Research Article

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Characterization of rutting resistance of warm-modified asphalt mixtures tested in a dynamic shear rheometer

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Abstract: The current study aims to evaluate the rutting resistance of warm miox asphalt (WMA) taking into consideration the influence of production temperature. Rediset WMX, Sasobit, and Rediset LQ were used to manufacture WMAs. WMA was manufactured at 125°C (for a modified soft binder, 100/150) and 135 and 145°C (for a modified hard binder, 40/60), while the control hot mix asphalt (HMA) was manufactured at 145 and 155°C for soft and hard binder, respectively. Although WMAs manufactured using hard binder (40/60) were successfully produced at a temperature 20°C lower than that for the control HMA, its rutting performance was inferior to that of the control HMA with both Rediset LQ and Rediset WMX; while the rutting performance of the Sasobit-modified hard binder–asphalt mixture was equal to that of HMA because Sasobit increases the stiffness of binder. On the other hand, all WMAs produced at a temperature of 145°C performed better than or equal to HMA. In summary, binder grade has an important role in the dosage of additive, performance, and the reduction of the manufacturing temperature of WMA; on the other hand, WMA additives delay the degradation of rutting rate for mixes, the results also showed that WMAs have an equal performance to or better performance than that of conventional HMA.

Keywords: rutting, WMA, Sasobit, Rediset, DSR, MSCR

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1 Introduction

The existing thought in asphalt industry is that warm asphalt mixtures could play a potential role in improving the overall performance of asphalt mixtures with particular reference to achieving economic and environmental objectives. There is no doubt that the manufacture of hot mix asphalt (HMA) makes a significant contribution to the release of pollutant gases and has high energy consumption as a result of the necessity to heat the aggregate and binder of the asphalt mixture at temperatures above 150°C. The effect of including Sasobit on the resistance of rutting of asphalt mixtures has been evaluated by a number of researchers. It has been shown that the rutting resistance of mixtures incorporating Sasobit satisfied the permissible limit after 10,000 loading cycles using the Hamburg wheel-tracking test [1,2]. Likewise, the outstanding rutting resistance of Sasobit-modified asphalt mixture was corroborated by using an asphalt pavement analyser as it was highlighted that the Sasobit-warm miox asphalt (WMA) [3,4] and the associated HMA exhibited similar rutting resistance levels and satisfied the required standard. In fact, the inclusion of 1.5% of Sasobit in the asphalt mixture resulted in an asphalt mixture that had the same rutting resistance as the control HMA after 8,000 cycles of loading.

Furthermore, despite the fact that Mohammad *et al.* [5] revealed that asphalt mixtures incorporating Sasobit had lower modulus values in comparison with that of a control mix, other studies carried out by Yang *et al.* [6], Haggag *et al.* [7], and Petit *et al.* [8] highlighted that asphalt mixtures containing Sasobit showed higher stiffness values in comparison with that of the corresponding HMA. It has also been reported that asphalt mixtures manufactured using Sasobit exhibited an increase in stiffness, especially at lower temperatures and higher frequencies. The reason behind this is that the incorporation of synthetic wax stabilizes the bitumen and consequently results in a more stable asphalt mixture because of its form of crystallization [8].

Xiao *et al.* [9] investigated and studied the effects of the addition of Sasobit on the performance of an asphalt mixture containing moist aggregate. It was found that there was no need for any additional treatment of the asphalt mixture in order to satisfy the required rutting resistance. Moreover, it was concluded that the inclusion of Sasobit in the asphalt mixture led to the best rutting resistance. This has coincided with research carried out by Bennert *et al.* [10], who investigated the effect of the moisture content of aggregate and the production temperature of the asphalt mixture, finding that, as the manufacturing temperature of the asphalt mixture decreased, the flow number dropped, apart from the mixture manufactured using Sasobit. The mixture incorporating Sasobit was capable of adequately maintaining the required values of flow number at the production temperature of 132°C using dosages of Sasobit at 1.0 and 1.5% by weight of bitumen and, furthermore, exhibited a higher stiffness and an improvement in the rutting resistance compared with that of the baseline mixture. In addition, Edwards *et al.* [11] found that the inclusion of Sasobit in asphalt mixture resulted in a small strain in dynamic creep testing compared with that of the associated control mixture. Therefore, it can be concluded and reported that the rutting performance of asphalt mixture modified with Sasobit is similar to or even better than that of baseline HMA.

The rutting resistance of WMA manufactured using 2 and 1% of Rediset WMX was investigated by Bennert *et al.* [10]. The results showed that the rutting resistance of WMA assessed with the Hamburg wheel-tracking test decreased as the manufacturing temperature decreased and that the rutting resistance of asphalt mixtures incorporating 2% of Rediset WMX was higher than that of the mixture incorporating 1%. Moreover, this superior performance in terms of rutting resistance was highlighted by Sampath [12], who reported that the inclusion of Rediset WMX in an asphalt mixture resulted in an adequate capability to satisfy and exceed the minimum limit of 10,000 cycles in the simple performance tester machine. However, Mo *et al.* [13] found that the inclusion of Rediset WMX in the production process of manufacturing asphalt mixtures did not lead to an analogous performance to that of the control HMA. It can therefore be concluded that the rutting performance of Rediset needs to be further evaluated. Furthermore, regarding the performance of Rediset LQ-modified asphalt mixtures, limited research has been conducted in this regard, and research on the rutting resistance of Rediset LQ-modified asphalt mixture has not been conducted thus far.

Topal *et al.* [14] characterized the influence of WMA additives (chemical, organic, and water-bearing additives) on the rutting resistance of bitumen and mixtures. They showed that WMA additives enhanced viscosity reduction, which resulted in a decrease in the manufacturing and compaction temperature of the asphalt mixture and consequently led to the reduction of emissions and energy costs as well. Moreover, it was found that all WMAs exhibited better performance in terms of rutting resistance compared with that of the corresponding HMA mixture. This agreed with research carried out by Syed *et al.* [15], who investigated the rutting performance of different warm mixtures produced with Terex foaming, Evotherm, Cecabase, and Cecabase+ using the Hamburg wheel-tracking test. It was revealed that WMAs had lower rut depth in comparison with that of the control HMA. However, the study did not consider the effect of reducing the production temperature as well as the influence of binder grade. Sun *et al.* [16] investigated the impacts of WMA technologies (wax-based and surfactant-based) and the binder content of reclaimed asphalt pavement (RAP) materials on fatigue and rutting resistance of asphalt binder using multiple stress creep and recovery (MSCR) and the linear amplitude sweep techniques. The study showed that the base/control binder yielded the poorest fatigue and rutting resistance compared with mixtures that included warm additives and RAP binder. Moreover, both RAP binder and warm surfactant-based additives increased and improved the rutting resistance of the binder, while warm wax-based additives significantly lowered the rutting resistance of the binder; however, this negative effect could be adequately alleviated by increasing the binder content of RAP materials. In general, the incorporation of RAP binder had a positive impact on the resistance of fatigue of the binders. However, this study only addressed the impact of WMA additives on the fatigue and rutting resistance of asphalt binder without paying attention to the effects of those additives on fatigue and rutting resistance of asphalt mixtures. It has been reported, however, that WMA with Evotherm, Cecabase, or foaming showed slightly higher rutting resistance in comparison with that of the control HMA through a field investigation [17]. In addition, Abd *et al.* [18–22] highlighted that Rediset LQ, Sasobit, and Rediset WMX significantly improved and increased the adhesion force between aggregate and binder, which could lead to the production of an asphalt mixture with better performance than that of conventional HMA.

2 Significance of the research

According to what has been presented in Section 1, to gain the advantages of these additives, the effect of manufacturing temperature as well as bitumen grade on the rutting resistance of WMAs must be further addressed because there is no clear picture about the level of reduction in the production temperature in manufacturing warm asphalt mixtures. The dynamic shear rheometer (DSR) is a popular method to evaluate the performance of asphalt mixture. For those reasons, DSR is used to study the rutting performance of WMAs with adoption of the MSCR technique.

3 Materials and sample preparation

3.1 Materials

The current study adopted two grades of binder, namely 40/60 and 100/150. The dosages of Rediset LQ, Rediset WMX, and Sasobit were 0.5, 2, and 2% by the weight of the binder, respectively. Tables 1 and 2 present the raw properties of bitumen and warm additives, respectively. Aggregate granite was adopted in the current study. Table 3 presents the raw properties of the granite.

3.2 Mix design

The control asphalt mixtures and WMAs were manufactured using a gap-graded hot-rolled asphalt (HRA) based on the specification of the British Standards Institute recipe [23]. Those mixtures are suitable for a surface course as the nominal maximum aggregate size is 10 mm, while the binder content is 7.8%. Steel moulds of 305 mm × 305 mm × 65 mm dimensions were used to prepare asphalt mixture slabs. A roller compactor was adopted to compact those slabs at four pressure levels: 25, 40, 50, and 72 psi. The pressure of each level was applied and operated for ten cycles based on BS EN 12697-33 [24]. After that and before de-moulding, the slabs were left overnight (24 h) to cool to environmental temperature. Figure 1 illustrates the distribution of particle size of used aggregate while Table 4 illustrates the codes of all the asphalt mixtures under investigation.

The code is clearly defined by the type of mixture, the production temperature used, the binder grade, and the type of additive included in the WMA.

Table 1: Raw properties of bitumen

Binder grade	Penetration @25°C	Softening point °C
40/60	45	54.3
100/150	104	43.0

3.3 Preparation of rutting test samples

The preparation method of the DSR shown in Figure 2 is described in detail in the study conducted by Abd and Al-Khalid [18]. It should also be mentioned that the preparation and selection of cylindrical specimens for DSR was based on the method suggested by Ahmed and Khalid [25].

4 MSCR

MSCR was conducted using a Kinexus DSR. This DSR could be used to build a continuous sequence to apply MSCR. Three stress levels were used in the current study. For hard (40/60 penetration grade) modified asphalt mixture, the stress levels were 50, 100, and 250 kPa, respectively; while for soft (100/150 penetration grade), the stress levels were 25, 50, and 75 kPa, respectively. At each stress level and for all asphalt mixtures, the stress was applied for 300 s for loading and then 500 s were

Table 2: Physical properties of additives

Properties	Rediset WMX	Rediset LQ	Sasobit
Form	Pastilles	Liquid	Flakes
Colour	Light brown	Dark brown	Off-white to pale brown
Odour	Ammoniacal	Slight	Practically odourless
pH	Not applicable	10 at 0.1 solution	Neutral
Melting point	80–95°C		Above 100°C
Boiling point	>100°C	215°C	—
Flash point	253°C	165°C (Pensky-Martens)	285°C (ASTM D92)
Solubility in water	Practically insoluble	Partly soluble	Insoluble

Table 3: Specifications of aggregate

Properties	Granite
Apparent particle density	2.67^{*}–2.71^{**} mg/m^3
Polished stone value	58^{*}
Water absorption	$1.7\%^{*}$, $0.6\%^{**}$
Los Angeles coefficient	27
Aggregate abrasion value	2.9
Oxidizable sulphides	$0.02\%^{*}$, $0.41\%^{**}$
Acid soluble sulphate	$0.02\%^{*}$, $0.05\%^{**}$
Water soluble sulphate	$<0.01^{*}$, $<0.001^{**}$

*Coarse aggregate. **Fine aggregate.

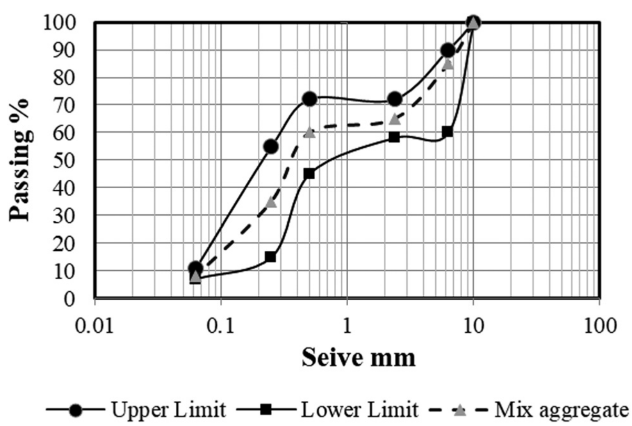

Figure 1: Distribution of particle size of the aggregate.

allowed for recovery. It should be noted that five DSR samples were tested for each stress level sequence; moreover, the testing was conducted at a temperature of 25°C. Figure 3 illustrates the setting of a DSR sample in the machine, while Figure 4 shows the typical curve of an MSCR result and the creep parameters, *i.e.*, maximum, recovered, and permanent shear strain, that were used in evaluating the creep performance.

5 Results and discussion

Figure 5 presents the maximum shear strain of WMAs produced at 135°C with a binder grade of 40/60. It can be noted that at different levels of stress, the maximum shear strain of all modified WMAs produced at a temperature of 135°C was higher than that of the baseline HH manufactured at 155°C because of the lower production temperature, as the bitumen was softer as a result of reduced ageing oxidization and inadequate drying of the aggregate. Furthermore, Rediset LQ improves the adhesion between aggregate and binder but has no function to increase the stiffness of the binder, while Rediset WMX is a viscosity reducer and active adhesive but again it cannot completely offset the reduced oxidative ageing. Figures 6 and 7 present the permanent and recovered shear strain, respectively. However, Sasobit increases the stiffness of bitumen, which consequently results in a stiffer asphalt mixture; therefore, although the bitumen in the WHSa mixture produced at a temperature of 135°C was certainly less oxidized than that of the control mix, Sasobit can offset that by increasing the binder stiffness. The reason behind this is that Sasobit can form a lattice structure, which largely prevents the movement of bitumen molecules by constructing bridges which that connect between them. In consequence, Sasobit increases and improves the viscosity of bitumen at service temperatures. For this reason, as shown in Figure 7, an asphalt mixture modified with Sasobit has a strain level similar to that of the control mixture manufactured at 155°C.

Figure 8 illustrates the maximum shear strain for warm-modified asphalt mixtures manufactured at 145°C, which is only 10°C less than that of the control mixture HH. It is obvious, in terms of reaching the maximum strain, that all warm-modified asphalt mixtures manufactured at 145°C performed better as well as the control mixture provided that the effect of the reduction in the

Table 4: Code definitions of HMAs and WMAs

Mixture code	Type of mixture	Production temperature (°C)	Binder grade	Warm additives
HH	Hot mix asphalt	155	40/60	—
HS	Hot mix asphalt	145	100/150	—
WHSa	Warm mix asphalt	145 and 135	40/60	Sasobit
WHRw	Warm mix asphalt	145 and 135	40/60	Rediset WMX
WHRl	Warm mix asphalt	145 and 135	40/60	Rediset LQ
WSSa	Warm mix asphalt	125	100/150	Sasobit
WSRw	Warm mix asphalt	125	100/150	Rediset WMX
WSRl	Warm mix asphalt	125	100/150	Rediset LQ

Figure 2: Cylindrical DSR specimens ready for testing.

manufacturing temperature was taken into account. Sasobit and Rediset WMX have the ability to salvage the mixture properties because of the availability of wax. One might think that the availability of wax could make the mixture more brittle, which would prevent it retain its original properties, but both Sasobit and Rediset WMX have wax in their structure. The wax solidifies into small microscopic particles and, more importantly, it uniformly distributes among the molecules of bitumen. In fact, this phenomenon can result in a remarkable increase in the stiffness of bitumen in a similar conjuncture way to material reinforced by fibres. Therefore, both Sasobit and Rediset WMX allow the mixture to regain its original properties.

Furthermore, when the difference in production temperature of asphalt mixtures was reduced from 20°C to only 10°C lower than the control, a significant improvement in the rutting performance of WMAs manufactured using a binder grade of 40/60 was found in comparison with that of the associated baseline mixture, as illustrated in Figures 9 and 10, which show the permanent and recovered shear strain, respectively. As aforementioned, Rediset WMX is a viscosity reducer as well as surfactant because it has a long-chain aliphatic hydrocarbon structure as well as an $-NH_3^+$ group. These can therefore chemically react with the surface of aggregate resulting in improved adhesion between the aggregate and binder at a lower temperature. Rediset LQ is an active adhesive, compaction aid, and surfactant. It can consequently enable the binder to create a strong bond of adhesion between the bitumen and the surface of the aggregate as a result of displacing residual moisture, which could be available due to incomplete drying of the aggregate surface. However, it should be noted that this cannot happen unless the bitumen temperature

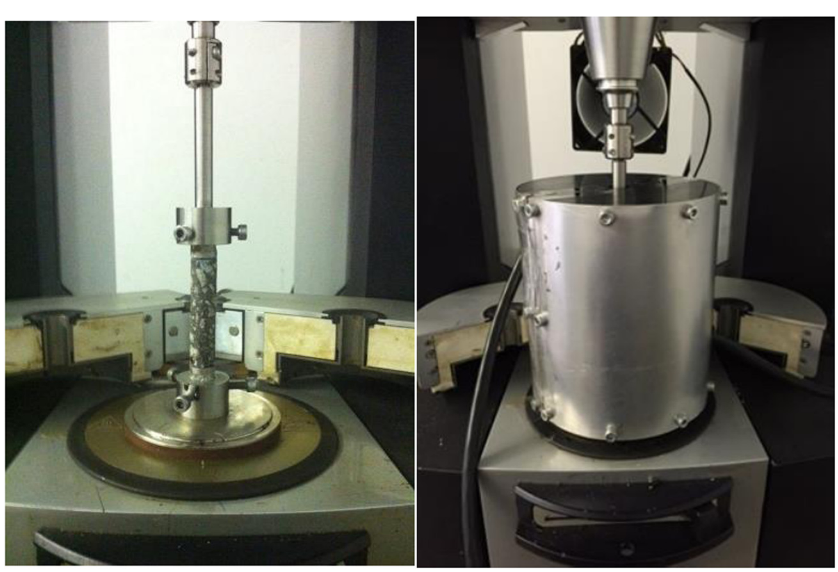

Figure 3: DSR sample ready for testing in the DSR.

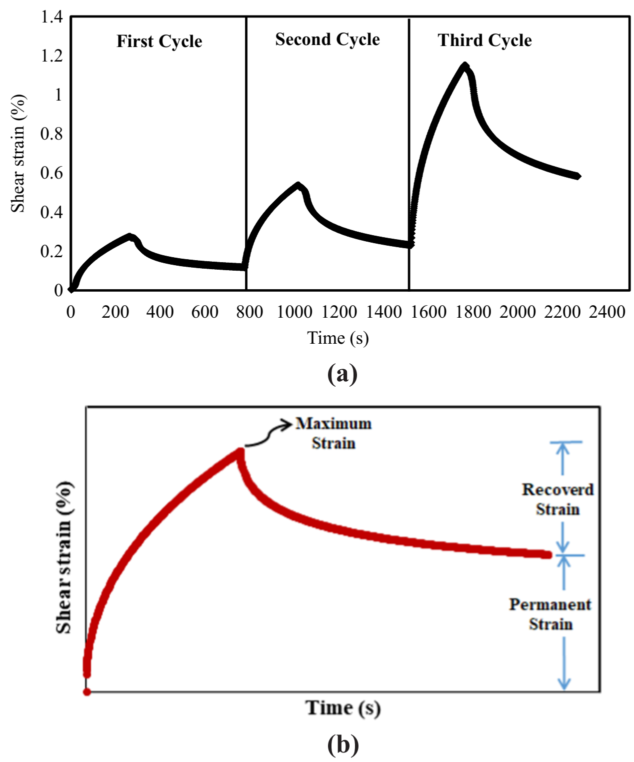

Figure 4: Typical curve of an MSCR result. (a) Three cycles. (b) Typical one cycle.

reaches an appropriate level so that the bitumen can adequately adhere to and diffuse into the surface of the aggregate. As a matter of fact, even though WMA can be successfully produced at temperatures less than that needed to manufacture conventional HMA, the effect of the binder grade has to be considered to acquire the desired performance of asphalt mixtures. A recommendation can therefore be made that WMA produced using a binder grade of 40/60 should not be manufactured at a temperature lower by more than 10°C than that required to manufacture the corresponding HMA.

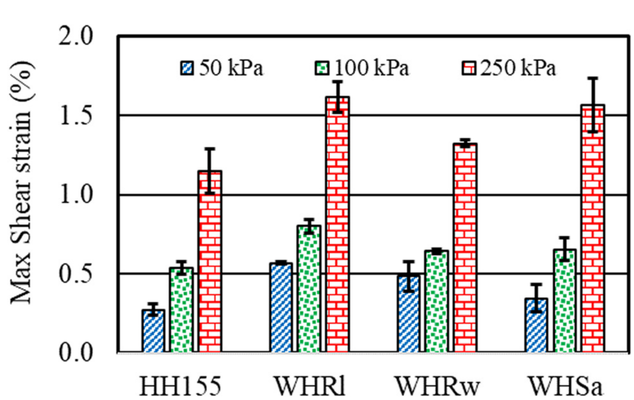

Figure 5: Maximum shear strain at each testing cycle of WMAs manufactured at 135°C.

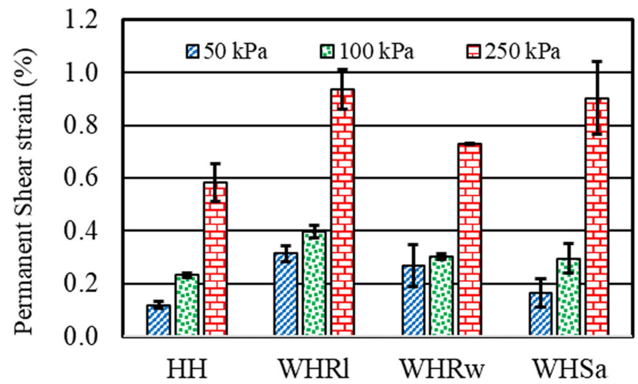

Figure 6: Permanent shear strain at each testing cycle of WMAs manufactured at 135°C.

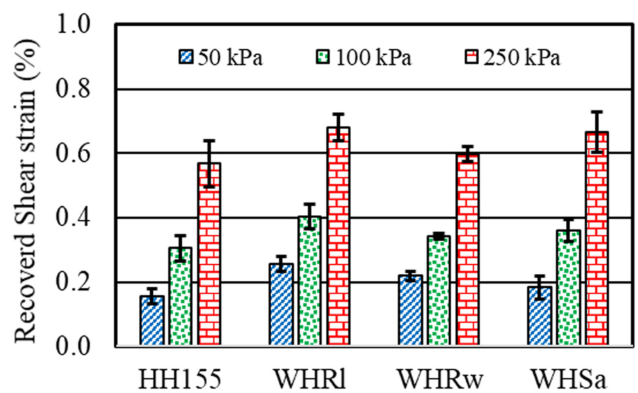

Figure 7: Recovered shear strain at each testing cycle of WMAs manufactured at 135°C.

Furthermore, and more importantly, the effect of Sasobit on improving resistance against permanent deformation was more significant when WMA was manufactured at 145°C than at 135°C as the binder was more oxidized than in the first scenario, and also because Sasobit liquefies the bitumen

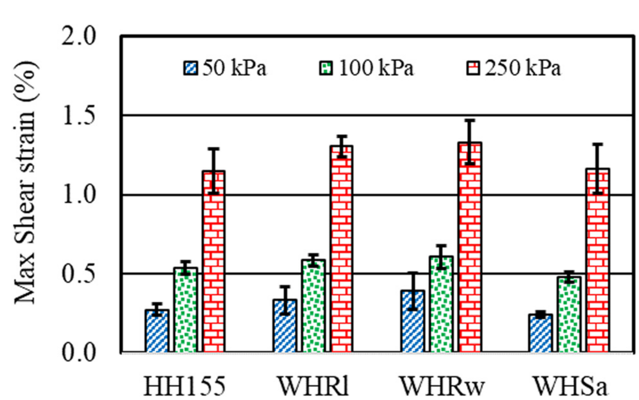

Figure 8: Maximum shear strain at each testing cycle of WMAs manufactured at 145°C.

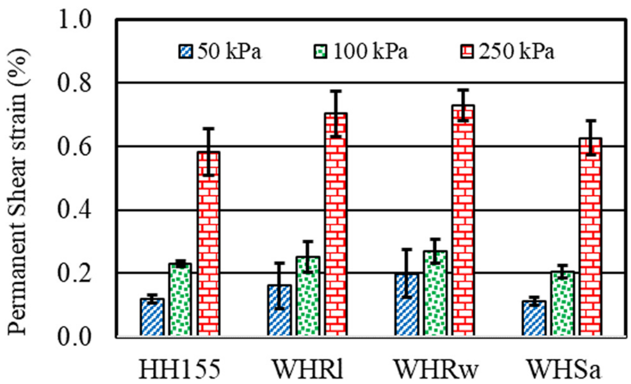

Figure 9: Permanent shear strain at each testing cycle of WMAs manufactured at 145°C.

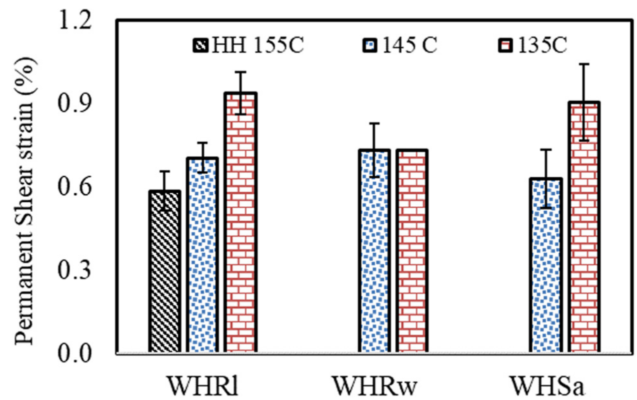

Figure 12: Final permanent shear strain at the termination of the MSCR test.

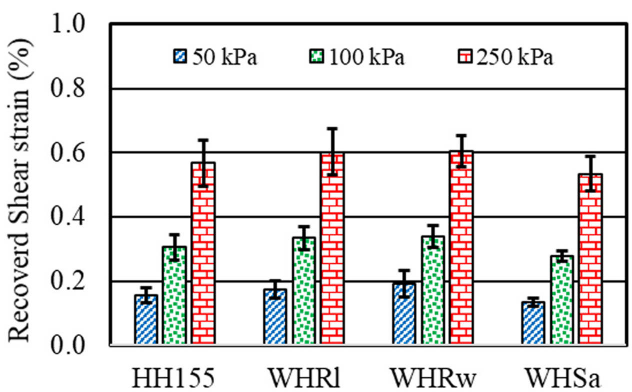

Figure 10: Recovered shear strain at each testing cycle of WMAs manufactured at 145°C.

at a higher temperature, which results in a reduction of viscosity and enhancement in the adhesion or bonding between the aggregate and binder. This finding agrees with a study carried out by Abd and Al-Khalid [18], who investigated the potential influence of production temperatures on the fatigue cracking of WMA, addressing the impact of binder grade. In fact, the potential impact of level of reduction in the production temperatures of WMAs is very clear.

Figures 11–13 show the final levels of maximum strain, permanent strain, and recovered strain at the end of the MSCR sequence and a comparison between the effects of production temperatures. It is very obvious that the maximum shear strain and permanent strain of warm-modified asphalt mixtures decreased significantly as the production temperature of those mixtures increased from 135 to 145°C, because the production temperature plays a potential role in determining the level of adhesion between aggregate and bitumen in spite of the advantage of warm additives in reducing the production temperature of asphalt mixtures. In other words, although warm additives can decrease the production temperature of asphalt mixtures, there is a certain level of reduction in the manufacturing temperature that cannot be exceeded to ensure an adequate adhesion between aggregate and bitumen, as highlighted and recommended by Abd *et al.* [21,22].

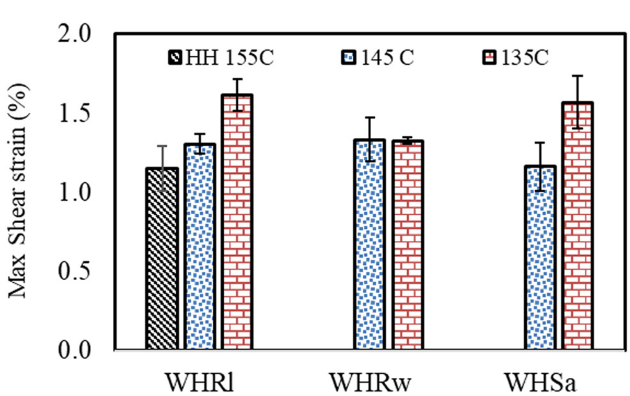

Figure 11: Final maximum shear strain at the termination of the MSCR test.

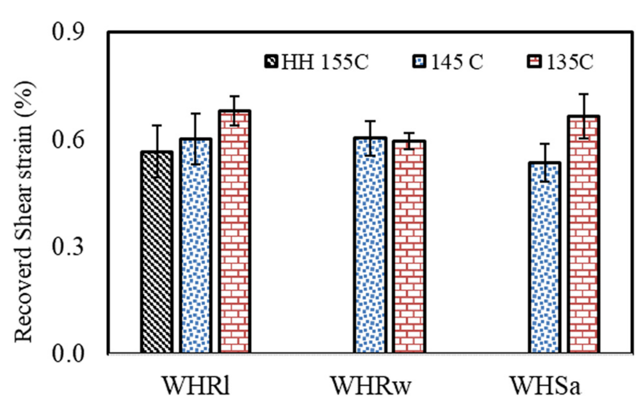

Figure 13: Total recovered shear strain at the termination of the MSCR test.

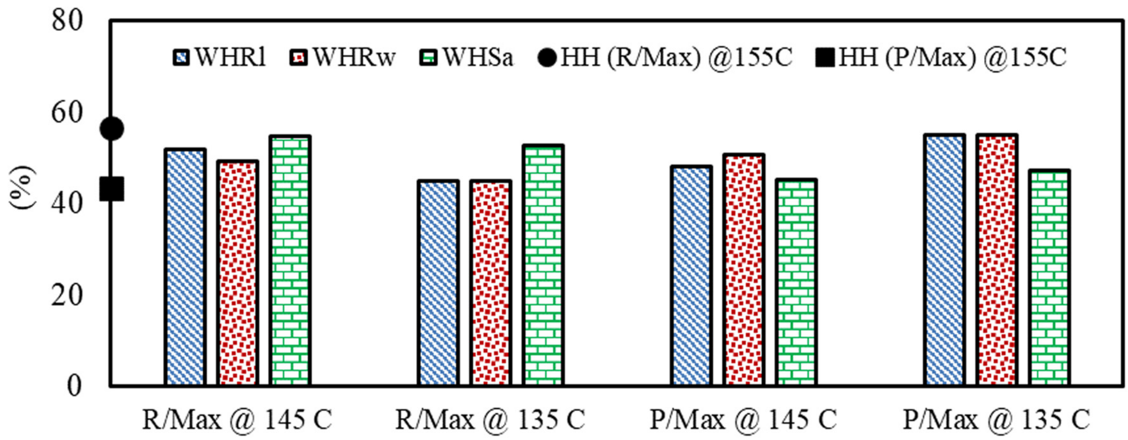

Figure 14: Final percentages of recovered and permanent strain at the termination of the first cycle of MSCR.

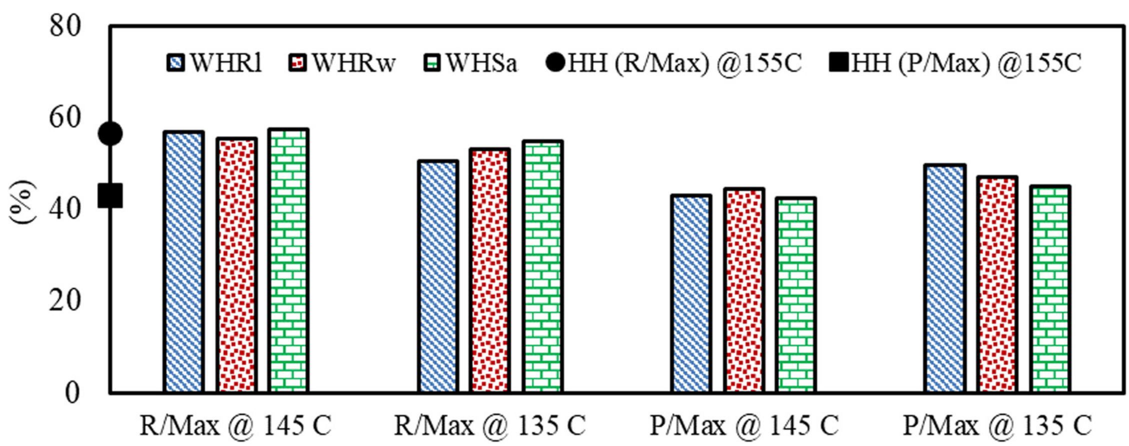

Figure 15: Final percentages of recovered and permanent strain at the termination of the second cycle of MSCR.

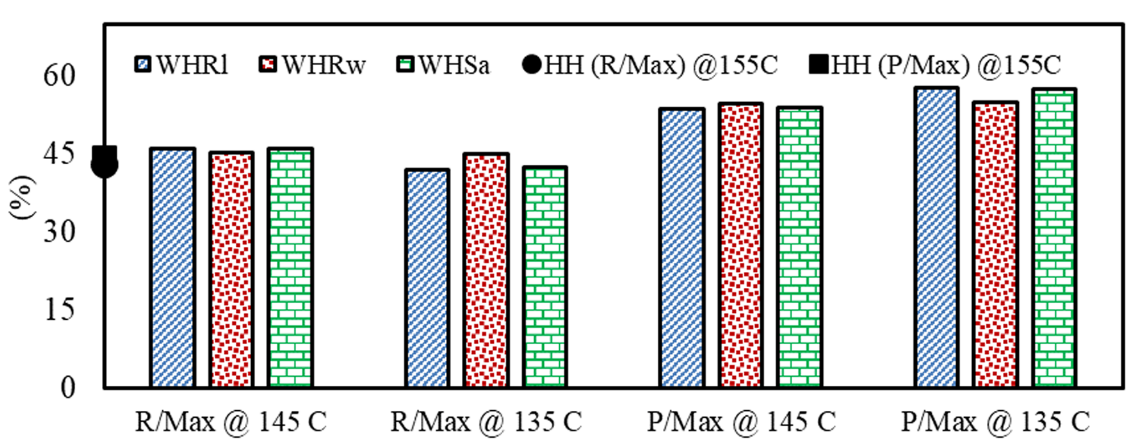

Figure 16: Final percentages of recovered and permanent strain at the termination of the third cycle of MSCR.

To further investigate the impact of those warm additives on the degradation of rutting resistance of asphalt mixtures, Figures 14–16 present the percentages of the result of dividing the permanent strain and recovered strain by the maximum shear strain at the end of each stress level of the MSCR test for WMAs manufactured at

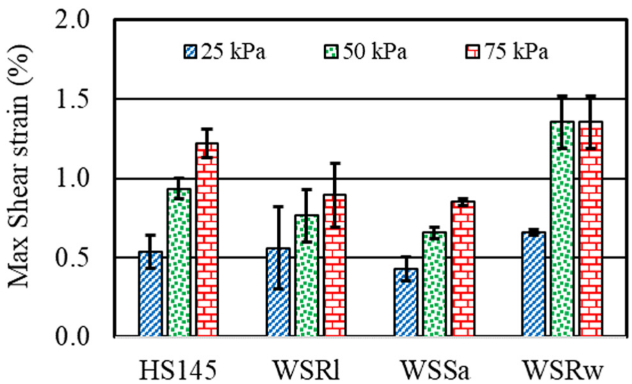

Figure 17: Maximum shear strain at each testing cycle of WMAs manufactured at 125°C.

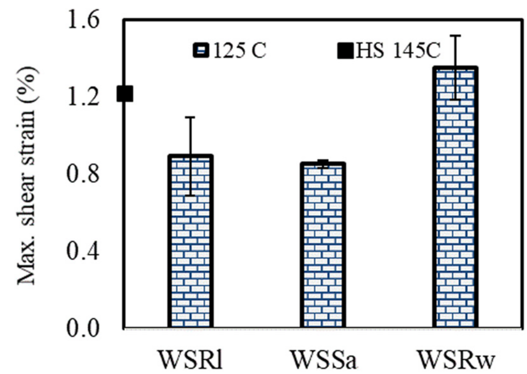

Figure 20: Final maximum shear strain at the termination of MSCR.

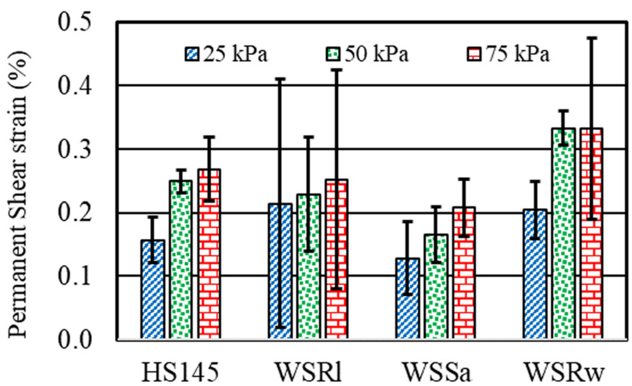

Figure 18: Permanent shear strain at each testing cycle of WMAs manufactured at 125°C.

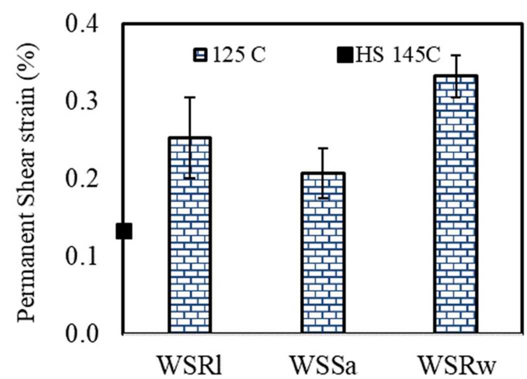

Figure 21: Final permanent shear strain at the termination of MSCR.

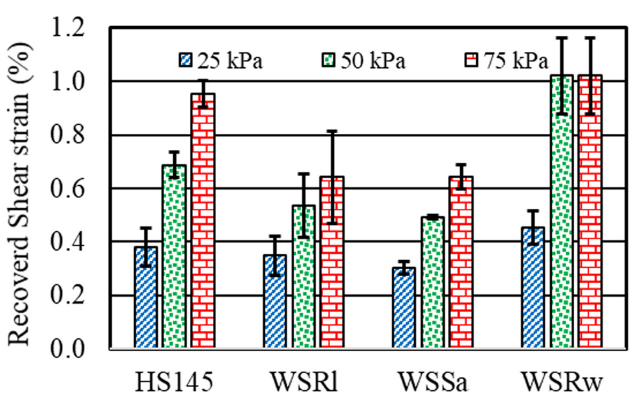

Figure 19: Recovered shear strain at each testing cycle of WMAs manufactured at 125°C.

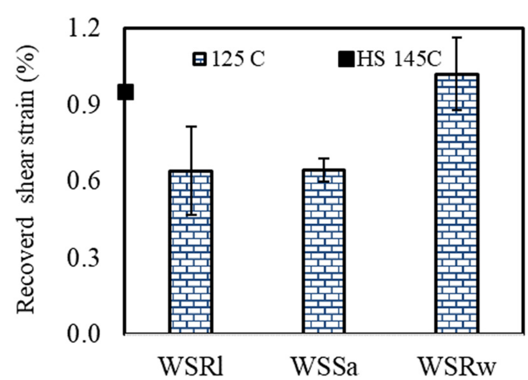

Figure 22: Final recovered shear strain at the termination of MSCR.

135 and 145°C. As presented, the percentages of P/Max (permanent strain/maximum strain) and R/Max (recovered strain/maximum strain) of warm-modified mixtures manufactured at 135°C were higher than those of the corresponding control mixture. However, those percentages decreased as the production temperature increased.

There is no doubt that the impact of binder grade on the rutting resistance of WMA is very clear. Figures 17–19

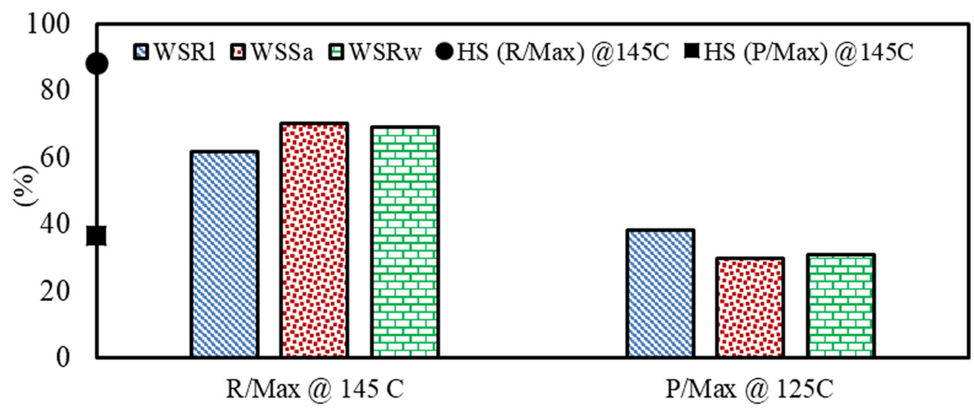

Figure 23: Final percentages of recovered and permanent strain at the termination of the first cycle.

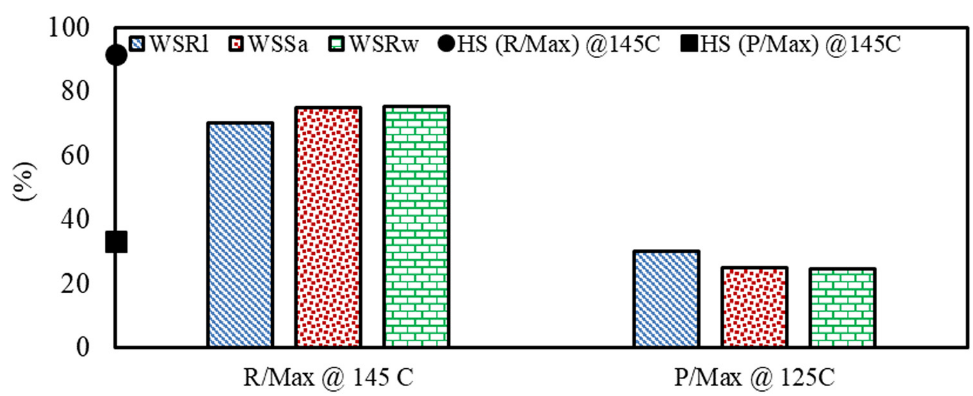

Figure 24: Final percentages of recovered and permanent strain at the termination of the second cycle.

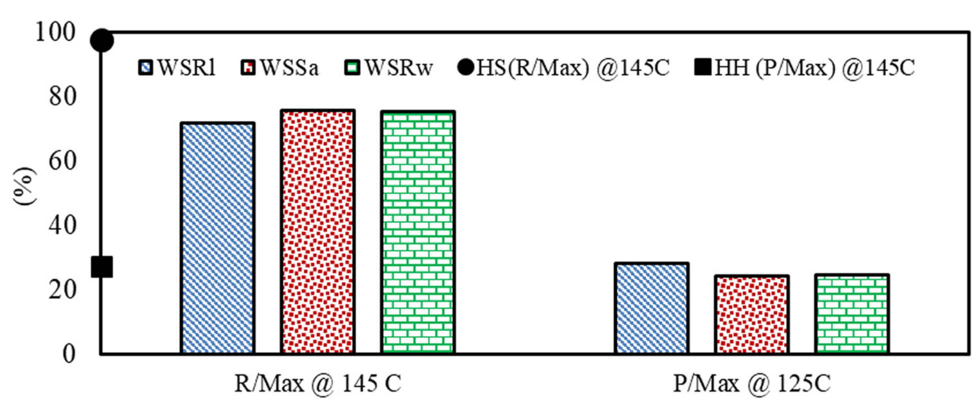

Figure 25: Final percentages of recovered and permanent strain at the termination of the third cycle.

show the maximum, permanent, and recovered shear strain of WMAs manufactured at 125°C using 100/150 penetration grade. It is noticeable that, although the decrease in the manufacturing temperature of the asphalt mixture was up to 20°C compared with that of baseline asphalt mixture manufactured at 145°C, the rutting performance of all WMAs manufactured using 100/150 was comparable with or even better than that of baseline mixture HS at different levels of stress. The exception was in the case of Rediset WMX as the WSRw mixture had slightly higher shear strain than that of the control mixture and also exhibited slightly greater permanent deformation. This was also clear at the end of the MSCR test as presented in Figures 20–22. It can be noted that WSRw mixture had slightly higher maximum shear and permanent shear strain than that of the control mixture. The recoverable strain, on the other hand, was comparable with that of the control mixture. In addition, as presented in Figures 23–25, the ratios of permanent strain to maximum shear strain and recovered strain to maximum shear strain are equal or less than those of the control mixture at each stress level. In other words, WMAs performed equally to control mixtures and a 20°C reduction in the manufacturing temperature is acceptable.

Binder grades have a significant potential function in determining the appropriate reduction in the manufacturing temperatures of asphalt mixtures. As presented, the results generally proved that the improvement in the rutting resistance of WMAs produced using binder grades of 40/60 and 100/150 can only be symmetrical and equal at different reductions of manufacturing temperature for each binder grade.

6 Conclusion

Three warm additives and two virgin binders were used to evaluate the effects of those additives on the rutting behaviour of asphalt mixtures tested in a DSR. Furthermore, the impacts of producing temperature and binder grade were also addressed. Based on the aforementioned findings, conclusions can be drawn as follows:

1. It was highlighted that manufacturing temperature ultimately controls the durability of the asphalt mixture. To achieve the desired rutting resistance of WMAs, there should be a distinction between the amount of reduction in the manufacturing temperature of asphalt mixtures produced using hard and soft binders, or the recommended dosages of warm additives can be revealed according to the binder grade. After addressing the impact of production temperature, the rutting resistance of all WMAs under investigation was improved and their performance was equal to that of the associated control mixtures.
2. Rediset LQ, Rediset WMX, and Sasobit can also prevent or delay degradation in the rutting resistance of asphalt mixtures. Long-term performance of WMAs should be investigated, addressing the impact of level of reduction in the production temperature. This point will be the subject of another study and publication by the authors.
3. According to what has been presented, a minimum production temperature of WMAs should be specified by highway agencies to reach the desired rutting and fatigue resistances in the asphalt mixture taking into consideration the impact of the grade of binder as well as its source.
4. DSR is a robust and effective tool to investigate the rutting performance of asphalt mixtures.

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