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The effects of laboratory ageing on rheological and fracture characteristics of different rubberised bitumens

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ABSTRACT: Ageing of bituminous materials can result in loss of the durability of a flexible pavement. Using rubberised bitumens can enhance pavement performance while at the same time it solves a serious waste disposal problem. Combining Warm Mix Asphalt (WMA) additives with rubberised bitumens reduces the difficulties associated with the production of asphalt mixtures using this modified binder. This work was conducted to study the effect of ageing using fundamental parameters based on performance, i.e., CTOD and Glover-Rowe parameters have been related to pavement cracking. Different unmodified bitumens and rubberised bitumens were short-term aged using the Thin Film Oven Test (TFOT) and long-term aged using the Pressure Ageing Vessel (PAV). The rheological and fracture properties of the binders were studied before and after laboratory ageing. The results indicated that rubberized bitumens are more resistant to laboratory ageing. However, the pre-treatment with Sasobit® seemed to be detrimental when the materials were evaluated based on their fracture properties. The results also showed that base bitumen properties can affect the ageing mechanism of rubberised bitumens. Using softer bitumen could produce rubberised bitumens with superior anti-ageing properties when the analysis is based on linear viscoelastic properties using the Glover-Rowe parameter. However, these improvements were significantly reduced after ageing when the analysis is based on fracture properties.

KEYWORDS: ageing, rheology, fracture, rubberized bitumen, WMA additive

1. Introduction

The main factors that affect the durability of asphalt pavements are ageing and moisture damage with ageing generally stiffening the binders and making them less ductile [1]. This stiffening can reduce the ability of the pavement material to dissipate the stresses generated from low-temperature contraction and expansion, and/or heavy traffic loads leading to deteriorating performance of the pavement and increasing the cost of maintenance. Ageing also affects the cohesive properties of binders and the adhesion at the binder and aggregate interface. In general, ageing can be attributed to the oxidation, as well as loss of some of light oils, that occurs at elevated temperatures during asphalt mixture production (short-term ageing). This is followed by oxidation that continues after placing the asphalt materials in the pavement (long-term ageing). Additional elements that may contribute to ageing include molecular structuring over time (steric hardening) and actinic light (primarily ultraviolet radiation, particularly in arid conditions) [1].

The changes in the rheological properties of Recycled Tyre Rubber Modified Bitumen (RTR-MBs) after laboratory ageing have been investigated by many researchers [2-5]. The relative degree of change in the rheological properties of RTR-MBs has been shown to vary depending on ageing conditions, rubber content, rubber particle size and the source of base bitumen. One such study by Huang [5] has investigated the effect of long-term oxidative ageing for modified binders manufactured using different rubber contents and bitumen types. The results from this research indicated that the addition of a lower rubber percentage (5% by bitumen mass) to a bitumen that has high sulphur and asphaltene content, resulted in a higher phase angle at the same oxidation viscosity which could be translated into better long-term fatigue performance.

In another study by Ghavibazoo et al, the addition of higher rubber concentration (20% by bitumen mass) improved low-temperature properties (higher m-value and lower stiffness) after oxidative ageing in comparison to 0 and 10% rubber concentration [2]. The effects of ageing on rubberised binders have also been studied by means of dynamic mechanical analysis (DMA) [4]. These analyses have shown that ageing increased the viscous behaviour for the rubber modified binders compared to the base bitumen behaviour which showed an increase in the elastic components with ageing.

The increase in the viscous behaviour, within the polymer dominant DMA response areas (high temperatures and low frequencies) after ageing has been attributed to a dissolution of the rubber network structure and a reduction in the size of rubber particles [4]. This increase in viscous behaviour is considered to be beneficial for the long-term durability of flexible pavements. Increasing the rubber dissolution due to the effect of ageing has also been shown to enhance the ageing characteristics of binders by lowering the hardening and carbonyl formation rates [6]. Also, some of the rubber compounds, such as carbon black, have antioxidant characteristics that can improve the ageing resistance of rubberised bitumens [3].

Rubberised bitumens are normally very viscous at high temperatures. Therefore, higher operating temperatures are required in order to handle those kinds of binders during asphalt mixture production. This leads to increased energy consumption and emissions as well as health and safety issues for workers. Only a few studies have considered adding WMA additives to rubberised bitumens to potentially reduce the need for these elevated temperatures. The inclusion of WMA additives in rubberised bitumen have shown improved workability and handling using reduced mixing and compaction temperatures [7-10].

In this study, the rubberised bitumens containing standard tyre rubber and pre-treated tyre rubber with WMA additives were evaluated before and after laboratory ageing. Dynamic Mechanical Analysis (DMA) was used to evaluate the viscoelastic properties while the Essential Work of Fracture (EWF) was used to evaluate the fracture properties of materials. In terms of the fracture testing, the Double Edge Notched Tensile (DENT) test was chosen due to its ability to evaluate the resistance of binders to fracturing when subjected to high levels of strain and yielding. Although previous studies dealing with ageing of rubberised bitumens have not investigated the fracture properties of these binders, evaluating the fracture properties has been shown to be a promising approach for developing performance-related characterization of bituminous binders [11].

2. Materials

2.1 Base bitumens

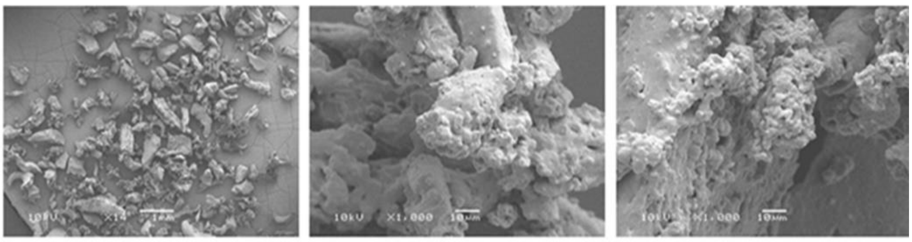
Two different grades of base bitumens were chosen; a ‘soft’ bitumen with a penetration of 200 dmm and a ‘hard’ base bitumen with a penetration of 40 dmm. The ‘soft’ bitumen is labelled S and the ‘hard’ bitumen is labelled H throughout the paper. Other rheological characteristics are shown in Table 1. The large differences in their grades were used to identify how the base bitumen can influence the interaction with crumb rubber and ageing mechanisms.

Table 1. The characterisations of base bitumens

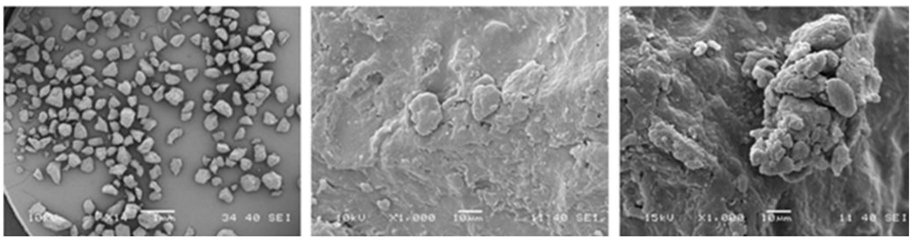
Ageing states	*Index*	*Binder "S"*	*Binder "H"*
Unaged binder	Penteration @25 ºC, 0.1mm	200	40
	Softening point ºC	37.0	51.4
	Rotational viscosity, Pa.s		
	@135 ºC	0.192	0.474
	@160 ºC	0.065	0.170
	Asphaltenes content	4.2%	15.2%
	G*/sinδ @ 60 ºC & 1.59Hz, kPa	0.615	1.95
TFOT aged residue	G*/sinδ @ 60 ºC & kPa	1.256	7.70
TFOT + PAV aged residue	G*.sinδ @ 20 ºC & kPa	1050	10027

2.2 Crumb rubber

Two types of recycled rubber, termed as N and W were used in the study. The standard crumb rubber, N, is a recycled crumb rubber obtained from used truck and passenger car tyres and ground using ambient grinding. On the other hand, the recycled crumb rubber, W, was obtained from 100% used truck tyres and cryogenically ground. The crumb rubber W was also pre-treated with an oil and Fischer–Tropsch (FT) wax component. The oil can help to decrease the movement of lighter fractions of the bitumen into the rubber particles and thus could decrease the impact of initial ageing (stiffening of the base bitumen). The FT-wax in W enables a reduction in production temperature while maintaining sufficient workability and compactability. The same materials were also used in previous research studies [12]. Fig. 1 shows different images of the recycled crumb rubbers taken using the Scanning Electronic Microscope (SEM).



a) N



b) W

Fig. 1 SEM images for the recycled crumb rubber N and W.

2.3 Rubberised bitumen

The rubberised bitumens were prepared using the wet process. The base bitumen was first preheated to 180°C before gradually adding the crumb rubber. The rubber content was set to be 18% by mass of the base bitumen. A Silverson L4RT high shear laboratory mixer was used to blend the materials. The blending of base bitumen and rubber particles continued at 180°C for two hours and at 3000 rpm. The processing conditions were adopted from previous studies that dealt with the optimisation of mixing conditions [13, 14]. High shear mixing has been adopted by various researchers and it has shown to produce rubberised binders with superior rheological properties compared to standard (low shear) mixing [5, 15-18].

3. Experimental programme

3.1 Ageing processes

The base bitumens and rubberised ones were aged in the laboratory using the thin film oven test (TFOT) for the short-term ageing and using the pressure ageing vessel (PAV) for the long-term ageing. In the TFOT, 50 g of the binders were poured into steel pans so that the binders have an approximately 3.2mm film thickness. The materials in the stainless pans were then conditioned at 163°C for 5 hours in a standard TFOT oven. The TFOT was preferred rather than the rolling thin film ovens test (RTFOT) because of concerns over the rubberised bitumens not uniformly covering the interior walls of the RTFOT glass containers during the ageing process and also having the RTR-MBs rolling out of the containers during ageing. Also, the rubberised bitumen and especially the ones produced using crumb rubber N tended to be very viscous at 163°C. This resulted in significantly different film thicknesses among the binders during the ageing process. While in the TFOT, the binder film thickness can easily be controlled at 3.2mm for all materials. Thus, it can be assured for comparison purposes that all the binders experienced the same ageing conditions. The residue from the TFOT was further conditioned in the PAV at 2.1 MPa pressurised air and 90°C for 20 hours

3.2 Dynamic Shear Rheometer Testing

An oscillatory frequency sweep test was conducted using a Bohlin CVO Model Dynamic Shear Rheometer (DSR). The binders were tested in strain control mode at 1% strain within the Linear Viscoelastic (LVE) region. The LVE region was checked using amplitude sweep strain controlled tests. The sweep frequencies were set to be between 0.1 – 10 Hz at multiple temperatures of 30˚C - 80˚C at 10˚C intervals. For temperatures between 30 to 80˚C, the parallel plate geometry of 25mm diameter and 1mm gap was used for the base bitumens.

However, a 2mm gap was used for the rubberised bitumens to allow sufficient gap for the swollen rubber particles that may affect the viscoelastic measurements. For temperatures between 0 to 30˚C, the parallel plate geometry of 8mm diameter and 2mm gap was used.

3.3 DENT test

The DENT test was performed on a force-ductility apparatus (ductilometer). More details about the test and the theory behind the essential work of fracture (EWF) can be found in a previous publication [12]. Fig.2 shows the DENT moulds that were modified from the original specimens of the elastic recovery test. The modification was conducted using brass inserts to have a gap width between of notches equal to 5, 10, and 15 mm. The LS-299 protocol was adopted to evaluate the fracture resistance of binders in their ductile state [19]. The test was conducted at 10 °C for base bitumen S and its rubberized bitumens; and 20 °C for base bitumen H and its rubberized bitumens. Using different testing temperatures were important to account for the different stiffness of materials in order to have approximately the same ductile failure for all binders [12]. The displacement rate was set at 50 ± 2.5 mm/min for all binders.

According to the EWF, the fracturing energy needed for splitting a specimen in its ductile state can be divided into two parts known as 'essential work' and 'non essential work'. It can be seen from Fig. 2 that the essential work takes place in the inner process zone while the nonessential or plastic work takes place in the outer plastic zone of the progressing crack [12, 20].

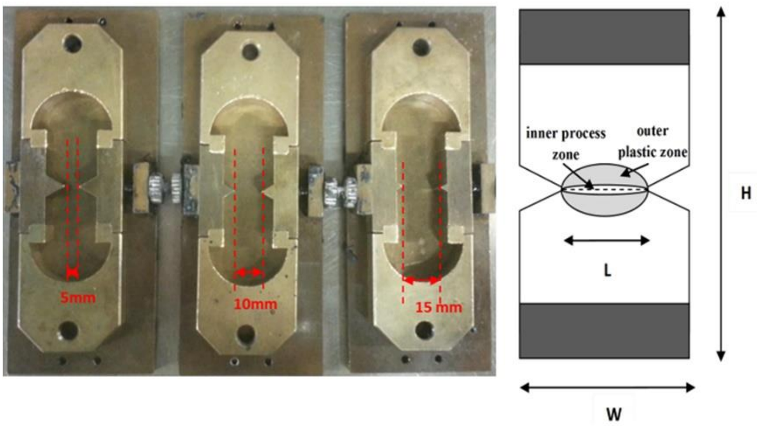


Fig. 2. DENT moulds and the location of the essential work and nonessential work during the progressing of cracking [12]

The specimen is tested at different ligament lengths (i.e. 5, 10, and 15 mm) and for each ligament length, the total work of fracture (W_T) is calculated using the following equation [12]:

$$W_T = w_e . l . B + \beta . w_p . l^2 . B \quad (1)$$

The total work of fracture (W_T) in the above equation needs to be divided by the ligament cross-sectional area ($l \ x \ B$) in order to transform it into specific terms [12]:

$$w_t = {}^{W_T}/_{l.B} = w_e + \beta . w_p . l \quad (2)$$

Where: W_T is the total work of fracture and computed from the area under the force-displacement curve (J), w_t is the total specific work of fracture (J/m^2), l is the ligament length (m), B is the sample thickness (m), β is a geometrical constant that is linked to the shape of the plastic zone, i.e., π/4 for a cylinder, w_e is the specific essential work of fracture (J/m^2), and w_p is the specific plastic work of fracture (J/m^3) [11, 12, 20]. The different ligaments (5, 10, and 15mm) can be plotted versus their w_t to produce a straight line using a linear fitting procedure as seen in Fig. 3. The specific essential work (w_e) is identified from the intercept of the line. This can be achieved by extrapolation to zero ligament. The slope of that strain line represents the geometry constant times the plastic work of fracture βw_p [12].

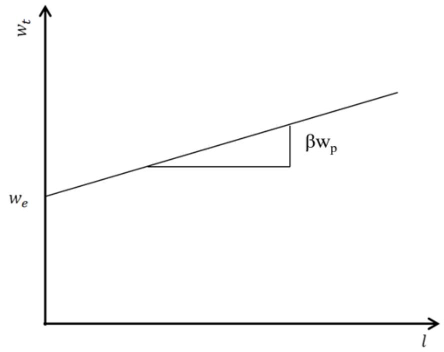


Fig. 3.. The specific essential of work and plastic work of fracture determination [12, 20]

The critical crack opening displacement (CTOD) is approximated from the ratio of w_e over the net section stress. It is recommended the CTOD should be calculated as w_e/σ_{net} based on the smallest ligament, 5mm, because a complete yielding normally occurs at the smallest ligament [12, 21].

4. Results and discussion

4.1 Dynamic Mechanical Analysis (DMA)

Evaluation of the effect of laboratory ageing was accomplished by means of DMA. The rheological changes due to ageing were, therefore, examined for different Recycled Tyre Rubber Modified Bitumen (RTR-MBs). Figs 4 to 6 show the master curves of complex modulus and Black diagrams, before and after laboratory ageing, for the base bitumens and their rubberised binders. The G* master curves at 30 °C reference temperature of the base bitumens, shown in Fig 4, generally increase with ageing. It is anticipated that due to the severe ageing conditions the change in the complex modulus after PAV ageing would be greater to that after TFOT ageing. Fig. 4 (b and d) show how the Black diagrams are affected by ageing. The laboratory ageing increased the elastic response of materials as the Black diagrams move towards lower phase angles with ageing. As the phase angle is associated with the ratio between the loss modulus (related to the viscous response) to the storage modulus (related to the elastic response), this means that ageing contributed to a greater increase in the storage modulus than in loss modulus which led to lower phase angles. This is in agreement with the general effect of ageing on rheological properties as an increase in G* and a decrease in phase angle

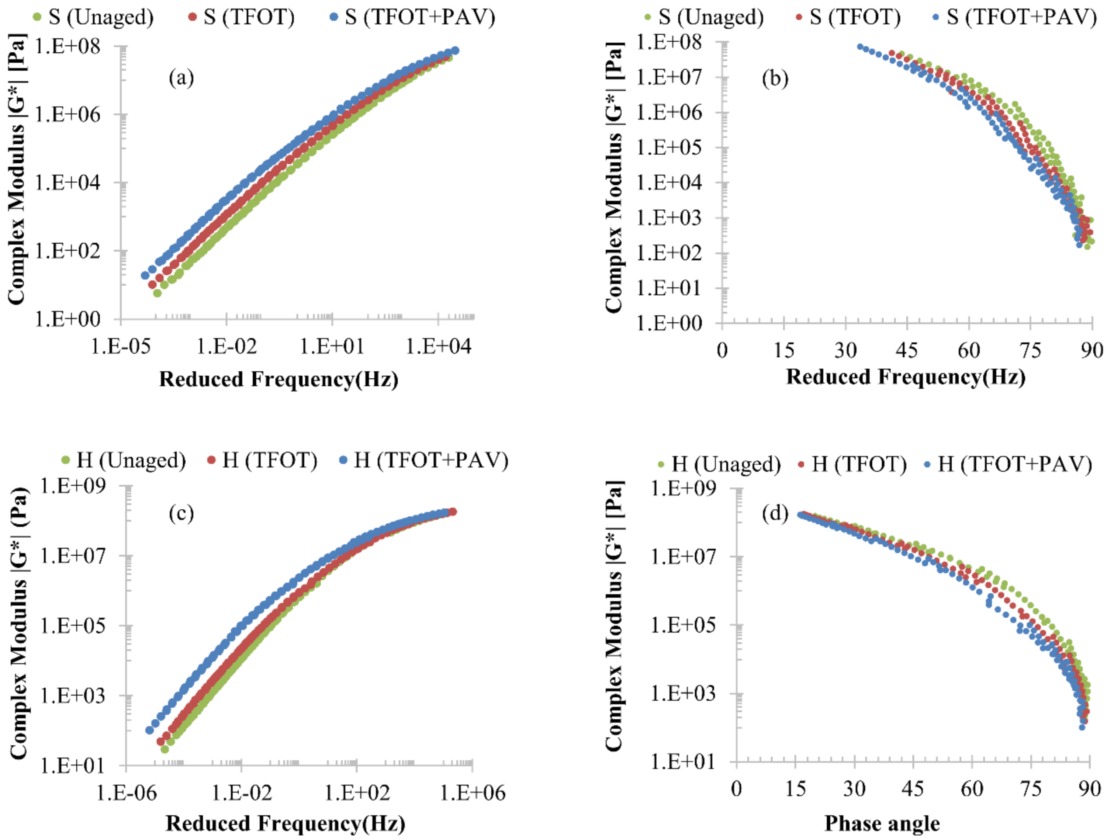


Fig. 4. The effect of laboratory ageing on the rheological properties of the base bitumens

For the rubberised bitumens modified by the rubber N, as seen in Fig. 5, the laboratory ageing affects the master curves of complex modulus similarly to that seen in the base bitumens. However, the relative increase in the complex modulus after ageing is not significant compared to that found for the base bitumens. Also, the master curve at high frequencies after PAV ageing slightly decreases as seen in Fig. 5 (c). The Black diagrams shown in Fig. 5 (b and d) are typically different from that seen in the base bitumens. The

Black diagrams appear separated after ageing, specifically after PAV ageing for H-N material. The phase angles at low G* values (10^4 Pa and below) moved towards higher phase angles meaning more viscous response with ageing. It has been shown that rubber particles could be dissolved or reduced in size when they are subjected to ageing at higher temperatures. This verifies the hypothesis that the rubber particles potentially undergo some degradation during the ageing process by means of devulcanisation/depolymerisation [3, 4].

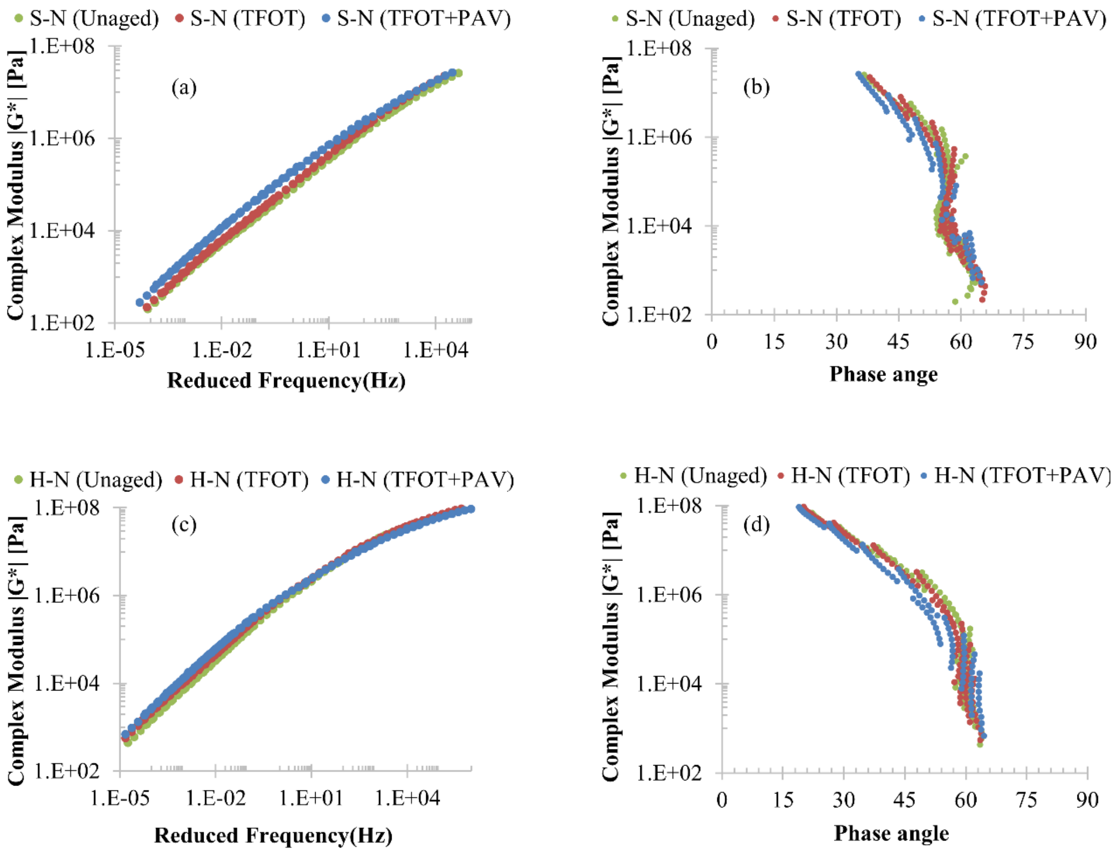


Fig. 5. The effect of laboratory ageing on the rheological properties of the RTR-MBs produced using crumb rubber N

Fig. 6 shows the changes in the master curves of complex modulus and Black diagram after ageing for rubberised bitumens produced using crumb rubber W. The effect of ageing, shown in Fig. 6, is similar to that found in Fig. 5. However, there is a reduction in G* after PAV ageing as shown in Fig 6 (a) at reduced frequencies lower than 10^{-3} Hz. Also, there is greater increase in phase angles after PAV ageing in Fig. 6 (b and d) compared to the increase found in Fig. 5 (b and d). The results suggest that the rubber network in S-W and H-W binders was more susceptible to devulcanisation/depolymerisation during PAV ageing. This could be attributed to the high percentage of natural rubber in W as it was derived from100% recycled truck tyres. The percentage of natural rubber is considerably higher in truck tyres compared to passenger cars [22].

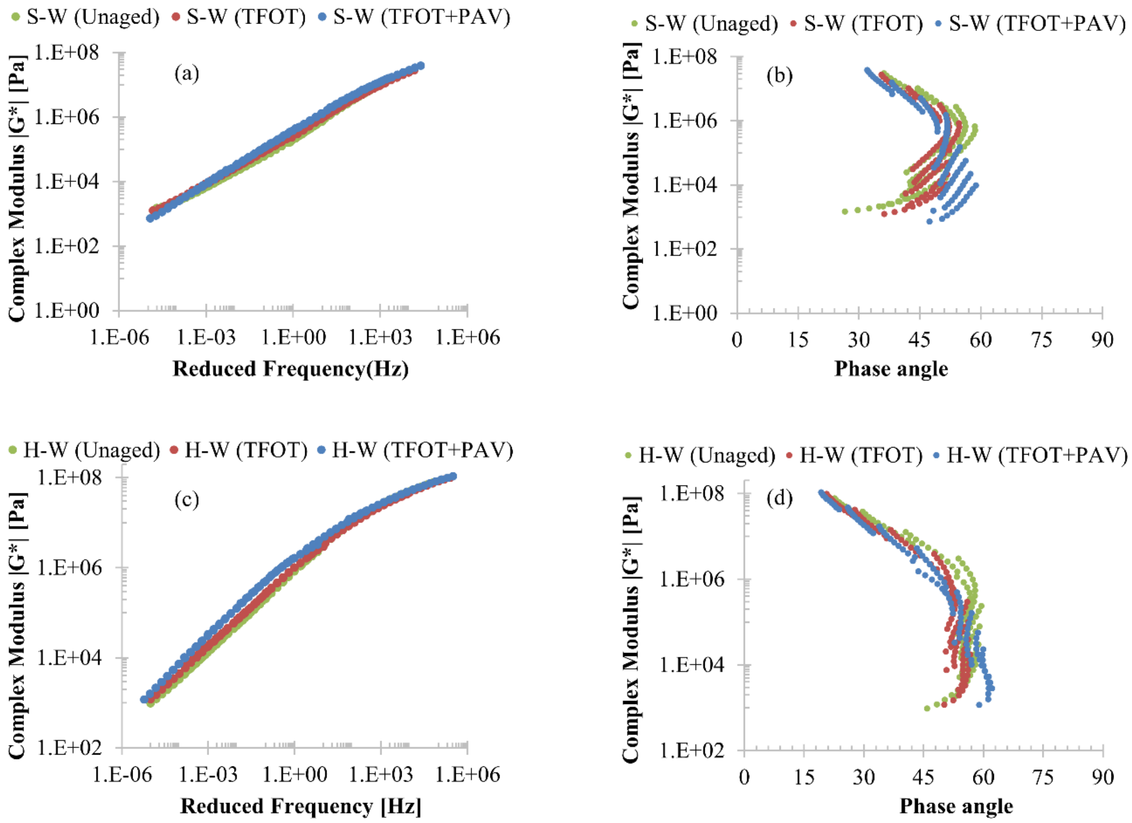


Fig. 6. The effect of laboratory ageing on the rheological properties of the RTR-MBs produced using crumb rubber W

The ageing indices shown in Fig. 7 were computed in order to better understand the effect of ageing on the rheological responses of these binders. The complex modulus |G*| at 1.59 Hz and over a range of temperatures (30 to 80 ℃) were, therefore, computed before and after laboratory ageing. The results of ageing indices suggest that the soft bitumen S is more susceptible to oxidative ageing than the hard bitumen. This may be attributed to the high amount of light fractions that are available in bitumen S that are more susceptible to oxidative ageing. Also, the ageing indices indicate that the rubberised bitumens are generally less affected by ageing than the base bitumens at temperatures higher than 30 °C. The addition of rubber can, therefore, compensate or reduce the hardening effect of ageing on the rheological properties by maintaining the viscous response of matrials. The effect of adding rubber is more apparent after TFOT+PAV where the RTR-MBs exhibited significantly lower ageing indices. The RTR-MBs can be expected to be better at resisting long term ageing in comparison to their base bitumens.

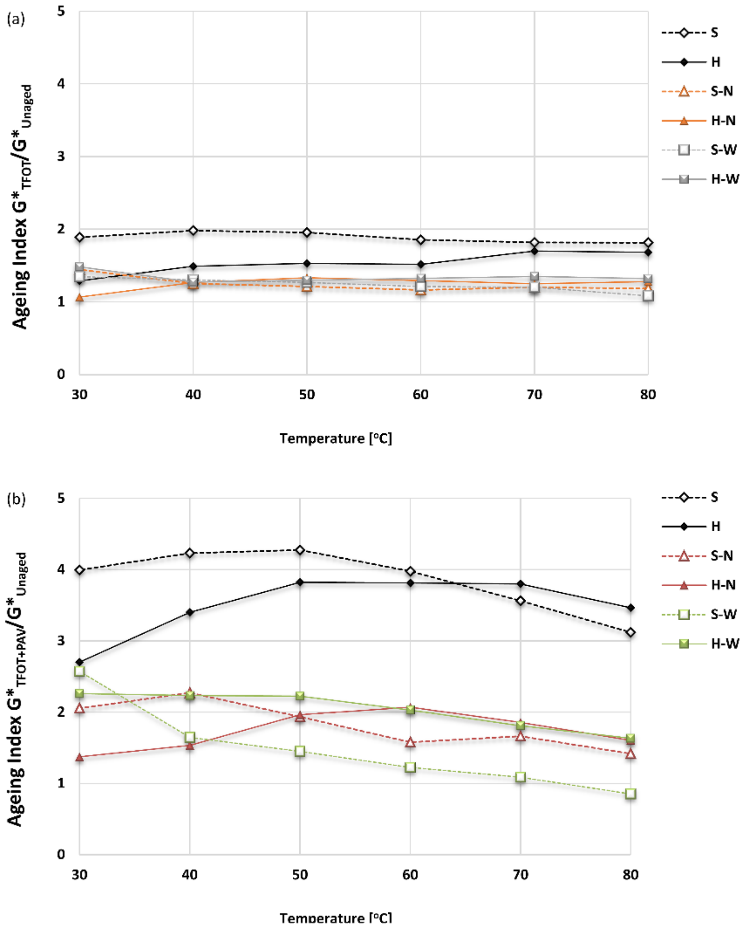


Fig. 7. The ageing indices for base bitumens and rubberised bitumens (a) after TFOT (b) after TFOT+PAV

4.2 Glover-Rowe Parameter

Researchers have suggested that the use of Black Space can also provide adequate information about the ability of materials to resist cracking and also to capture the ageing impacts on bituminous materials [23-25]. The change in G* and phase angle in Black Space was, therefore, suggested to serve as an adequate indicator to evaluate the resistance of bituminous materials to age-related cracking [26-28]. Previous field studies have found a good correlation between the ductility of binders and pavement cracking [23, 29]. Subsequent work established a unique relationship between the ductility test (1 cm/min ,15°C) and the viscoelastic properties of binders at a frequency of 0.005 rad/s and 15°C [23, 28]. Based on this relationship, Rowe [30] and King et al. [24] generated a criterion for damage curves in the Black Space using the following equation:

$$\frac{G^{*}\,(\cos\delta)^{2}}{\sin\delta} \qquad (3)$$

The above equation is known as the Glover–Rowe (G-R) parameter [27] and it is computed from the complex modulus and phase angle (δ) of the binder at a frequency of 0.005 rad/s and 15°C. The two curves (the dotted and continuous curves) shown in Fig. 8 represent the G-R parameter at values of 180 kPa and 450 kPa, respectively. These values are deemed to control the onset of cracking; a value of 180 kPa and larger is associated with the onset of cracking and is linked to a ductility of 5 cm, while a value of 450 kPa and larger is associated with significant cracking and is linked to a ductility of 3 cm [28].

Fig. 8 shows the G* and phase angle (δ) values for the soft base bitumen and its associated RTR-MBs at a frequency of 0.005 rad/s and 15°C plotted in Black Space along with the G–R curves that correspond to the G-R value of 180 kPa (onset of cracking zone) and the solid line corresponds to the G-R value of 450 kPa, (significant cracking zone). All binders would have no cracking related issues according to this analysis. The neat bitumen showed an expected behaviour with ageing, however the rubberised binders have been affected differently by the oxidative ageing and behaved oppositely, i.e. showed an increase in the phase angle which means shifting towards more viscous behaviour with ageing. These results are similar for both rubberised binders, with and without pre-treatment with oil and wax, and represent an improvement between these RTR-MBs and the aged soft base bitumen. The analysis of the hard bitumen in Fig. 9 resulted in a different behaviour than the soft bitumen and associated RTR-MBs with all the materials (base bitumen and RTR-MBs) showing a similar trend with ageing. These results suggest that the base bitumen greatly influences the ageing mechanism of rubberised bitumens. It can be seen that all binders became more elastic and stiffer but are still positioned beneath the cracking potential curves even after TFOT+PAV ageing. Pre-treatment with wax (W), although presenting similar behaviour to the standard RTR-MB, did slightly exceed the limit of cracking onset after TFOT+PAV ageing.

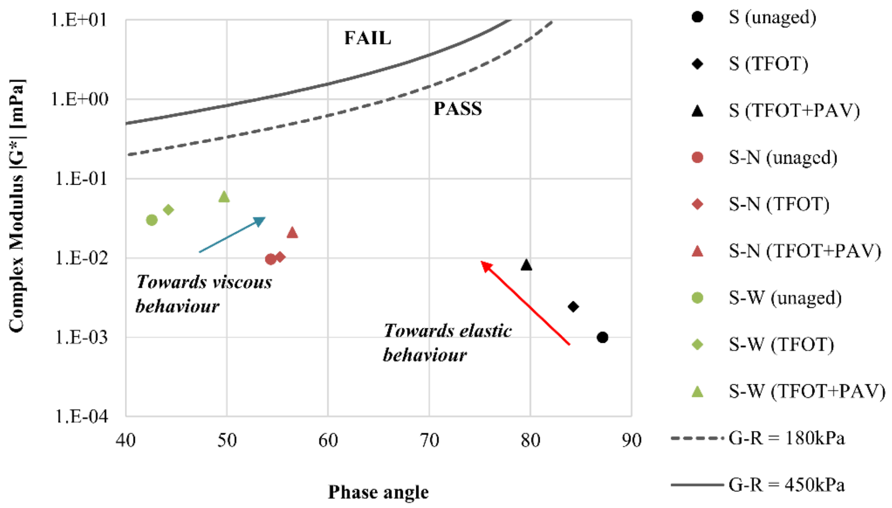


Fig. 8 G-R parameter obtained for the soft base bitumen and its rubberised bitumens

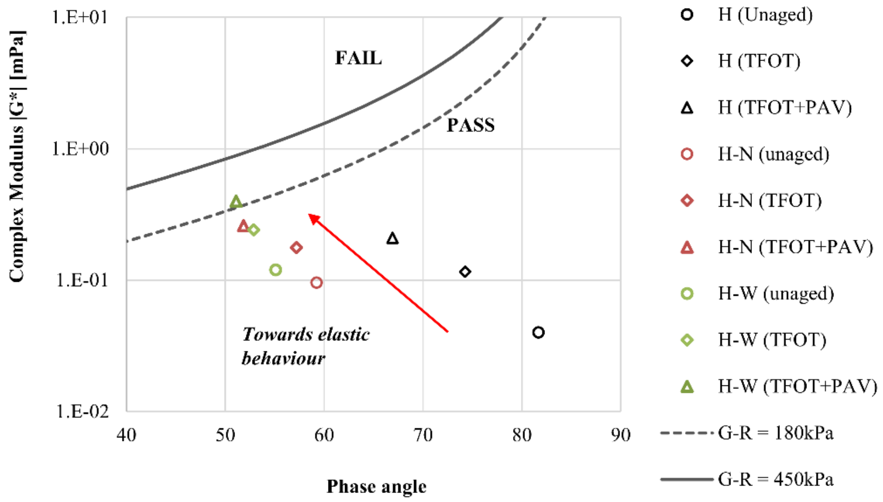


Fig. 9. G-R parameter obtained for the hard base bitumen and its rubberised bitumens

4.3 Fracture analysis

Fig. 10 and 11 show the force–displacement curves that can be plotted from the data of the DENT test. The figures demonstrate excellent repeatability of the DENT test. The figures also show the influence of ligament length on the force-displacement curve and show that each binder has a unique failure mechanism. The base bitumens have one maximum load while the rubberised bitumens produced using crumb rubber N exhibit two maximum load peaks. It can be seen that the second yield point of unaged S-N binder was even higher than the first point. A behaviour known as strain-hardening found in some polymers could be responsible for the two yielding points. Researchers working on asphalt materials stated that strain-hardening can also be found in polymer modified bitumens [31, 32]. The maximum load is associated with the yielding around the ligament area while the crosslinked network found in the rubberised bitumens resulted in materials acting as two-phase systems resulting in two yielding points [32]. The fracture properties are generally enhanced by the addition of rubber as can be seen from the force–displacement curves of rubberised bitumens. The addition of rubber resulted in toughening of the materials, i.e. it made them stronger and more flexible which can be translated into better fracture properties. It can be seen from Figs 10 and 11 (g, h, i) that RTR-MBs produced using crumb rubber W are stronger but less ductile than the other binders. It is possible that the crystallisation effect of wax could make the modified binders stiffer and less able to stretch [33]. The effect of laboratory ageing by TFOT and TFOT+PAV can be qualitatively described from the shape change of the force–displacement curves. The laboratory ageing results in the curves shifting towards larger forces and lesser elongation. When the effects of using different base bitumens are examined, the binders manufactured using the soft bitumen can generally elongate more (greater ductility) than the hard binders although they are always weaker.

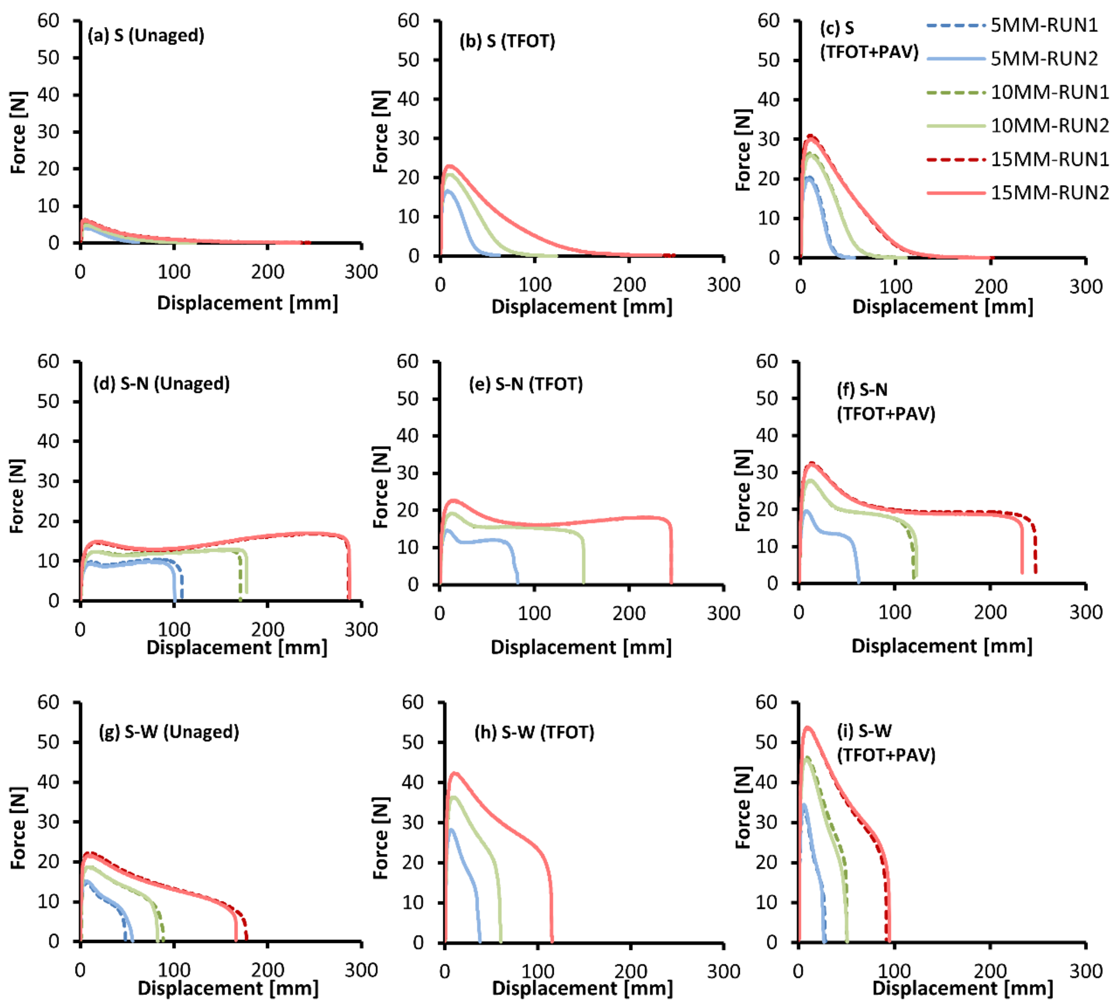


Fig. 10. The force-displacement curves for the soft bitumen and its rubberised bitumens

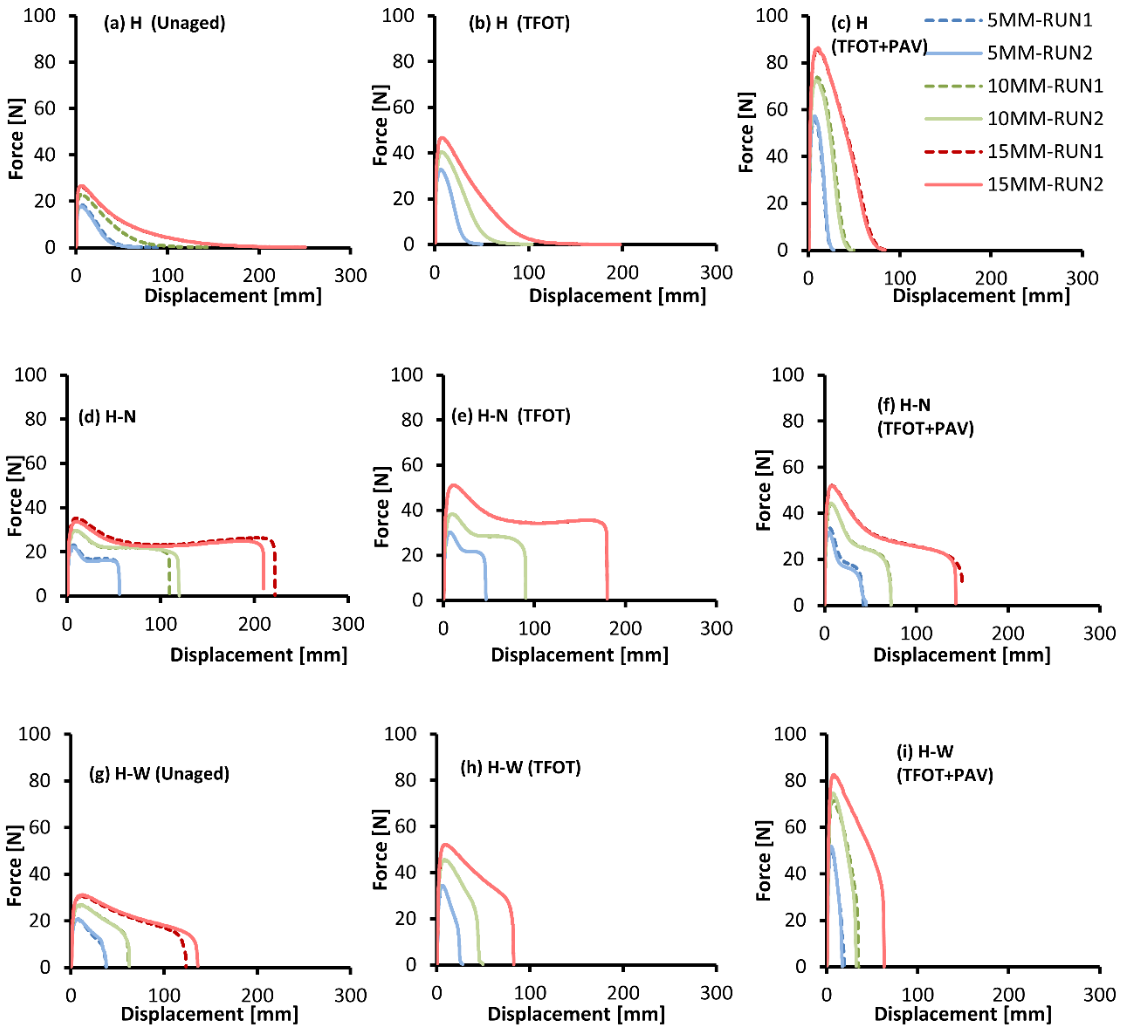


Fig.11 The force-displacement curves for the hard bitumen and its rubberised bitumens

The essential work of fracture, w_e, and the CTOD are shown in Figs. 12 and 13, respectfully. It can be seen in Fig. 12 that there is no consistent trend with ageing for the w_e. For the base bitumens, S and H, the w_e always increases with ageing, which may be considered as fracture resistance improvement with ageing. However, this conclusion would only be correct if the test was conducted at an equi-stiffness-temperature. The fracture energy parameters, i.e.w_e and CTOD, of binders change considerably with stiffness, and since the stiffness increases significantly with ageing, the values of w_e can be expected to increase with ageing. For the rubberised bitumens produced using crumb rubber N, the trend depends on the base bitumen with w_e decreasing with ageing for the S-N binder while increasing with ageing for the H-N binder. For rubberised bitumens produced using the pre-treated crumb rubber W, the trend depends on ageing condition with w_e increasing after TFOT ageing but decreasing after TFOT+PAV ageing. The inconsistency in the values of w_e for rubberised bitumens could be attributed to the different extent of rubber swelling and/or disintegration and to the different extent of base bitumen oxidation with ageing.

On the other hand, the CTOD values for both base bitumens and RTR-MBs seem to have the same trend with ageing. Fig. 13 shows that the CTOD values decrease with ageing and this agrees with the general effect of ageing on the ductility of binders. This is consistent for all binders. Ageing makes the binders stiffer and less able to stretch; therefore, the relative effect between them (load and displacement) was different with respect to w_e. However, the CTOD contains information about the tensile fracture energy represented in w_e and this is normalised using the tensile yield stress, σ_{net}. CTOD gives an indication of the strain tolerance of binders and it is not affected by the variation in stiffness among binders as in the case of w_e. The CTOD can, therefore, be considered a good discriminating parameter to quantify the effect of ageing. Fig. 14 presents the fracture performance index calculated based on the CTOD values to evaluate the effect of modifying the base bitumens by adding different crumb rubbers:

$$\text{Fracture performance index (FPI)} = \frac{CTOD_{RTR-MB}}{CTOD_{base\ bitumen}}$$

Fig. 14 suggests that the rubber modification without WMA additive can enhance the fracture properties of base bitumens. The addition of rubber N to the soft bitumen S significantly increased the CTOD of the unaged binder. However, it seems that the rubber network of the unaged S-N binder was largely disintegrated after ageing. Adding the same crumb rubber N to the harder bitumen H did not markedly increase the CTOD to the same degree as it did with the soft bitumen S. The reduction in CTOD of H-N due to oxidative ageing, as shown in Fig. 13, was very small compared to S-N. Fig. 13 shows that the reduction in CTOD of the soft bitumen S after TFOT and TFOT+PAV ageing was about 10% and 17%, respectively, compared to the reduction in CTOD of the harder bitumen H of 22% and 51%, respectively. Consequently, the fracture performance index of binders S-N and H-N showed a totally opposite trend to each other, as can be seen in Fig. 14, where the FPI decreases with ageing for binder S-N while it increases with ageing for binder H-N, compared to their base bitumens.

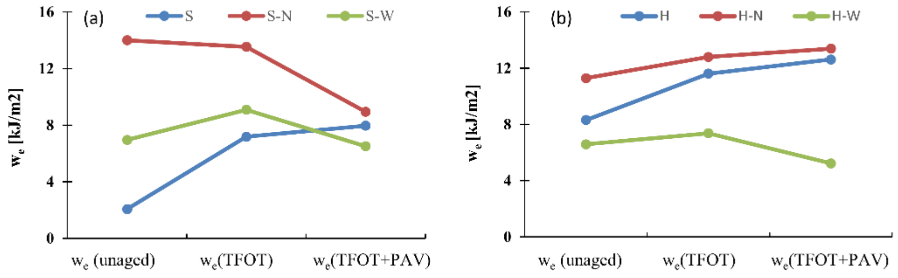


Fig. 12. The essential work of fracture we of binders under different ageing condition

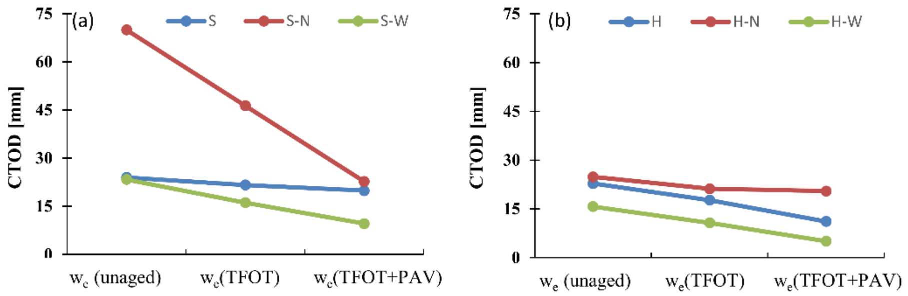


Fig. 13. The CTOD values of binders under different ageing condition

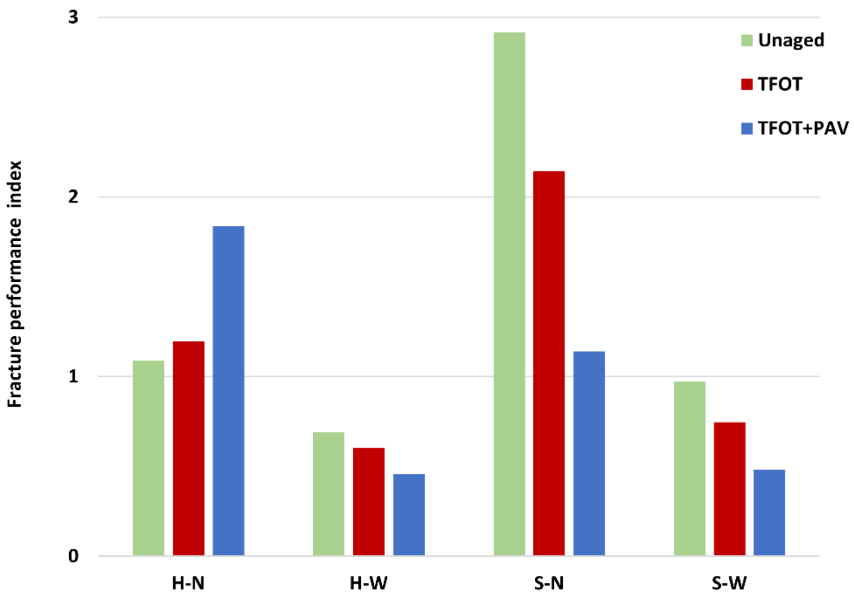


Fig. 14. The performance of RTR-MBs with respect to their base bitumens as a function of artificial ageing

5. Conclusions

The main conclusions and findings that can be warranted based on the analysis presented in this paper are as follows:

1. The modification by recycled rubber can change the ageing mechanism of binders. It was shown that the added rubber could be partly disintegrated and dissolved due to the ageing conditions. The dissolution of rubber into the bitumen can result in increasing the viscous behaviour of binders and compensate the hardening effect of ageing. Thus, the modification by recycled rubber is useful for improving the ageing characteristics of binders.
2. The fracture properties of binders, before and after ageing, were impaired by the wax.
3. The results of the Glover-Rowe parameter have shown that the rubberised bitumens produced using soft bitumen demonstrate superior anti-ageing properties. The rubberised bitumens produced using softer bitumen shifted towards more viscous behaviour with ageing.
4. The CTOD obtained from the DENT test was reliably sensitive and consistent to the effects of ageing. It is, therefore, recommended to use the CTOD as a discriminating tool to rate and evaluate the performance related properties of binders.
5. The addition of rubber contributes to improve the ageing resistance of modified binders by providing some sort of oxidation shielding. It also helps to protect the light fractions of base bitumen that are absorbed by rubber particles from being more susceptible to ageing. The dissolution/dispersion of rubber particles that occurs during ageing can also retard the hardening rate by reducing the bulk viscosity of the binders.

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