mixer, and (b) Steel roller

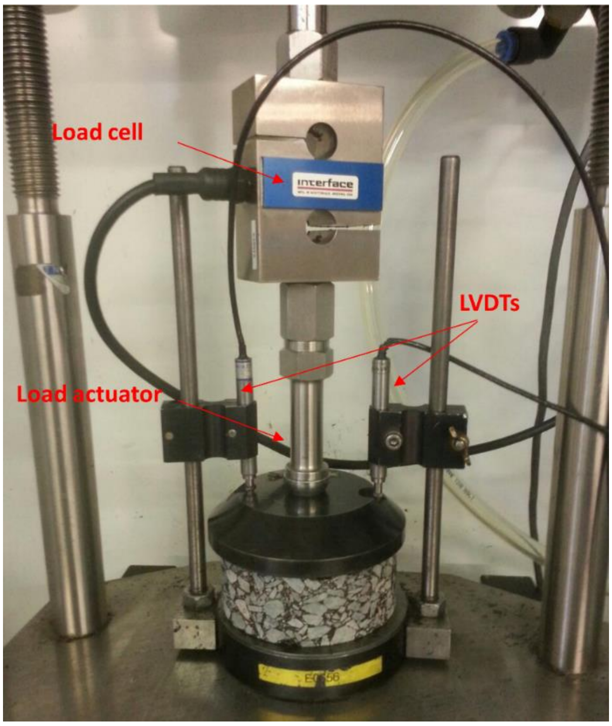


Fig. 3. RLAT testing configuration in NAT

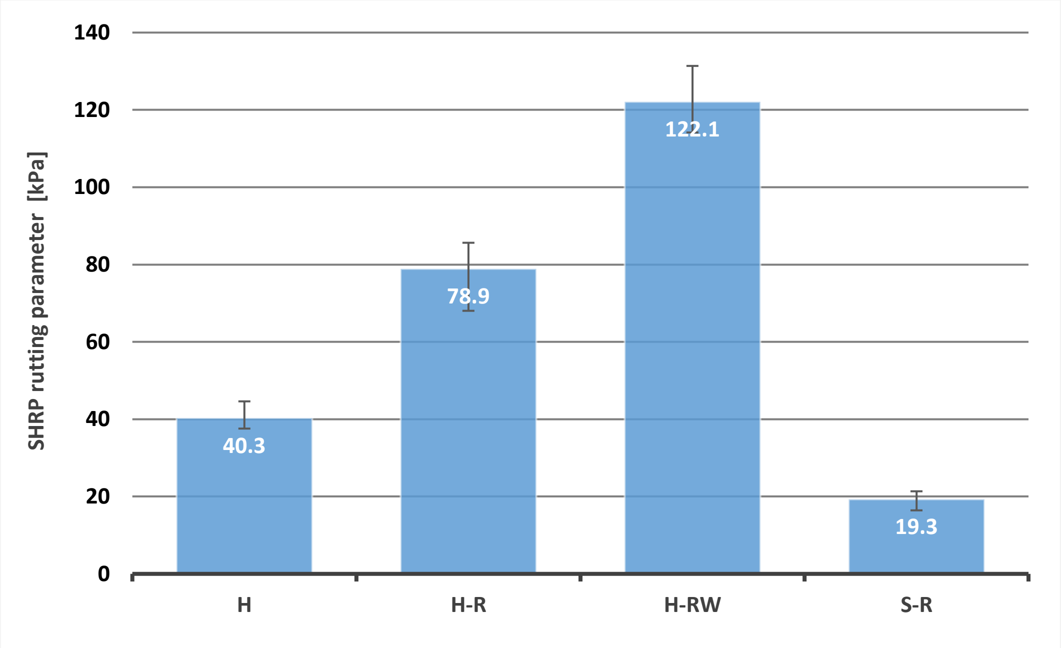


Fig. 4. The results of SHRP rutting parameters at 50 °C

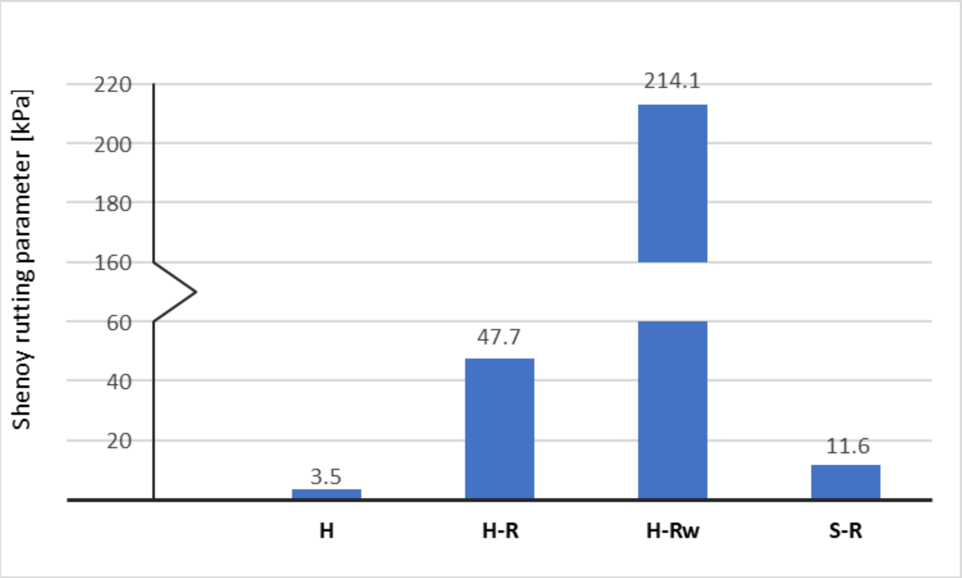


Fig. 5. The results of Shenoy rutting parameters at 50 °C

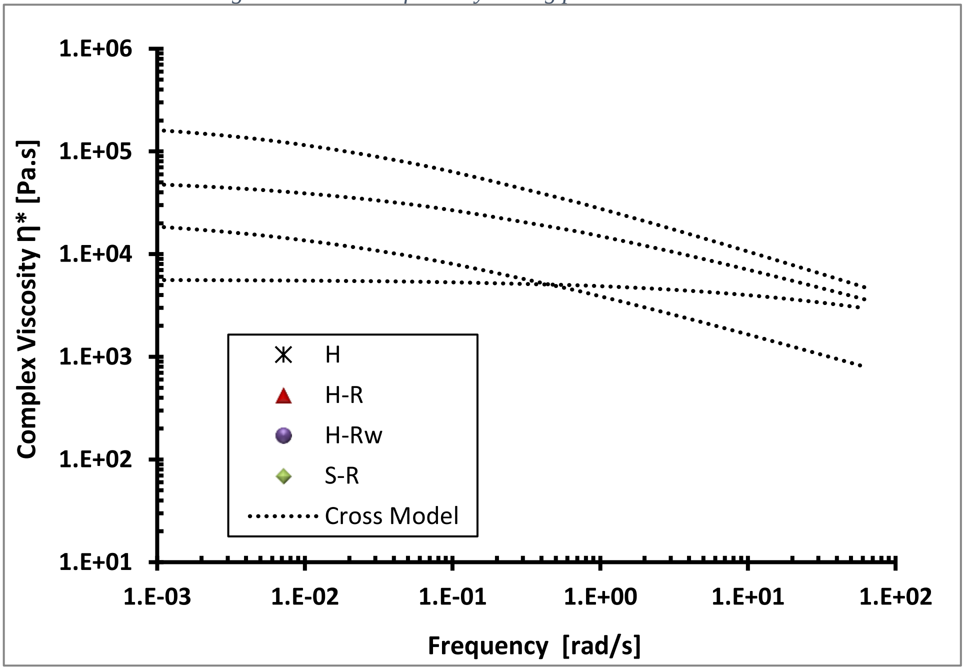


Fig. 6 Complex viscosity of different binders at 50 °C

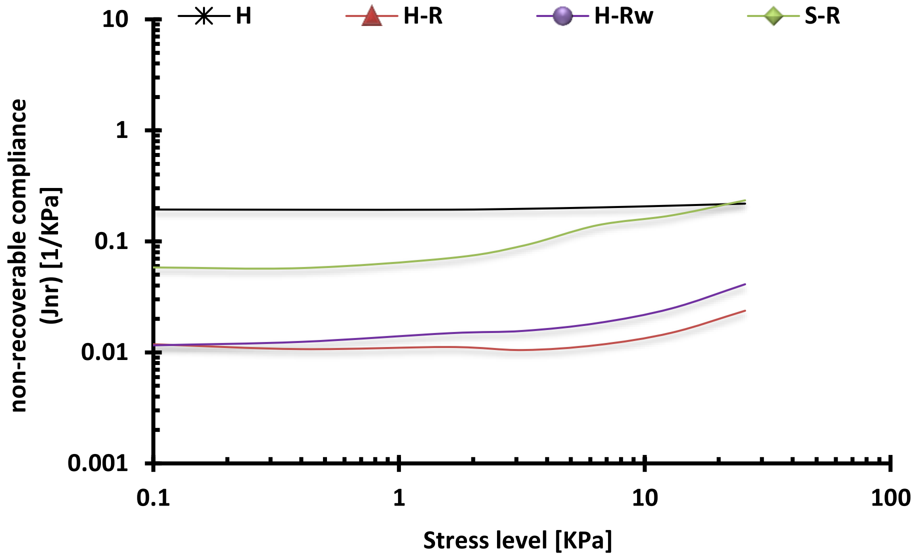


Fig. 7 Jnr of binders at 50 °C

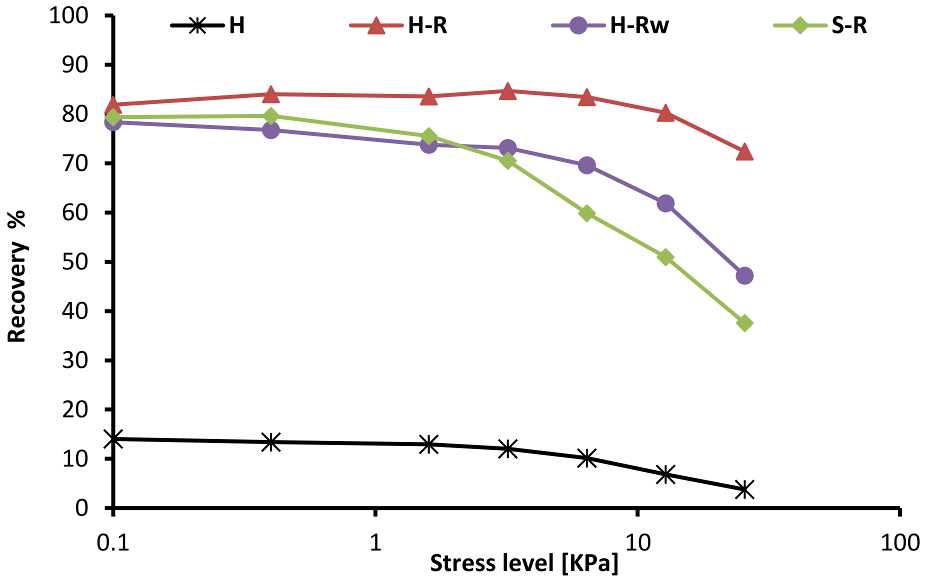
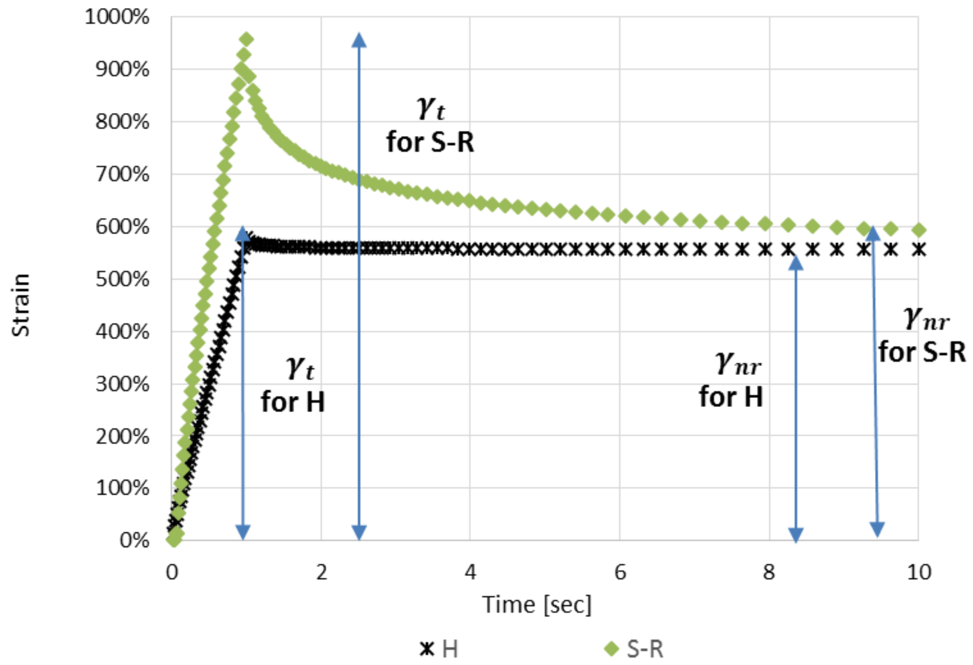


Fig. 8 Recovery percentage of binders at 50 °C



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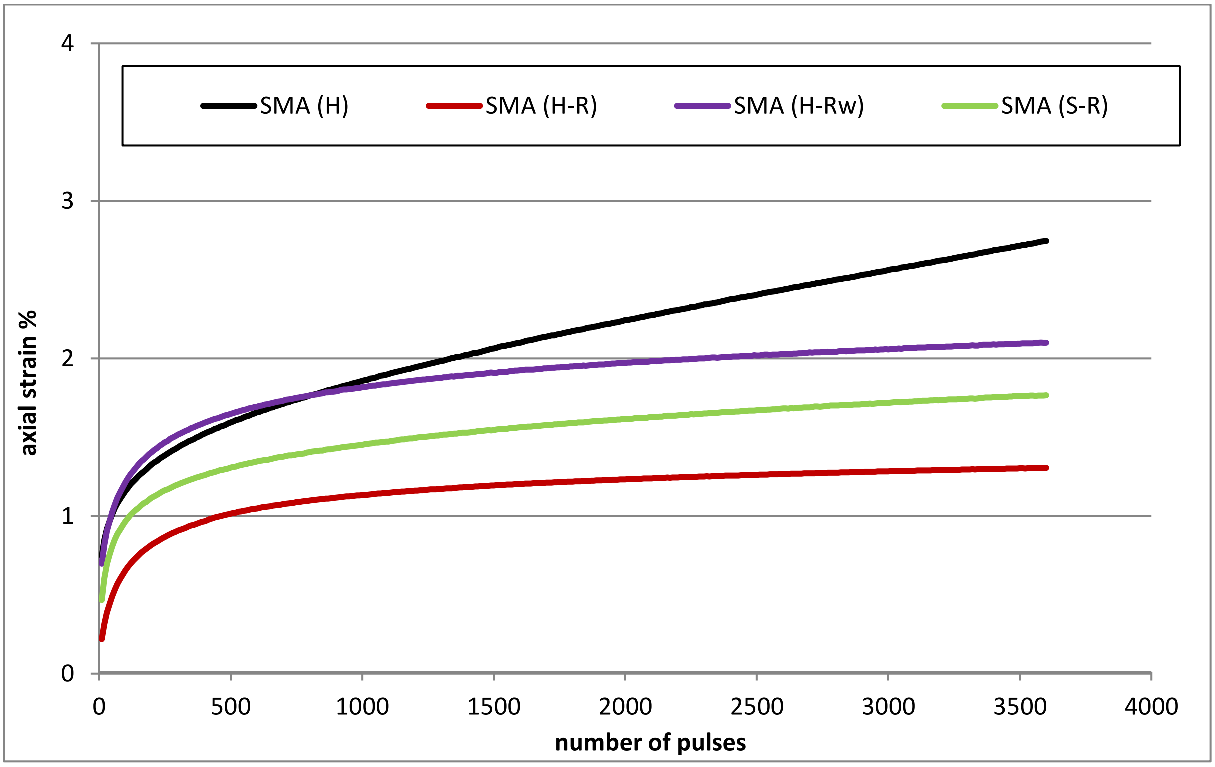
549 *Fig. 9 One cycle results of MSCR test for binders S-R and H, at stress level of 25.6 kPa, and temperature of 50 °C*

550



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552 *Fig. 10 : RLAT results of different mixtures tested at 100kPa stress and at 50°C temperature*

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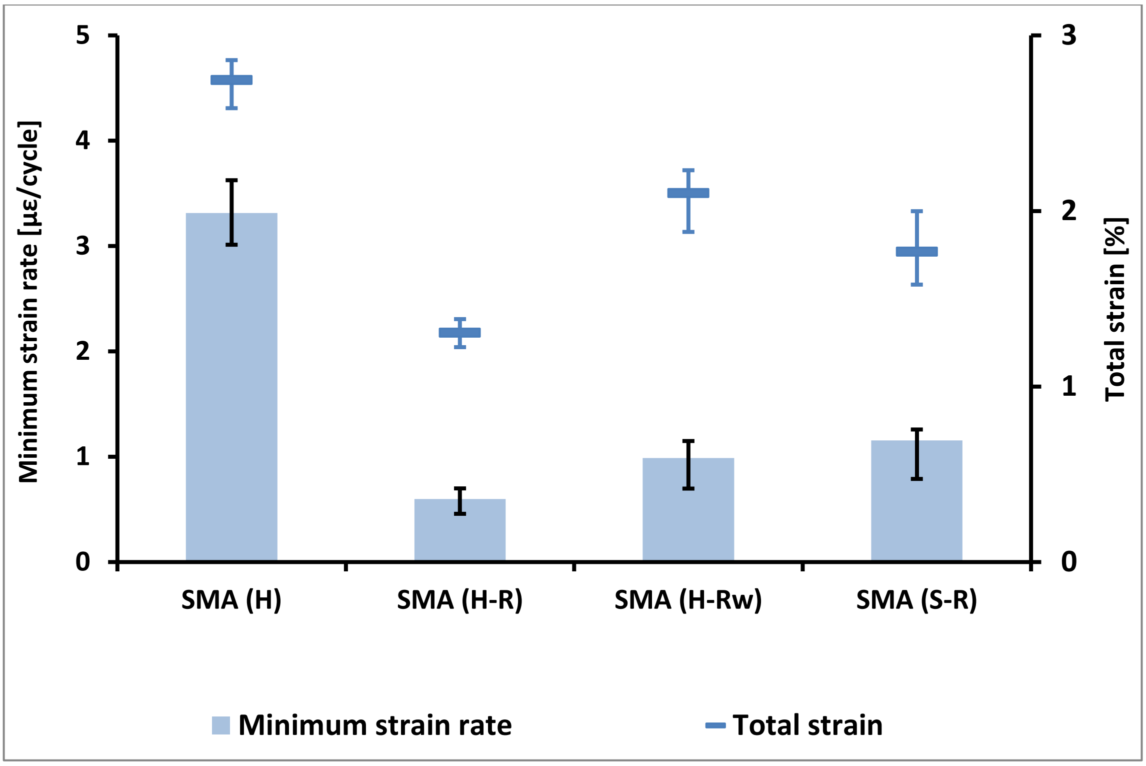
554 
Minimum strain rate [με/cycle]
5
4
3
2
1
0
Total strain [%]
3
2
1
0
SMA (H)
SMA (H-R)
SMA (H-Rw)
SMA (S-R)
Minimum strain rate
Total strain

Fig.11 RLAT results in terms of the minimum strain rate and total strain

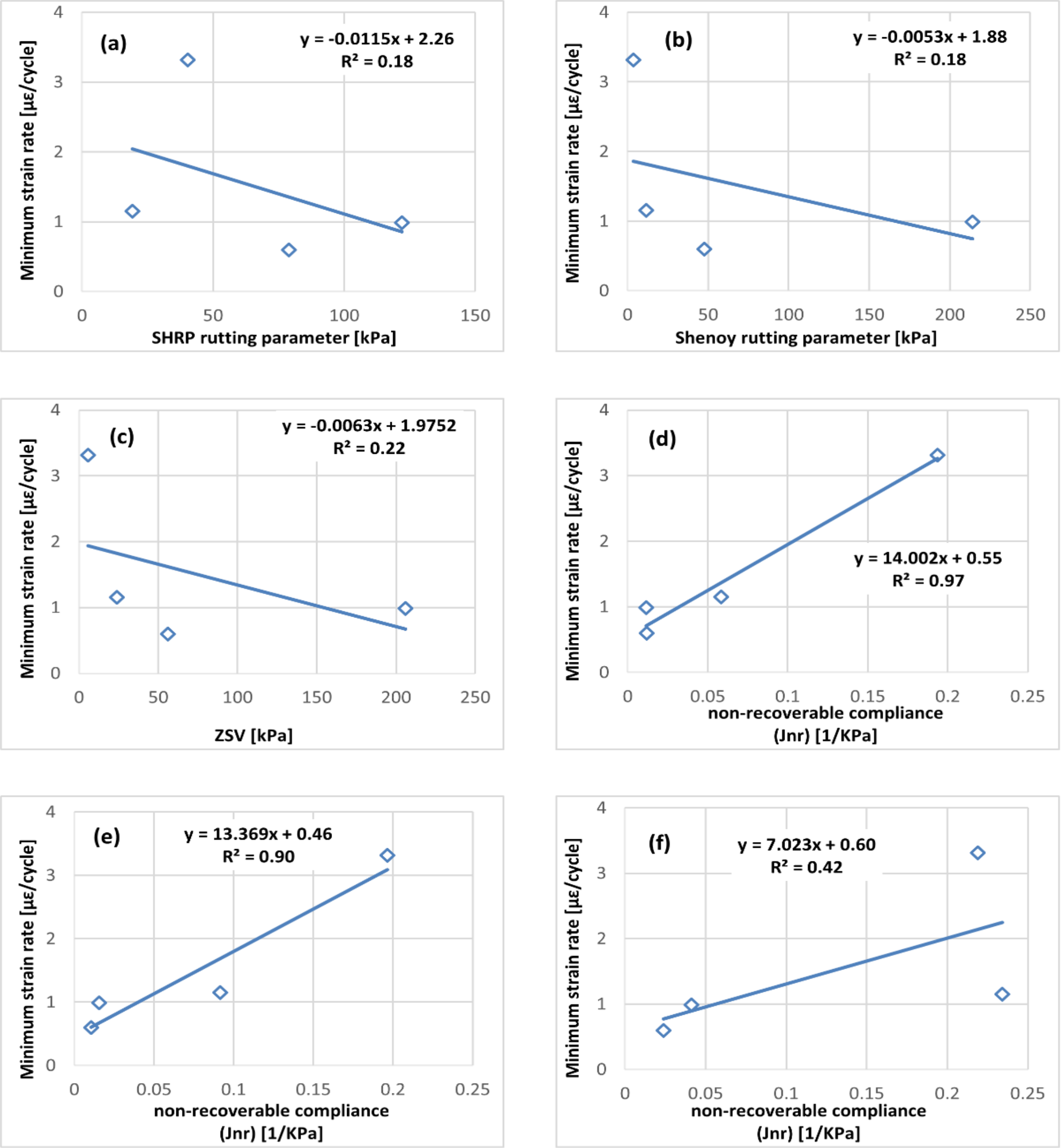


Fig. 12 Correlation between different rutting parameters with the minimum strain rate of mixtures; (a) SHRP, (b) Shenoy, (c) ZSV, (d) Jnr @ 0.10 kPa stress level, (e) Jnr @ 3.2 kPa stress and (f) Jnr @ 25.6 kPa stress

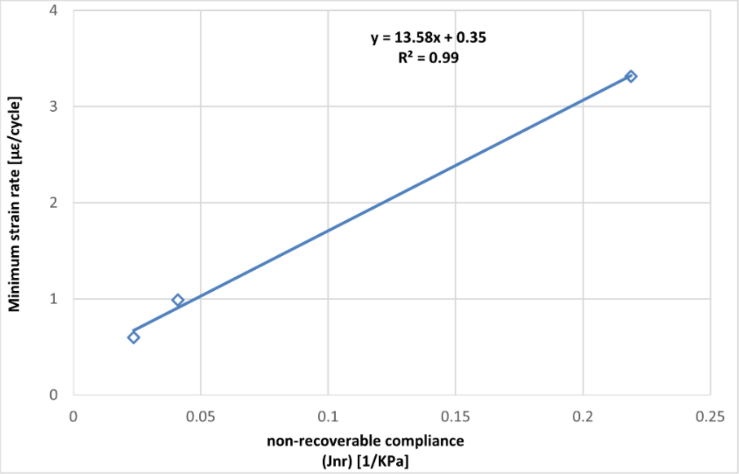


Fig. 13 Correlation between Jnr @ 25.6 kPa stress with the minimum strain rate after removing S-R

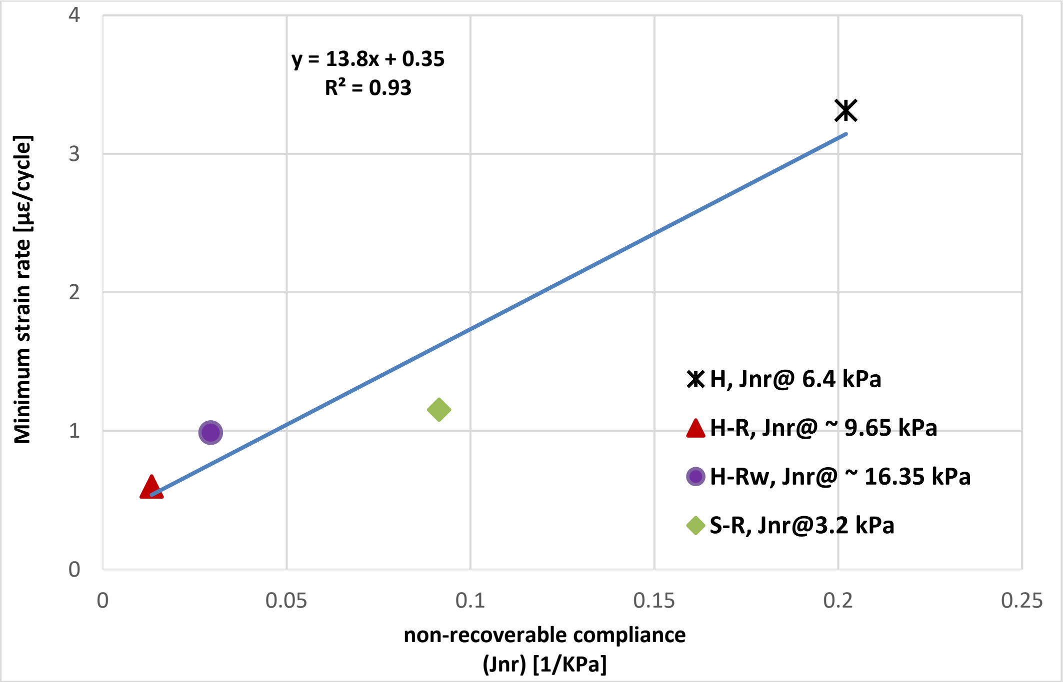


Fig. 14 Correlation between Jnr obtained at different stress levels with the minimum strain rate