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EARN

Laboratory study on moisture and ageing susceptibility characteristics of RA and WMA mixtures

Deliverable Nr. 7

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Deliverable Nr. 7 - Laboratory study on moisture and ageing susceptibility characteristics of RA and WMA mixtures

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Executive summary

The objective of Work Package 3 (WP3) is to assess whether reclaimed asphalt (RA) and warm mix asphalt technologies adversely affect the moisture and ageing susceptibility characteristics of asphalt pavements. For this study, site trials of mixtures with and without RA have been laid in Dublin, Ireland, from which cylindrical samples were cored and utilised for laboratory testing. The coring procedure and laboratory testing were carried out in two stages; in the first stage, field cores were taken 24 h after the construction of the trial section was completed and were evaluated for their susceptibility to moisture damage, while in the second stage asphalt cores were taken 12 months later and then tested under the same conditions. In this manner, apart from the effect of moisture, also the effect of field ageing on the mechanical response of the selected mixtures was evaluated.

This deliverable report summarises the findings of WP3. In the following sections, the experimental methodology utilised for the evaluation of the mixtures is described and the laboratory test results of sub-tasks 3.2.1 and 3.2.2 are presented. This way, the mechanical response degradation due to moisture damage and field ageing are quantified. In addition, the effect of using reclaimed asphalt and warm mix additives on the durability of asphalt mixtures is evaluated.

1 Introduction

The use of reclaimed asphalt (RA) and secondary materials has grown extensively due to the associated environmental benefits, i.e. reduction of the use of virgin materials and of the amount of waste send to landfills, which contribute to the development of sustainable asphalt pavements. The challenge for engineers is to achieve pavement materials with similar mechanical performance to those of the equivalent material made of virgin components, and at the same time to consider ways to increase further the RA content in pavement mixture design. Similarly, traditional technologies for asphalt mixture production are gradually being replaced by warm mix asphalt (WMA) technologies, which allow the production and laying of the material at lower temperatures, with significant benefits in terms of lowering fuel consumption and decreasing the production of greenhouse gases. Obviously, the benefits arise from the use of RA and WMA can be compromised if performance of the mixture in the long-term is poor.

The development of sustainable road infrastructure requires, among other things, the construction of asphalt pavements with enhanced durability characteristics. From the moment of construction and continuing during their service life, asphalt pavements are continuously exposed to a combination of traffic loading and environmental influences. Environmental conditions such as fluctuating temperature, humidity, precipitation, oxygen, freeze-thaw cycles and ultraviolet radiation influence the material properties constantly. To counteract these influences, an increase in the operational and maintenance costs is needed in order to fulfill the desired service life of the pavement system. Global warming and climate change events such as temperature extremes, high mean precipitation and rainfall intensity may further increase the probability and rate of pavement deterioration. There is thus a strong need to obtain an improved understanding of the influence of environmental factors on the long term performance of asphalt pavements.

In the EARN project, moisture damage and ageing due to oxygen diffusion were assumed to be the two important parameters that can shorten pavement life and accelerate pavement distresses. The use of reclaimed asphalt, secondary materials and lower temperatures will affect the various factors in different ways, further complicating an already complex situation.

A serious cause for diminishing the long-term performance of an asphalt pavement is the presence of water in the pavement structure and the detrimental effect that water has on the mechanical properties of the mixture. Moisture-induced damage is an extremely complicated mode of distress that leads to the loss of stiffness and structural strength of the asphalt and eventually to the premature failure of the pavement structure.

Regardless of the mix composition, asphalt mixtures will suffer from moisture damage at some time during their service life. In reality, a dislodging process of the aggregates occurs, which is known as ravelling or stripping of the asphalt mixture. The loss of the aggregates from the mixture may exhibit either a cohesive (i.e. within the binder which consists of bitumen and filler) or an adhesive (i.e. within the binder-aggregate bond) failure pattern. Even though not necessarily initiated by the presence of water, most pavement distress mechanisms (cracking, permanent deformation, ravelling, etc.) will be increased in extent and severity with the presence of water or other forms of moisture (Miller and Bellinger, 2003). An improved understanding of moisture-induced damage in asphalt and more moisture-resistant materials will have a significant impact on pavement maintenance expenditure, particularly because rainfall is predicted to increase due to global warming.

For an asphalt mixture that is exposed to moisture and/or to a constant movement of water through it, there are several moisture damage phenomena that can be identified, in particular moisture diffusion, mastic erosion and pumping action. Moisture diffusion in asphalt mixtures is a long-term process driven by the diffusion coefficient *D*, which depends on the characteristics of each type of binder. The moisture diffuses through the binder layers surrounding the aggregates and eventually reaches the interface area between them. Depending on the chemical characteristics of both the binder and the aggregates, the water can cause an adhesive failure of the binder-aggregate interface. In addition, the cohesive strength of the binder particles weakens as the moisture concentration increases within the binder film. A fast flow of water through an asphalt mixture can cause desorption of the weakened binder, referred to as "erosion". Once the outer layer of a binder film is eroded, the next layer of binder, now exposed to the water flow, can be damaged.

Pumping action can act accumulatively on the above damage mechanisms. In asphalt mixtures, the pores are generally interconnected and allow the water to move through the pavement. When some macro-pores in an asphalt pavement are saturated, the dynamic traffic load can cause excess pressure in these pores. Once the pore pressure increases to a high level, the binder film on the aggregate will break under the pressure and create a crack in the film, allowing water easy access to the surface of the aggregate. Additionally, the intense pore pressures can cause a local fast flow of water which contributes to the washing away, i.e. erosion of the binder.

Another important process that can cause slow alteration of the mechanical properties is ageing due to oxygen diffusion. The performance and durability of a pavement is significantly influenced by the performance of asphalt binders. Age hardening appears to be a complex phenomenon that alters the viscoelastic behaviour of the binder through chemical and/or physical processes in time and typically leads to embrittlement of the asphalt binder due to elevation of the complex modulus and reduction of the viscoelastic phase angle, making the asphalt more prone to damage under the same loads and strains. Therefore, binder ageing is a key factor for the design of long-lasting and better performing asphalt pavements. Depending on the availability of oxygen for diffusion in an asphalt pavement, asphalt binders will harden in time and become brittle; consequently the propensity of asphalt pavements to cracking increases (Ruan *et al*., 2003).

The use of reclaimed asphalt and/or warm mix additives can influence the abovementioned failure mechanisms. Even when the initial properties of the asphalt are the same at the time of construction, the change in material properties with time may be greater (or lesser) for those mixtures than for traditional hot mix asphalt and therefore this will have an influence on their durability. It is this potential difference that the project will investigate.

This deliverable report summarises the results of WP3. It aims to quantify the degradation of mechanical properties due to moisture damage and field ageing and investigate the effect of RA on moisture susceptibility and ageing of asphalt mixtures. In the following, a description of the experimental method employed in this study is given. Also, the results of the tests for both phases of the laboratory programme are reported and the influence of RA and WMA additives on the durability of asphalt mixtures is evaluated. Finally, conclusions are drawn, on the basis of which recommendations for characterising and limiting moisture susceptibility in RA pavements can be developed.

2 Experimental work

2.1 Mixture design

In the EARN project, the effect of reclaimed asphalt and WMA additives on the durability of asphalt pavements is studied on the basis of site trials. A typical surface course, SMA 10 mm with a target of 4 % to 6 % air voids, was produced according to the Irish and European standards. Four variants of the SMA mixture were determined and laid in the test sections, as shown in Figure 1.

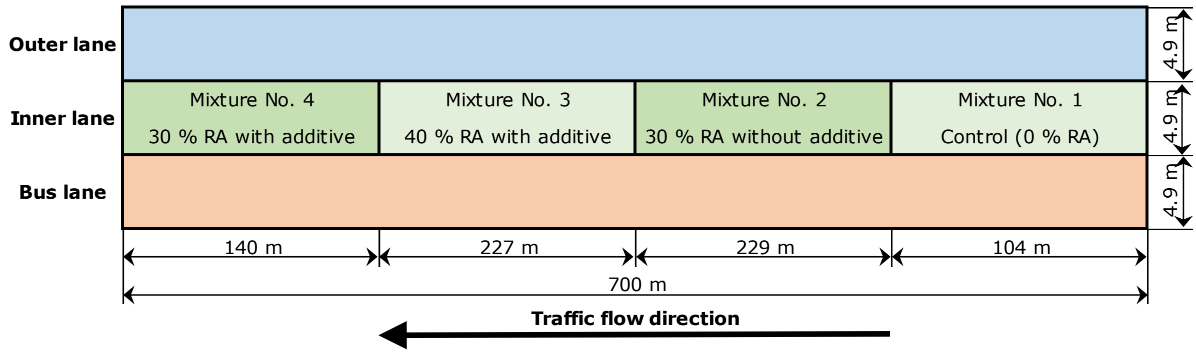

Figure 1. Schematic representation of the trail section

The variations of the 10 mm SMA mixture are 0 % RA as control; 30 % RA and no additive; 40 % RA and Cecabase RT 945 warm mix additive; and 30 % RA and Cecabase RT 945 warm mix additive. The grading curves for these mixtures are presented in Figure 2, illustrating the good agreement between the control mixture grading and those of the mixtures containing RA. Using the control mixture grading as the guideline allowed the best particle distribution for the mixtures, and consequently the best mixture design as illustrated in Table 1. More information on the mixture design and construction of site trials are given in Tabaković *et al.* (2014).

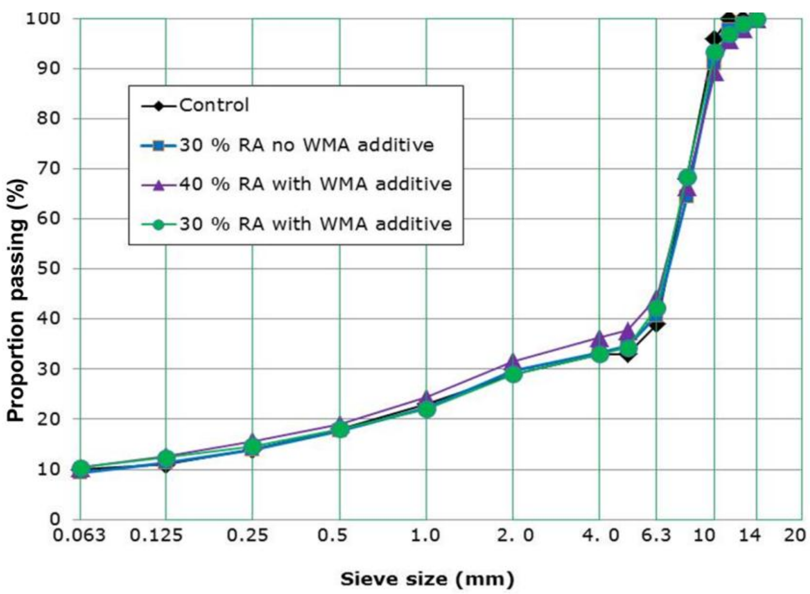

Figure 2. Particle size distribution

Table 1. Mixture design

Mixture	Proportional content (%)					
	RA	10 mm	CRF*	Filler	Fresh Binder	Warm Mix Additive**
1	0	65.9	22.8	5.7	5.6	0
2	28.6	43.8	17.0	5.7	4.9	0
3	38.1	34.4	17.1	5.7	4.7	0.3
4	28.6	43.8	17.0	5.7	4.9	0.3

**Crushed Rock Fines, **Warm mix additive added to mixtures 3 & 4 at 0.5 % of the total binder content*

2.2 Collection of samples

Overall, a total of 216 cores were collected and tested in WP3. For the first phase, a total of 108 cores (27 from each trial section) were collected 24 h after the construction of the test sections was completed, while for the second phase, another 108 cores were taken nearly one year after section construction. Both the unaged and field aged cores were then tested for their sensitivity to moisture damage in the laboratory. The coring procedure is shown in Figure 3.

a) Material sampling b) Coring c) A core sample

Figure 3. Collection of samples from site

The asphalt cores, collected from the field, were 100 mm in diameter and approximately 60 mm in height. As shown in Figure 4, the cores consisted of two different layers, i.e. SMA surface course and binder course. Therefore, prior to testing, the regulating material was removed by sawing the asphalt cores using a diamond saw. Then, height and bulk density measurements were performed in accordance with the European standards EN 12697-29 (CEN, 2002) and EN 12697-6 (CEN, 2012), Method B (SSD), respectively. The results for the unaged and aged cores can be found in Varveri *et al.* (2014a) and Varveri *et al.* (2014b), respectively.

Figure 4. Asphalt cores collected from site trials

2.3 MIST test protocol

2.3.1 Introduction

Over the years, several test procedures have been proposed for the evaluation of moisture susceptibility of asphalt concrete mixtures including the Boiling Water Test (ASTM D3625), Static Immersion Test (AASHTO T-182), Tunnicliff and Root Conditioning (NCHRP 274) and the modified Lottman (AASHTO T283) (Lottman, 1974). In Europe, the water sensitivity of asphalt mixtures is determined according to European standard EN 12697-12 (CEN, 2008). However, the moisture conditioning protocols described in the aforementioned tests fail to capture the time frame over which moisture infiltration occurs and furthermore disregard the short term moisture processes related to pumping action (Kringos *et al*., 2009). In addition, field observations have shown that stripping of open asphalt mixtures is a rather localised phenomenon in trafficked areas of a pavement which are oversaturated with water (Kandhal *et al*., 1989). These findings strengthen the claim that pumping action can be an important damage mechanism which acts concurrently with the long term damage processes and contributes to premature failure in asphalt pavements.

In the EARN project, a new moisture conditioning protocol (Varveri et al., 2014c) is utilised, which can distinguish the individual contributions of short- and long-term moisture damage to mixture degradation. The evaluation of the asphalt mixtures for their sensitivity to moisture is performed on the basis of their Indirect Tensile Strength (ITS) and the Indirect Tensile Strength Ratio (ITSR). At the same time, moisture sensitivity tests (according to the EN 12697-12 standard) are performed in University College Dublin as part of task 2.4. A comparison between the results obtained from the combined test and the EN 12697-12 test will be made in the final report (Nicholls *et al*., 2014).

2.3.2 Description of testing protocol

The same moisture conditioning protocol was applied to the fresh (unaged) and the field aged cores. For every phase, a total of 27 cores were drilled from each trial section. For each mixture, the samples were divided into two subsets. The first subset was subjected to moisture conditioning, while the other subset was stored in a climate chamber at dry conditions at 20 °C. In order to address the individual damage mechanisms associated with the two types of damage inducing processes, the moisture conditioning protocol is a combination of two different conditioning methods: (a) bath conditioning and (b) cyclic water pore pressure application.

Cyclic pore pressures were applied on the asphalt samples by means of the moisture induced sensitivity tester (MIST), Figure 5. MIST is a self-contained unit, which includes a hydraulic pump and a piston mechanism that is designed to cyclically apply pressure inside a sample chamber. Moisture conditioning is performed by placing a compacted asphalt sample in the chamber and filling it with water. Then the water is pushed and pulled through the sample, thus creating pressure cycles between zero and the chosen pressure. One can choose the pressure, temperature and the number of conditioning cycles to replicate different combinations of traffic and environmental conditions (InstroTec, 2012).

Figure 5. Moisture induced sensitivity tester.

As illustrated in Figure 6, the samples were immersed in a bath with distilled water at an elevated temperature of 60 °C, in order to facilitate the infiltration of water into the asphalt mixture and, consequently, accelerate the long-term degradation of the material properties. At fixed time intervals of 3 and 6 weeks, three samples per mixture were removed from the bath, placed in a bath at 20 °C for 2 h and then maintained in a climatic chamber at 20 °C until tested. An additional three samples per mixture were removed from the bath and further conditioned in MIST; 4000 cycles of pressure were applied at a temperature of 60 °C and a pressure of 70 psi (0.48 MPa). After MIST application, the samples were placed in a water bath, at 20°C for 2 h. Then the indirect tensile test (ITT) was performed in accordance with EN 12697-23 (CEN, 2003).

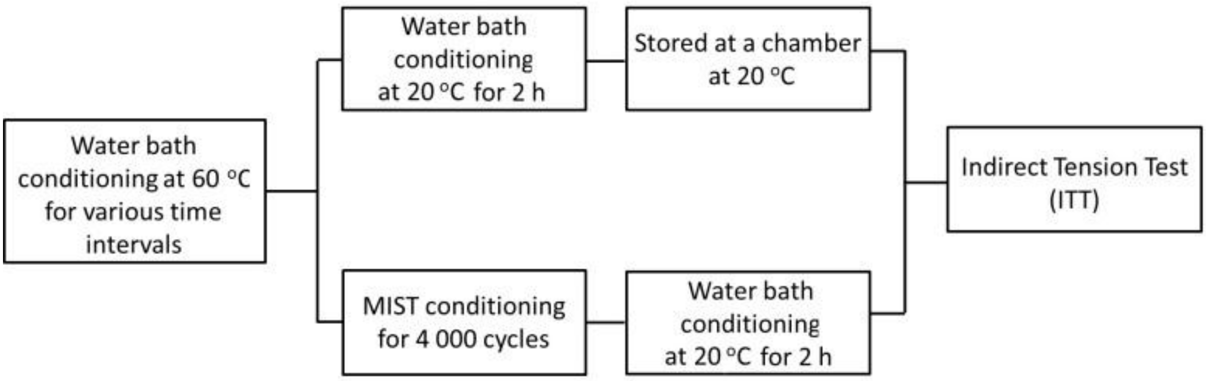

Figure 6. Schematic of the applied moisture conditioning protocols

After the samples were delivered, six samples per mixture were stored in a climate chamber at 20 °C. The samples were kept in the chamber at dry conditions during the moisture conditioning period, and then tested together with the conditioned samples at each defined time interval. In this way any effects on strength due to age hardening, while in storage, were taken into account. Table 3 shows the number of samples tested for every conditioning regime for each phase in WP3.

Table 3. Testing matrix

Conditioning mode	Mixture	Week 0	Week 3	Week 6
Dry	A	6	3	3
	B	6	3	3
	C	6	3	3
	D	6	3	3
Bath	A	-	3	3
	B	-	3	3
	C	-	3	3
	D	-	3	3
Bath & MIST	A	3*	3	3
	B	3*	3	3
	C	3*	3	3
	D	3*	3	3

**Only MIST conditioning was applied on the dry subset at week 0.*

3 Test results

The evaluation of the asphalt cores for their moisture damage and ageing susceptibility was performed on the basis of the indirect tensile strength (ITS) and the indirect tensile strength ratio (ITSR). Figure 7 shows the effect of isothermal storage, at dry conditions, on the strength of both unaged and field aged mixtures.

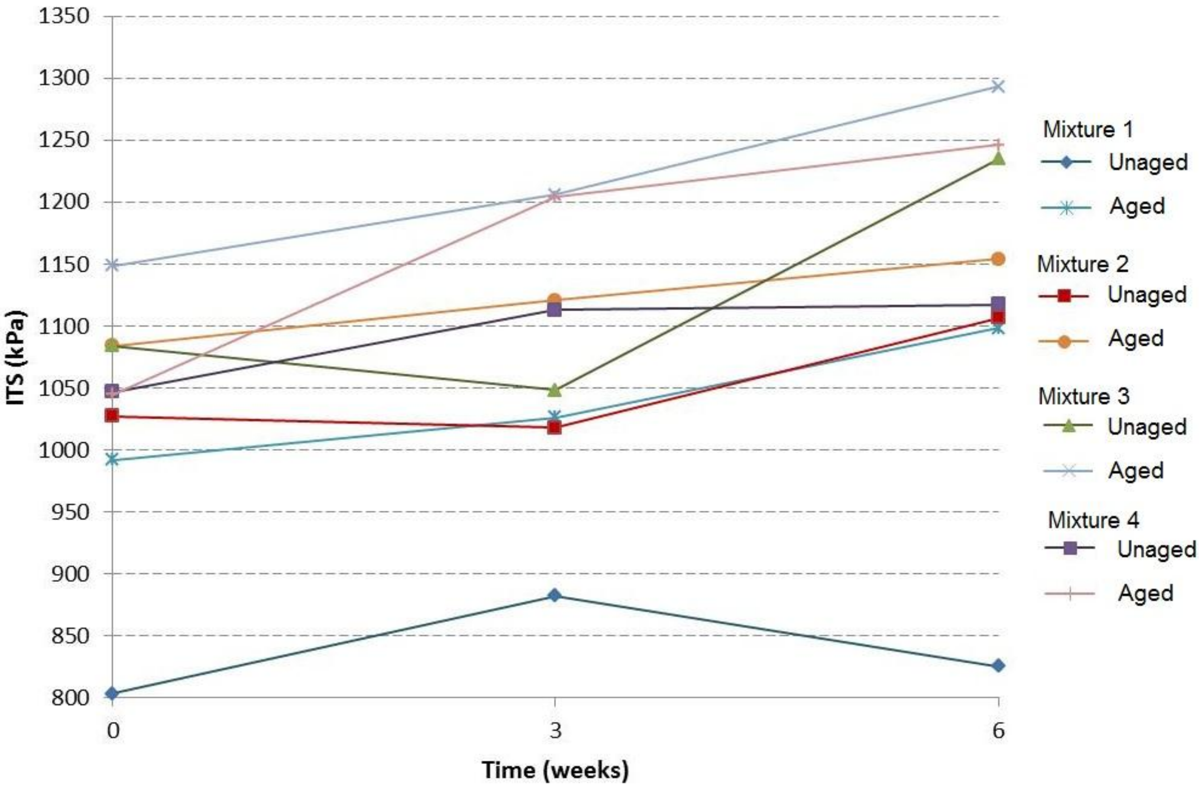

Figure 7. Effect of isothermal storage on tensile strength

The tensile strength of the mixtures was found to increase with time, due to physical hardening of the asphalt binder, for the samples that were kept in storage. As shown in Figure 7, hardening rates vary for the different mixtures. Physical hardening appears to influence more the mixtures with higher RA content. However, in general, smaller differences in the ITS values are expected for RA mixtures, due to the fact that asphalt binders in RA mixtures have already undergone oxidation, so the hardening rate of the RA mixture is anticipated to be slower.

The mean ITSR values (from 3 replicas) for the fresh (unaged) and field aged samples are shown in Figures 8 and 9, respectively. The results are presented for both bath and bath-MIST conditioned samples at the each time interval. Also, the coefficient of variation for each mixture was calculated and presented on the top of the bars. The solid red line represents the threshold value below which an asphalt mixture is considered to be more susceptible to moisture damage, according to Dutch (CROW, 2010) and Irish standards. The tensile strength ratios of the RA mixtures, in which a WMA additive is added or not, were lower than the conventional hot mix asphalt for the unaged mixtures. Nevertheless, the ITSR values of the RA mixtures, after field ageing, were found to be higher than the control mixture. The results showed that Mixture 4, which had the higher RA content and a WMA additive, performed better against moisture damage compared to other variants.

Overall, the results indicate that the RA mixtures (with and without WMA additives) underwent a curing process that leads to an increase in strength with time. Specifically, the mechanical performance of Mixture 1 (0 % RA) is significantly deteriorated after one year of field ageing, thus suggesting Mixture 1 is more prone to moisture damage. On the other hand, all RA mixtures showed the opposite trend. Mixture 2 (30 % RA; no WMA additive) was found to be susceptible to moisture damage both before and after field ageing; nevertheless, its performance was slightly improved after ageing. In the same way, Mixtures 3 (30 % RA plus WMA additive) and 4 (30 % RA plus WMA additive) had high tensile strength ratios before ageing, which were further improved after field ageing.

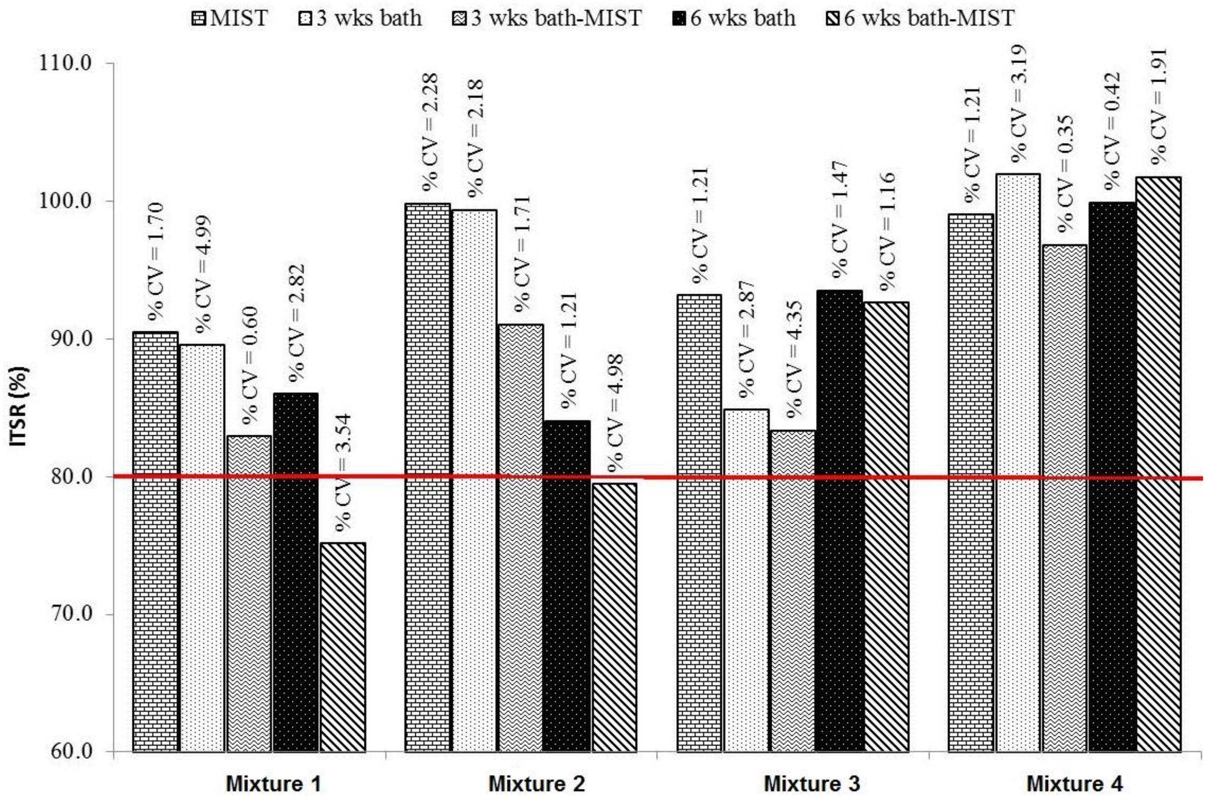

Figure 8. Mean ITSR values for fresh (unaged) samples

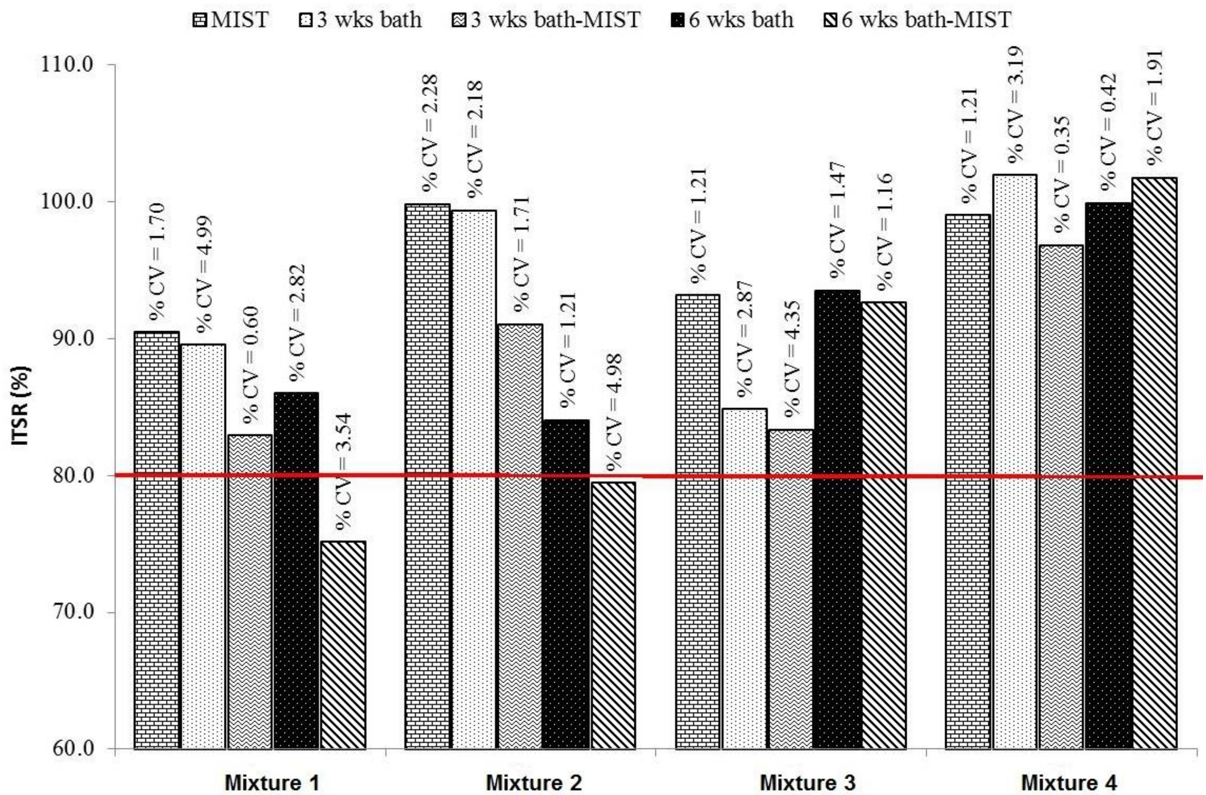

Figure 9. Mean ITSR values for aged samples

Overall, the mixtures containing RA had a lower reduction in strength, before and after ageing, compared to the control mixture after the application of the different moisture conditioning protocols, as shown in Table 3. From the results, the contributions of the short- and long-term moisture damage on the strength of the samples were quantified. Specifically, Mixture 1 (0 % RA) had the highest reduction in strength for all conditioning protocols. Mixture 2 (30 % RA; no WMA additive) was found to perform better against moisture damage after only bath conditioning; especially after it underwent ageing in the field. However, after the application of the combined protocol the reduction in strength was significantly higher. The results showed that, for Mixture 2, the weakening effect of moisture diffusion (through bath conditioning) was more apparent after the first 3 weeks and resulted to high levels of damage when cyclic pore pressures are applied.

Table 3. Average reduction in strength

<table>
<tr><th rowspan="4">Conditioning method</th><th rowspan="4">Time (weeks)</th><th colspan="8">Mixture</th></tr>
<tr><th colspan="2">1</th><th colspan="2">2</th><th colspan="2">3</th><th colspan="2">4</th></tr>
<tr><th>Fresh (unaged)</th><th>Aged</th><th>Fresh (unaged)</th><th>Aged</th><th>Fresh (unaged)</th><th>Aged</th><th>Fresh (unaged)</th><th>Aged</th></tr>
<tr><th colspan="8">Strength reduction (%)</th></tr>
<tr><td rowspan="3">Bath</td><td>0</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>3</td><td>+1.01</td><td>-10.5</td><td>-15.75</td><td>-0.7</td><td>-4.05</td><td>-15.2</td><td>-7.12</td><td>+1.9</td></tr>
<tr><td>6</td><td>-6.08</td><td>-14.0</td><td>-14.00</td><td>-16.0</td><td>-13.51</td><td>-6.5</td><td>-9.01</td><td>-0.1</td></tr>
<tr><td rowspan="3">Bath & MIST</td><td>0</td><td>-4.17</td><td>-9.6</td><td>+0.21</td><td>-0.2</td><td>+0.58</td><td>-6.8</td><td>-1.32</td><td>-1.0</td></tr>
<tr><td>3</td><td>-3.92</td><td>-17.1</td><td>-14.03</td><td>-9.0</td><td>-3.31</td><td>-16.7</td><td>-9.68</td><td>-3.2</td></tr>
<tr><td>6</td><td>-10.54</td><td>-24.9</td><td>-27.29</td><td>-20.6</td><td>-19.32</td><td>-7.4</td><td>-18.58</td><td>+1.7</td></tr>
</table>

Furthermore, the results demonstrate that the use of WMA additives improved the moisture susceptibility of unaged and field aged mixtures. Mixture 3 (30 % RA plus WMA additive) showed a decreasing strength with increasing bath conditioning time; however it appeared to be insensitive to the application of cyclic pressure, indicating that Mixture 3 is more probable to fail cohesively, due to the weakening of the binder, rather than adhesively. This can be attributed to the antistripping effect of the Cecabase RT 945 WMA additive, which seems to improve the adhesion properties of the aggregate-binder systems. Mixture 4 (30 % RA plus WMA additive), exhibited the best performance against moisture damage. The rate of strength degradation was extremely low, particularly after field ageing; comparable strength levels were measured after the various conditioning scenarios.

The aforementioned observations are depicted in Figures 10 to 13. The red curve demonstrates the effect of moisture diffusion on tensile strength due to bath conditioning alone, while the green curve shows the influence of the combined conditioning protocol (bath and MIST) on strength. The difference between the red and the green curve corresponds to the contribution of the cyclic pore pressures to the total strength degradation of the samples.

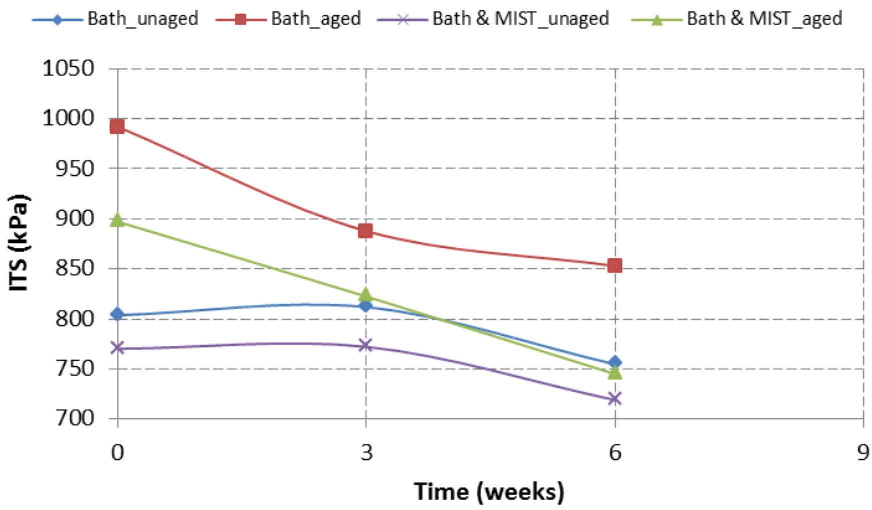

Figure 10. Tensile strength of Mixture 1 (Control; 0 % RA)

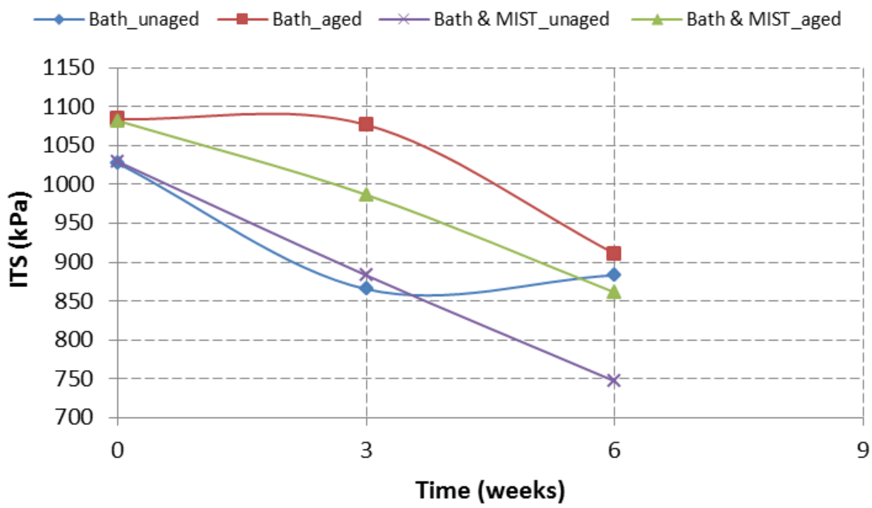

Figure 11. Tensile strength of Mixture 2 (30 % RA; no WMA additive)

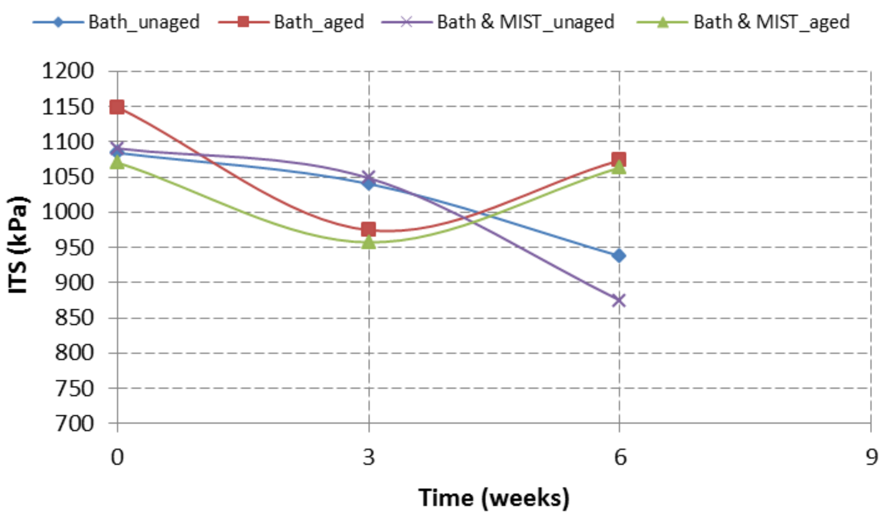

Figure 12. Tensile strength of Mixture 3 (40 % RA; WMA additive)

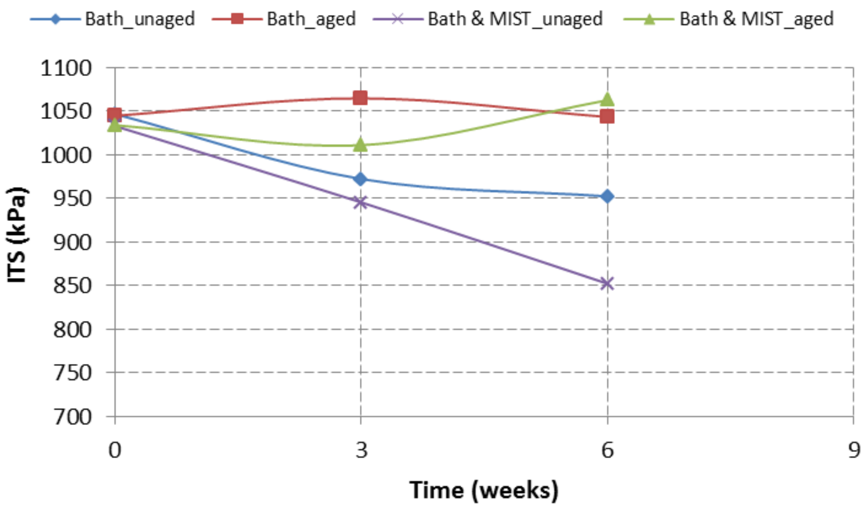

Figure 13. Tensile strength of Mixture 4 (30 % RA; WMA additive)

The contribution of the cyclic pore pressures to the total damage of the samples is given as the gap between the two curves corresponding to the different conditioning protocols. Two different damage mechanisms (i.e. moisture diffusion and high pore pressure development) are present in the combined protocol. The results show that pore pressure development does not seem to have a significant effect on the tensile strength of the mixtures containing reclaimed asphalt and WMA additive.

On the other hand, for the control mixture and the mixture without WMA additive, it can be observed that the gap, and therefore the influence of pore pressure, increases with bath conditioning time. This change can be explained by the fact that long moisture diffusion conditioning, degrade further the properties of the mixtures, resulting in a greater reduction in strength for the same amount of MIST conditioning.

The results indicate that the performance of the mixtures against moisture damage is improved by the use of warm mix additives. In general, both Mixtures 3 and 4, which contain an additive, show a better behaviour compared to Mixture 2. In particular, because the only variance between Mixtures 2 and 4 is the use of the additive, it is clear that the positive effect additives can have on the ITS. Furthermore, it can be observed that a change in the amount of RA content, from 30 % to 40 %, does not result in major differences in the ITS and ITSR values, mainly for the aged samples.

4 Conclusions

In this study, an experimental programme was undertaken in order to investigate the effect of RA on the moisture damage and ageing susceptibility of asphalt mixtures. This report summarises the findings of tests performed on cylindrical samples, which were collected from the field 24 h and one year after laying the site trials. Four variants of a typical SMA 10 mixture were prepared. The variations were 0 % RA as control; 30 % RA and no additive; 40 % RA and warm mix additive; and 30% RA and warm mix additive.

For the characterisation of the moisture susceptibility characteristics, a new moisture conditioning protocol was utilised, which can quantify the effects of short- and long-term moisture damage to mixture degradation. The Indirect Tensile Strength (ITS) and the Indirect Tensile Strength Ratio (ITSR) were used for the evaluation of moisture damage resistance of the mixtures. The main conclusions of this study are the following:

- The inclusion of RA has an effect on mixture tensile strength. The ITS values were found to increase with increasing RA content.
- A change in the amount of RA content, from 30 % to 40 %, was not found to create major differences in the dry and wet ITS and ITSR values.
- The rate of strength degradation due to moisture damage was found to be lower for the mixtures containing RA compared to control mixture. The RA mixtures had a lower reduction in strength, before and after ageing, after the application of the various moisture conditioning protocols.
- The TSR values of the RA mixtures, with and without WMA additive, were found to improve for the field aged mixtures. The results indicate that the asphalt mixtures underwent a curing process that lead to an increase in strength with time and enhanced their response to moisture damage. Therefore, it is recommended that ageing considerations are made when performance testing is necessary to validate the mix design with respect to moisture damage susceptibility.
- The use of warm mix additive was found to increase the resistance to moisture damage induced both by bath and bath-MIST conditioning. A comparison between Mixtures 2 and 3, which had the same amount of RA and only differed with respect to the addition of WMA additive, clearly demonstrates the positive effect the WMA additive has on the moisture damage susceptibility characteristics of the mixtures.

5 Acknowledgement

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