

## Effects of Combined Environmental Factors on Stiffness and Rutting Properties of Warm Mix Asphalt

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### Abstract

Warm mix asphalt (WMA) is a sustainable clean product that can be fabricated at lower temperatures. This is an environmentally friendly mixture due to its lower emission and energy consumption in asphalt production plants. Moisture conditioning and aging process are two environmental factors that can adversely affect the stiffness properties of this product. In the field, WMAs are subjected to both moisture damage and aging. In this paper, a new laboratory method was used for evaluating the combined effects of aging and moisture conditioning of WMA samples. WMA specimens were fabricated at various compaction temperatures with different amounts of a surfactant-wax warm additive. Stiffness properties of asphalt mixtures were quantified from the resilient modulus and dynamic creep test. The results showed that moisture conditioning and aging are competing to affect the stiffness properties of mixtures. Polymer modified asphalt mixtures were found to be less susceptible to moisture damage when compared to mixtures fabricated with unmodified binder. Compaction temperature was the most significant factor that affected the resilient modulus of WMA. In the dynamic creep test, the combined effects of aging and moisture conditioning reduced the cumulative micro strain of samples regardless of binder type, additive content and compaction temperature.

**Keywords:** Warm mix asphalt; Aging; creep; Moisture damage; Resilient modulus.

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## 1. Introduction

There is a claim that aging increases the stiffness properties of asphalt mixtures, while moisture damage decreases its stiffness. Field evaluation of moisture damage of asphalt mixtures shows that pavement usually gains strength for a short time due to aging and then begins to weaken due to moisture damage [Kim, 2009]. In reality, asphalt mixtures are simultaneously subjected to both aging and moisture damage.

In the past, some limited studies were carried out for investigating the combined influence of aging and moisture conditioning on the technical properties of asphalt materials. Copeland, Youtcheff and Shenoy used modified pull-off test to evaluate the influence of moisture conditioning and long-term aging on the bond strength of different polymer modified asphalt binders [Copeland, Youtcheff and Shenoy, 2007]. It was found that the adhesive strength of binders reduces when aging process is combined with moisture conditioning. Thomas used water in the form of vapour while conducting the PAV-aging test to determine its impact on the chemical and rheological properties of the aged asphalt binders [Thomas, 2002]. This idea was derived based on the assumption that water is present during the aging of asphalt pavements in the field. The results showed that asphalt binder source played an important role on the oxidation aging.

Lu and Harvey evaluated the effects of hydrated lime and liquid anti-stripping agents on the properties of asphalt mixtures subjected to vacuum saturation and conditioned in a humid environment [Lu and Harvey, 2006]. Analysis of the results after every four months showed that most of the detrimental effects of moisture occurred during the first 4 months and the subsequent reduction of strength or stiffness in

the later stages became small. In other study, Khan et al. used saturation aging tensile stiffness (SATS) test to combine these two phenomena using high pressure and elevated temperature [Khan et al., 2013]. It was found that the stiffness of specimens fabricated from basic aggregate is higher than those fabricated from acidic aggregate. Fan et al. evaluated the effects of cement-mineral filler on the water damage of asphalt mixture under different aging procedures [Fan et al., 2019]. The results showed that the mass ratio of cement to mineral filler must not exceed 1.

In the field, asphalt materials are simultaneously subjected to both aging and moisture damage, but these two processes are typically studied separately in the laboratory. According to Kim et al. aging and moisture cause weakening the pavement structures and inducing the formation of potholes [Kim et al., 2019]. Since, WMA is a relatively new technology, it is necessary to apply these conditioning processes on WMA to predict its performance in semi-real condition. Therefore, this paper demonstrates a new laboratory experimental approach for evaluating the combined and opposing influences of aging and moisture conditioning for WMA containing a surfactant-wax type additive as well as hot mix asphalt (HMA). Other variables affecting resilient modulus and creep properties of both WMA and HMA samples include compaction temperature, additive content and test temperature. In addition, continuous effects of these two phenomena on the stiffness properties of WMA and HMA samples were tested and quantified.

## 2. Materials and Methods

### 2.1 Materials

In this study, two asphalt binders were selected. Asphalt binder A was an unmodified 80/100 penetration grade binder, while asphalt binder B was a refinery product modified binder using butadiene styrene butadiene (SBS). Table 1 shows technical properties of the binders. Crushed granite aggregate with Los Angeles abrasion and aggregate crushing values, 23.86% and 19.25%, respectively, were used for fabrication of the samples. Malaysian Public Works Department gradation for mixture type AC14 [PWD, 2008] was used for fabrication of samples. Figure 1 shows the upper and lower limits of aggregate gradation. WMA was prepared using a warm additive, named Rediset with application rate of 1%, 2% and 3% by mass of binder. Rediset was blended into the binders using a high-shear stirrer for 30 minutes. It is a surfactant-wax based chemical warm additive that reduces the viscosity of asphalt binders at very high temperatures and improves the Superpave fatigue factor ( $G^* \sin \delta$ ) of asphalt binders at intermediate temperatures. The surfactant part of this product reduces the surface tension of asphalt binders, while its organic part (wax) reduces the viscosity of asphalt binders

[Hamzah et al., 2014]. Hence, the wettability of aggregate by the binder can be improved.

## 2.2 Test Plan

At first step of the test plan, the resilient modulus of the following asphalt mixtures fabricated using binder A and B were determined:

- Samples after compaction without being subjected to any aging and moisture conditioning (samples in conditioning cycle 0).
- Samples subjected to long-term oven aging based on the AASHTO R-30 [AASHTO, 2002] (samples in conditioning cycle 1).

- Samples from cycle 1 that were moisture conditioned and then subjected to long term oven aging (samples in conditioning cycle 2).

Long-term aging was conducted in an oven at 85°C for 3 days as shown in Figure 2. Seven types of moisture conditioning were applied on the samples as follows (See Figure 3):

- Vacuum saturation in distilled water for 30 minutes at room temperature (VSDW) as shown in Figure 3a.
- Vacuum saturation in distilled water for 30 minutes at 60°C and holding in this condition

**Table 1. Properties of asphalt binders**

Aging Condition	Properties	Asphalt Binder	
		A	B
Virgin Binder	Viscosity at 135°C (Pa.s)	0.38	1.66
	Softening Point (°C)	45	69
	Penetration (0.1 mm)	80	50
	Ductility (cm)	>100	90
	Flash Point (°C)	331	344
	$G^*/\sin \delta$ at 64°C (Pa)	1653	-
	$G^*/\sin \delta$ at 76°C (Pa)	-	2374
Short-term Aged Binder (RTFO)	$G^*/\sin \delta$ at 64°C (Pa)	2442	-
	$G^*/\sin \delta$ at 76°C (Pa)	-	3968
Long-term Aged Binder (RTFO+PAV)	$G^* \sin \delta$ at 25°C (MPa)	2.58	5.41

for an extra 30 minutes to release the vacuum as shown in Figure 3b.

- VSDW and then submerging in distilled water for 24 hours at 60°C as shown in Figure 3a and 3c.

- VSDW, freezing the samples in a freezer for 15 hours, and then submerging in distilled water for 24 hours at 60°C.
- VSDW followed by two freezing and thawing cycles.
- Vacuum, freeze and thaw with water containing sodium carbonate ( $\text{Na}_2\text{CO}_3$ ).

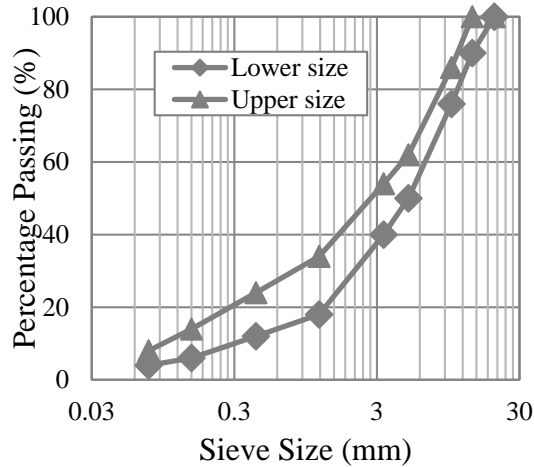


Figure 1. Upper and lower limit of aggregate gradation (PWD, 2008)



Figure 2. Long-term oven aging



a) Vacuum saturation at room temperature



b) Vacuum saturation at 60°C



c) Submerging samples in water  
Figure 3. Moisture conditioning of the samples

- Vacuum saturation in water mixed with sodium carbonate for 30 minutes at room temperature and then submerging in the water mixed with sodium carbonate for 24 hours at 60°C.

The presence of sodium carbonate increases the pH of water and enhances the stripping rate of asphalt specimens [Hicks, Santucci, and Aschenbrener, 2003]. According to Aman, the stripping process of porous asphalt was enhanced using sodium carbonate [Aman, 2013]. Soleimanian et al. reported that sodium carbonate can be used in chemical immersion test to determine the adhesion of binders to aggregate by means of boiling asphalt-coated aggregate in distilled water plus sodium carbonate [Soleimanian et al., 2003].

In the last conditioning method, 6.62 gm of Na<sub>2</sub>CO<sub>3</sub> was added into 1 liter water to moisture

condition the asphalt samples. This concentration level was effectively used for moisture conditioning of WMA [Hamzah et al, 2014].

The experiment design of second step is shown in Figure 4. In this step, the influences of compaction temperature, additive content and test temperature on the resilient modulus and creep properties of WMA and HMA specimens were evaluated.

In the third step of test plan, one of the moisture induced damage from the first study phase was selected for conditioning the specimens incorporating different additive contents and compacted at various temperatures. This conditioning method

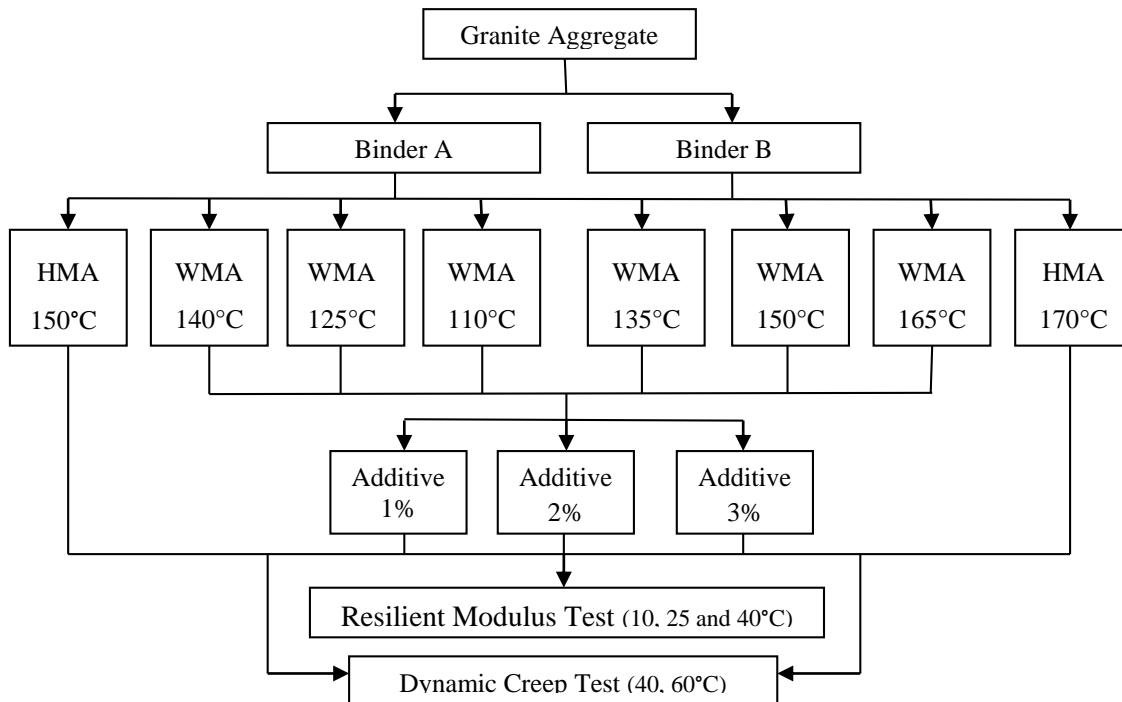


Figure 4. Second phase of experiment design

includes a series of vacuum, freeze and thaw on mixtures submerged in water with the addition of sodium carbonate. In this step, the effects of

continuous cycles of aging and moisture conditioning on the stiffness properties of WMA were investigated (See Table 2). The test

parameters and outputs for this step are presented in Table 3.

A gyratory compactor was used for compaction of all samples at  $7 \pm 0.5$  % air voids. Samples are designated according to X-WMA(Y) and X-HMA(Y) which refer to WMA and HMA mixtures fabricated using X binder type and compacted at Y temperature, respectively. Also, mixtures A and B refer to asphalt mixtures fabricated using binders A and B, respectively.

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**2.3 Asphalt Mixture Performance Test**

The resilient modulus and dynamic creep tests were selected to evaluate the stiffness properties of the samples. The resilient modulus is an important parameter in the mechanistic-empirical design of pavement layers. This test was performed on the conditioned and unconditioned specimens at 25°C using a Universal Asphalt Testing Machine in accordance with ASTM D4123 [ASTM D4123, 1995] procedures. Prior to the test, asphalt specimens were conditioned for 4 hours in an environmental chamber at the selected test temperature. For further investigation, unconditioned samples were tested at 10°C, 25°C, and 40°C to evaluate the interaction effects of test temperature with additive content and compaction temperature on the resilient modulus. The dynamic creep test was conducted on the conditioned and unconditioned samples at 40°C using the Universal Asphalt Testing Machine. The specimens were pre

**Table 2. Cycle of aging and moisture conditioning**

Cycle	Aging and Moisture Conditioning Process	Tests
0	Without any aging and moisture conditioning	Mr <sub>0</sub> and dynamic creep test
1	Aging of samples cycle 0 at 85°C for 3 days	Mr <sub>1</sub>
2	Moisture conditioning of samples cycle 1 and then aging at 85°C for 3 days	Mr <sub>2</sub>
3	Moisture conditioning of samples cycle 2 and then aging at 85°C for 3 days	Mr <sub>3</sub> and dynamic creep test

**Table 3. Test parameters and test outputs for multiple aging and moisture conditioning**

Test Parameters	Outputs
Rediset content	Mr <sub>0</sub> , Mr <sub>1</sub> , Mr <sub>2</sub> , Mr <sub>3</sub>
Compaction temperature	Cumulative micro strain
Binder type	Slope of strain
Conditioning cycle	Stiffness ratio

conditioned for a minimum of 4 hours in an environmental chamber. The resistance of the asphaltic mixtures to plastic deformation was determined from the repeated creep test. The

unconditioned samples were also tested at 40°C and 60°C.

**3. Results and Discussions**

### 3.1 Combined Effects of Moisture Conditioning Methods and Aging

Figures 5 and 6 present the effects of aging and moisture conditioning methods on the resilient modulus of asphalt mixtures A and B. Moisture conditioning reduces the stiffness of the mixtures. The effects of various moisture conditioning methods are shown in these figures. For instance, the effects of moisture conditioning using two time vacuum saturation and freeze-thaw are greater than the effects of other conditioning

methods. Also, conditioning in the chemical environments exhibits adverse effects on the resilient modulus of the samples. Comparison between Figures 5 and 6 shows obvious reductions in the resilient modulus of mixture A as compared to mixture B. This implies that the moisture susceptibility of mixture B is lower than mixture A. This may be due to the positive effects of blended SBS binder B that lead to improved adhesion, hence improves moisture susceptibility of the mixtures.

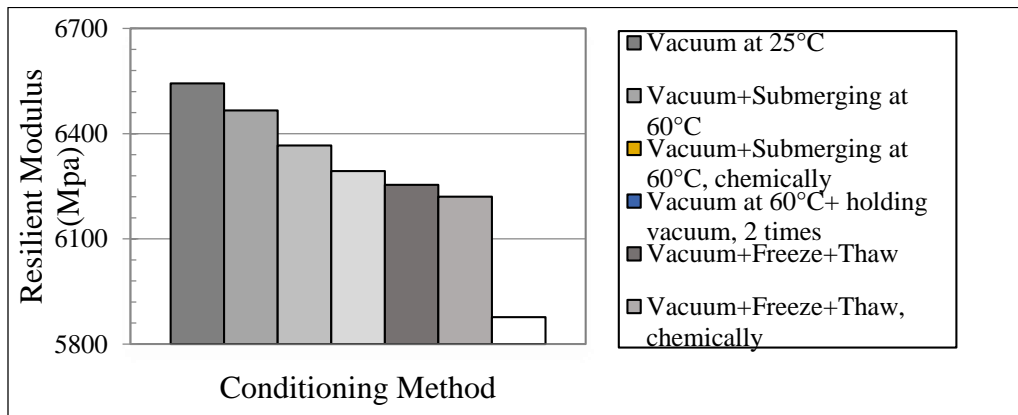


Figure 5. Effects of conditioning method on the resilient modulus of mixture A

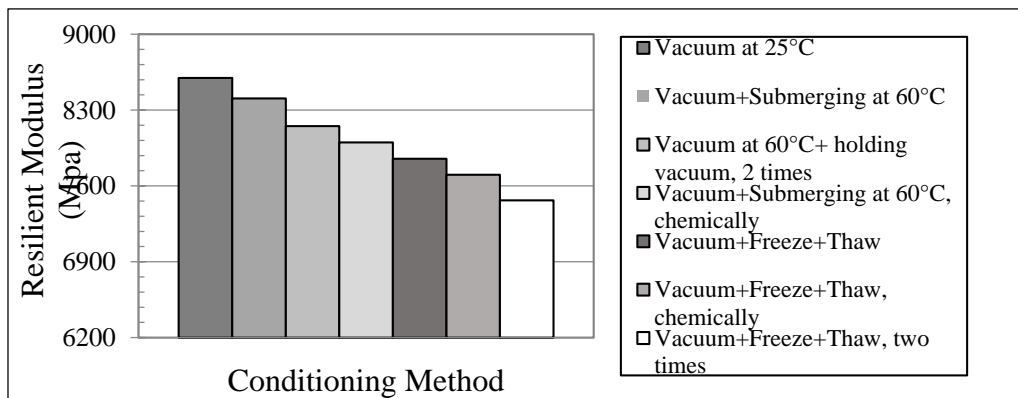


Figure 6. Effects of conditioning method on the resilient modulus of mixture B

### 3.2 Effects of Additive Content and Compaction Temperature

The relationship between resilient modulus and additive content for unaged mixtures A and B subjected to various compaction and test

temperatures are shown in Figures 7 and 8. The results show that compaction temperature, additive content and test temperature exhibit significant effects on the resilient modulus. Since higher compaction temperatures have stiffening effects on the binder rheology, the resilient modulus of samples fabricated at higher compaction temperatures is greater than those fabricated at lower compaction temperatures. Also, the resilient modulus of samples reduces when test temperature increases. Generally, the resilient modulus of WMA is lower than the corresponding values of HMA except for B-WMA165. This warm modified mixtures exhibits higher resilient modulus than HMA. It might be due to the wettability effects of this warm additive on the surface of aggregate at higher compaction temperature (165°C) when compared to the compaction temperature of B-HMA170.

From Figures 7 and 8 at 10°C test temperature, lower resilient modulus is generally related to higher additive content. However, when tested at 40°, lower resilient modulus is generally related to lower additive content (except for B-WMA165). Since higher stiffness at higher test temperature and lower stiffness at lower test temperature are desirable for asphalt mixtures, it can be concluded that the use of higher Rediset content can be more beneficial in terms of resilient modulus. Test results at 40°C show that the resilient modulus of mixtures B is higher than the corresponding values for mixtures A regardless of compaction temperature and additive content. In contrast, the resilient modulus of B-WMA135 and B-WMA150 are lower than that of mixture A-WMA110 and A-

WMA125. This fact might be due to the blending effects of polymerized material into binder B. As a result, the use of binder B generally improves the performance of warm modified mixtures.

The effects of additive content, compaction temperature, and test temperature on the cumulative micro strain using dynamic creep test are shown in Figures 9 and 10 for mixture A. The results show that all test parameters including additive content, compaction temperature, and test temperature have significant effects on the cumulative micro strain of WMA. The cumulative micro strain extracted from dynamic creep test can be used as criteria for evaluating the permanent deformation properties of asphalt mixtures. The cumulative micro strain of samples decreases when compaction temperature increases. It implies that WMA incorporating Rediset at lower compaction temperatures can be prone to rutting. As expected, the cumulative strain of WMA samples tested at lower temperatures (40°C) are low when compared to the corresponding samples tested at higher temperatures (60°C). All WMA samples tested at 40°C remained in the secondary zone of creep test, while mixture A-WMA containing 1%, 2%, and 3% additive compacted at 110°C and 125°C passes the secondary zone (at 40°C). The strain response of creep test can be divided into three zones [Daniel and Lachance, 2005]. In primary zone, strain rate decreases with loading time, while in secondary zone strain rate remains constant with loading time. In the tertiary zone, strain rate increases with loading time. Sample failure occurs at tertiary zone. Figure 11 shows a schematic form of the creep performance.



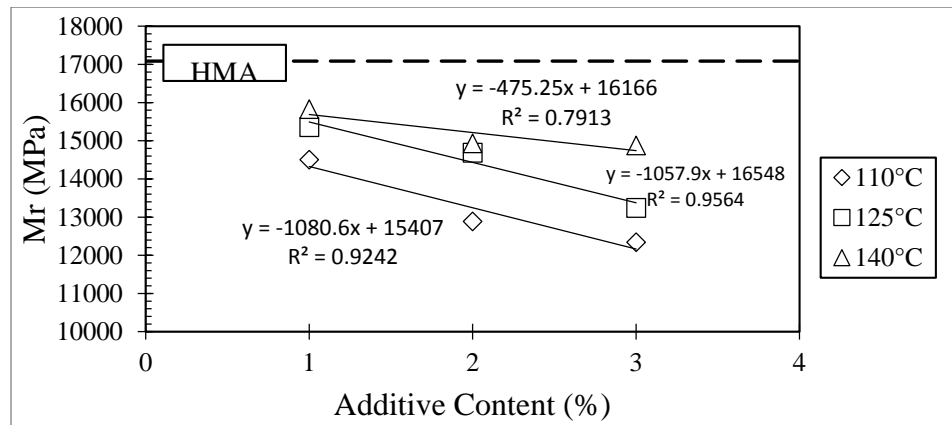
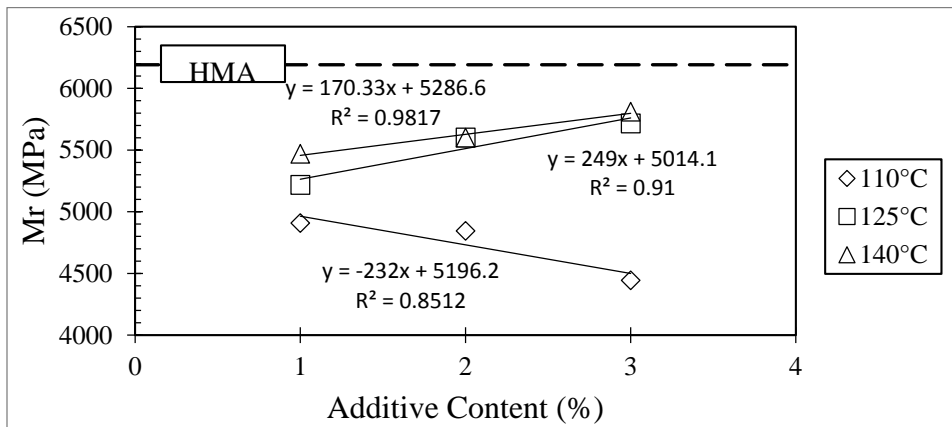
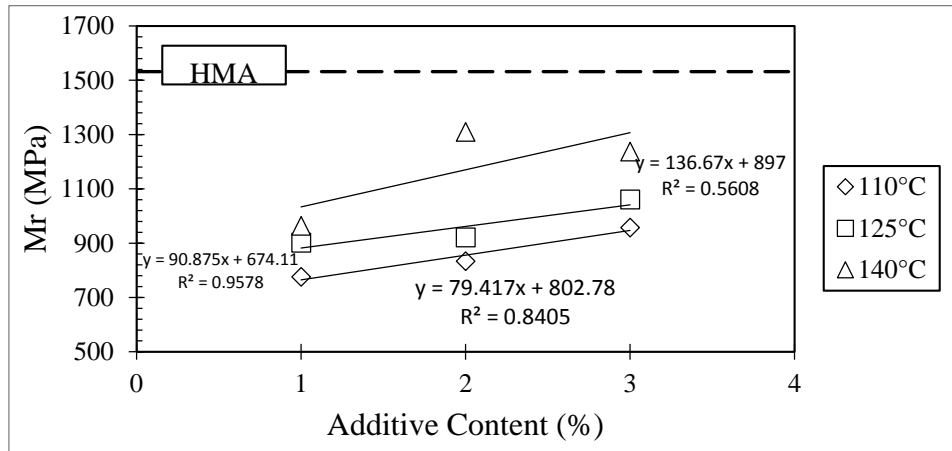


Figure 7. Relationship between resilient modulus and additive content for mixture A

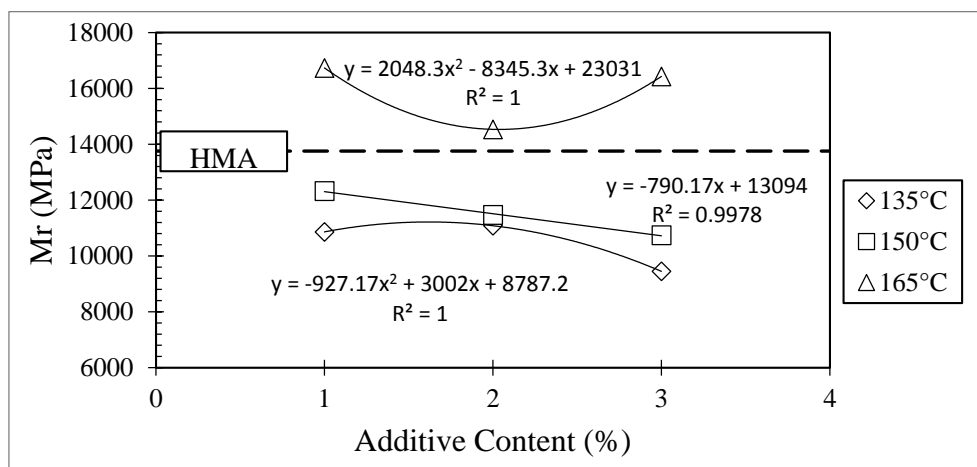
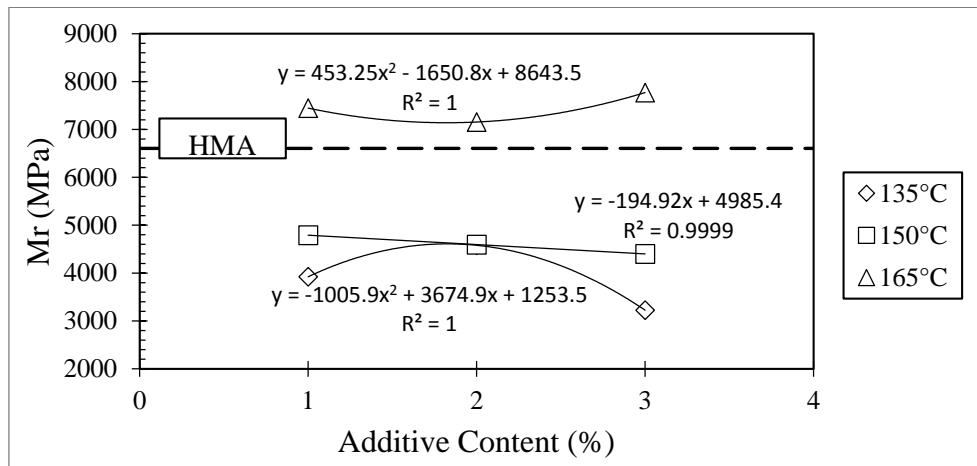
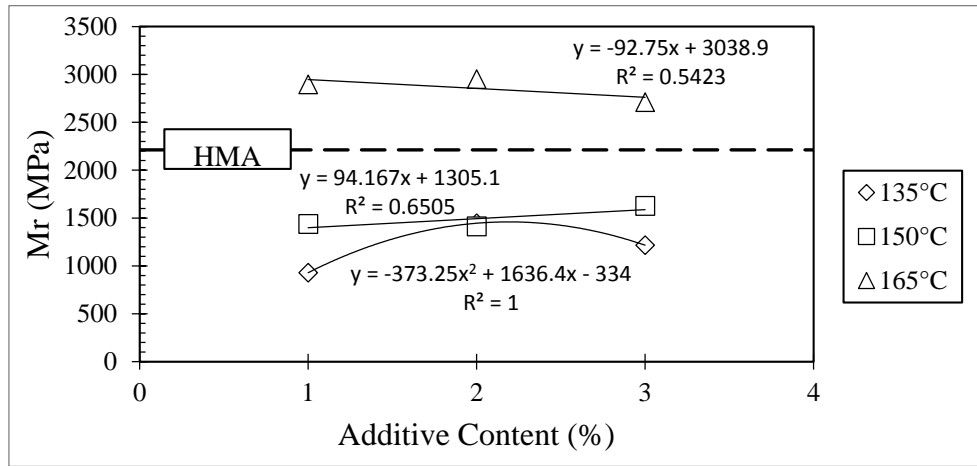
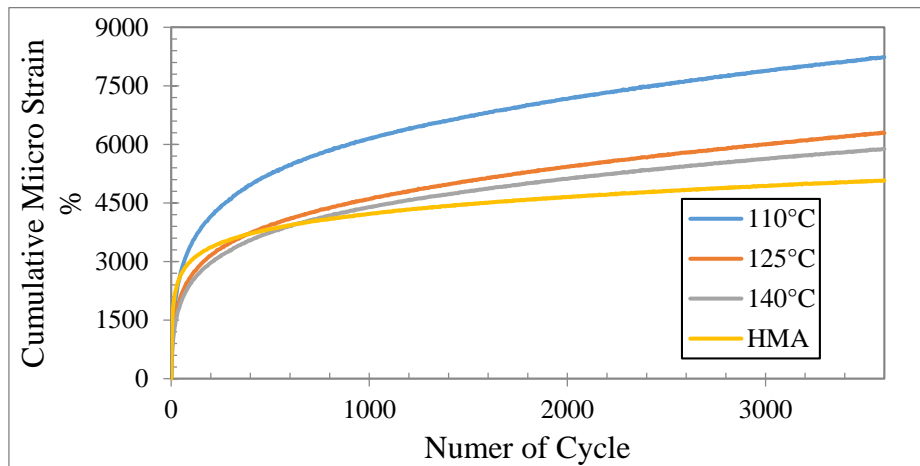
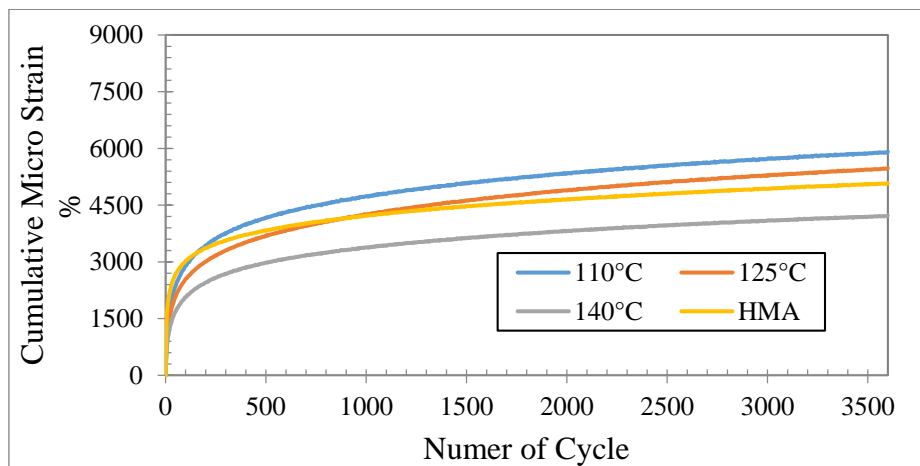


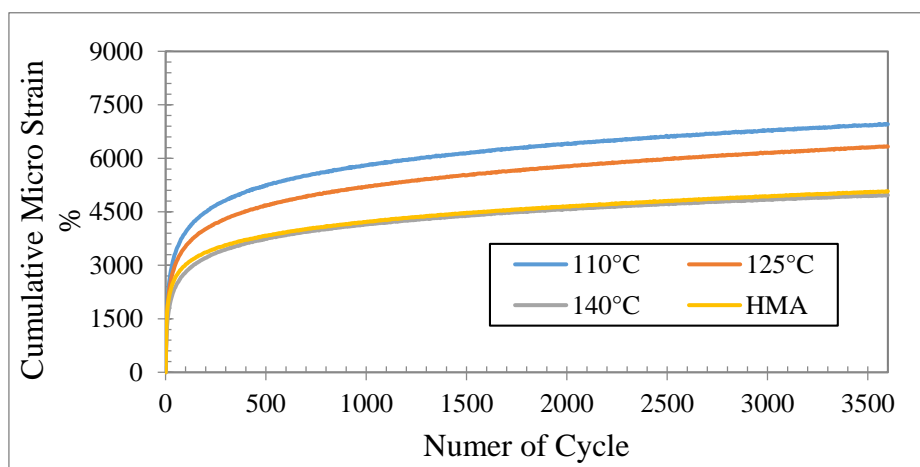
Figure 8. Relationship between resilient modulus and additive content for mixture B



a) 1% additive at 40°C

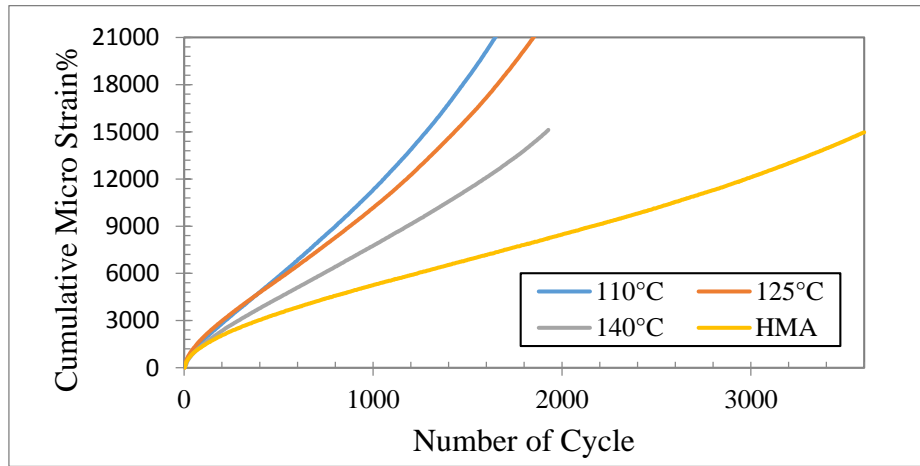


b) 2% additive at 40°C

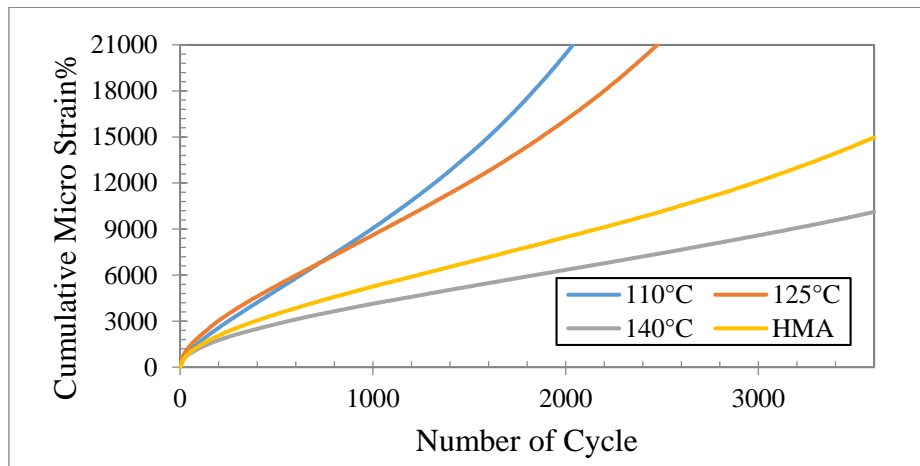


c) 3% additive at 40°C

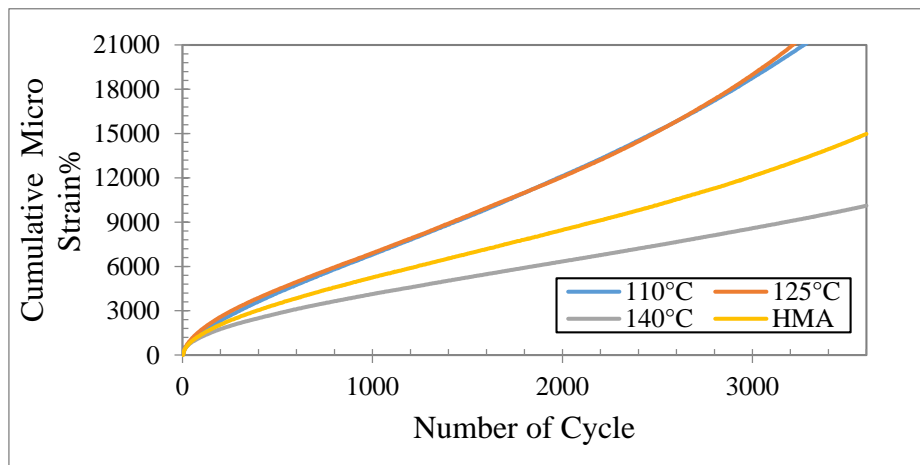
Figure 9. Cumulative micro strain versus dynamic creep cycles at 40°C



a) 1% additive at 60°C

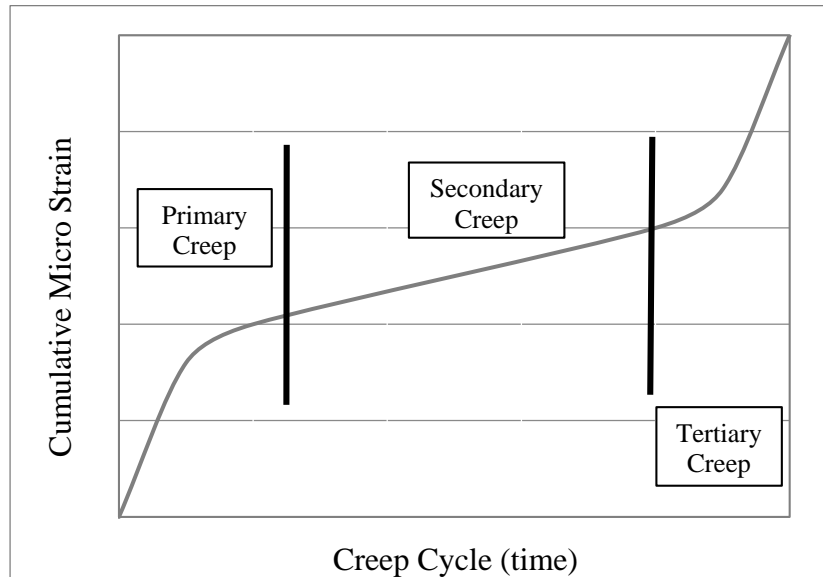


b) 2% additive at 60°C



c) 3% additive at 60°C

Figure 10. Cumulative micro strain versus dynamic creep cycles at 60°C



**Figure 11. Schematic form of the creep performance**

Evaluation of the effects of Rediset content on the creep performance of WMA shows that the use of 1% of this additive does not improve the creep performance of WMA at two test temperatures (40°C and 60°C) and all compaction temperatures (110°C, 125°C, and 140°C) as compared to HMA. When compacted at 140°C, the use of 2% additive at 40°C and also the use of 2% and 3% additive at 60°C exhibit lower cumulative micro strain when compared to the corresponding value of HMA. This might be due to the effects of the wax part of Rediset that crystallises in the binders at the high service temperatures or higher wettability effects of Rediset on the aggregate surface at elevated compaction temperatures.

### **3.3 Combined Effects of Aging and Moisture Conditioning for WMA Samples**

The effects of multiple aging and moisture conditioning on the resilient modulus of WMA and HMA at various cycles of conditioning are illustrated in Figures 12 and 13. Cycles 0, 1, 2, and 3 are also described in Table 4. As can be seen from Figures 12 and 13, in cycle 1 (long-

term aging), the resilient modulus of some mixtures increases, while in cycle 2, the resilient modulus of some mixtures reduces. It indicates that aging increases the resilient modulus of samples, while the moisture conditioning tends to decrease the resilient modulus. In the third cycle, the combined effects of aging and moisture conditioning do not significantly affect the resilient modulus of mixtures, especially for mixtures fabricated with binder A. It implies that in this stage, the effects of aging and moisture damage appear to balance each other. The evaluation of the effects of compaction temperature and additive content on the resilient modulus of WMA indicates that higher compaction temperatures increase the resilient modulus of WMA. The resilient modulus of A-WMA165 is greater than the corresponding value for HMA. In addition, higher additive content exhibits lesser effects on the resilient modulus.

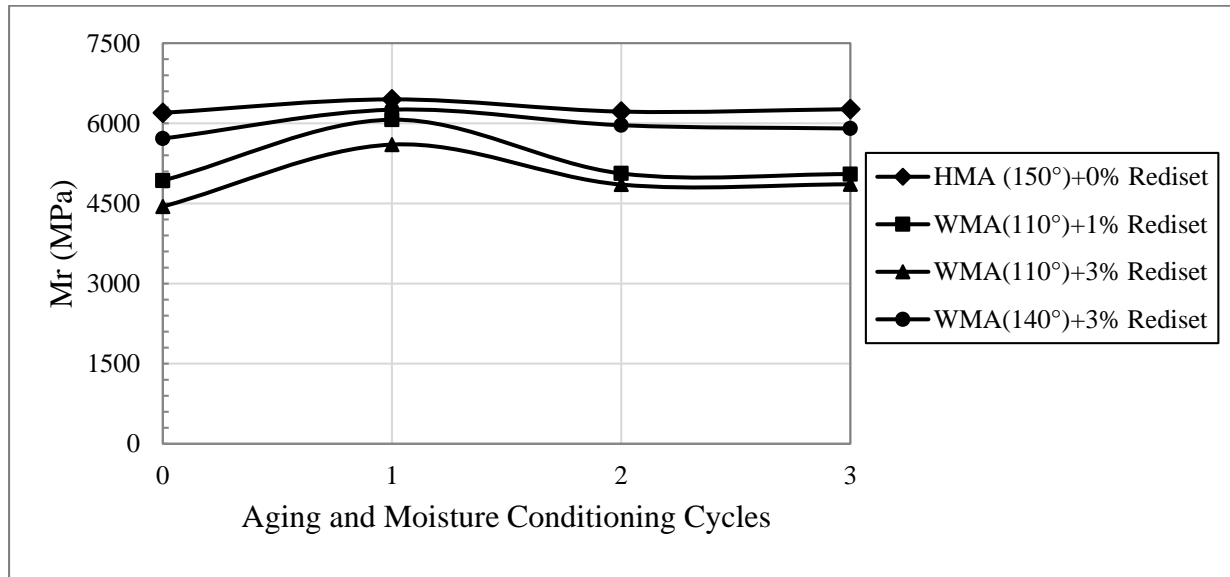


Figure 12. Combined effects of aging and moisture conditioning on the resilient modulus of mixture A

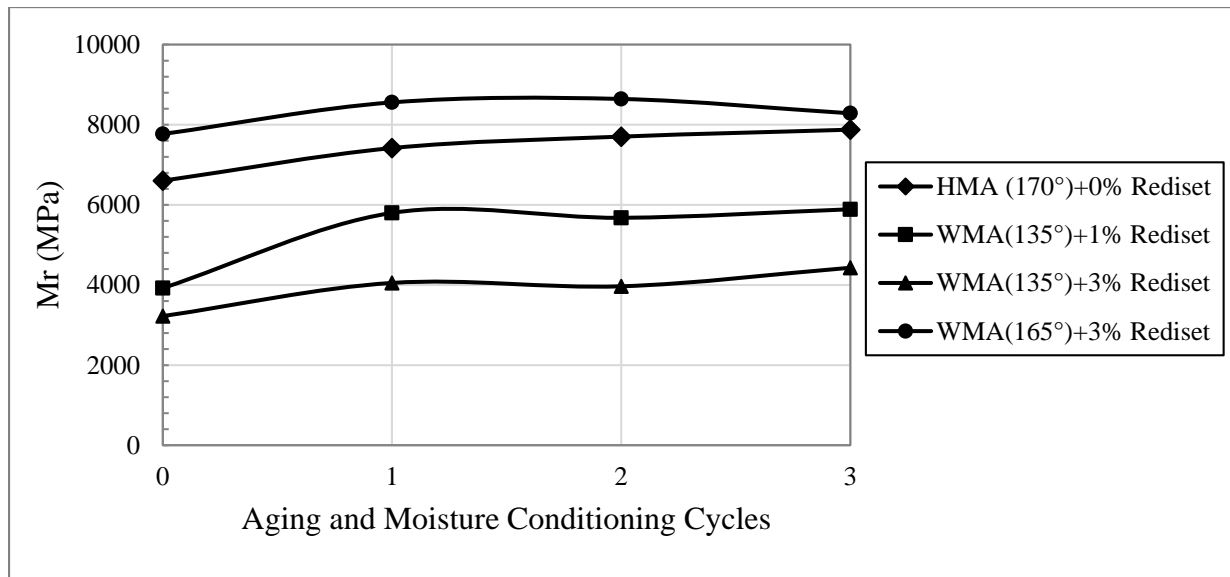


Figure 13. Combined effects of aging and moisture conditioning on the resilient modulus of mixture B

Table 4. Description of cycles 0, 1, 2, and 3 in multiple aging and moisture conditioning

Cycle	Description for Conditioning
0	Unaged and unconditioned sample
1	Long-term aging of unaged samples
2	Moisture conditioning + long-term aging of samples after cycle 1
3	Moisture conditioning + long-term aging of samples after cycle 2

The average resilient modulus of HMA and WMA incorporating different additive contents and compacted at different temperatures for each cycle of conditioning were calculated and shown in Figure 14. From Figure 14, the resilient modulus of mixture B is higher than that of mixture A. The resilient modulus of mixture A reduces after cycle 1. This implies that mixture A is more prone to moisture susceptibility compared to mixture B.

The cumulative micro strains of unconditioned and conditioned mixtures during the creep test were measured and the total creep micro strains of samples at the end of the test are reported in Figures 15 and 16. The unconditioned samples are referred to as the unaged samples, while conditioned samples are referred to as cycle 3 sample. The results show that regardless of the effects of binder type, additive content, and compaction temperature, the cumulative micro strain of the unconditioned samples are higher than the corresponding values of the conditioned samples. This implies that the rutting resistance of mixtures increases when they are subjected to moisture conditioning and aging. The cumulative micro strains of mixtures fabricated using binder B in both conditioned and unconditioned methods are lower than those mixtures fabricated using binder A. It seems that SBS modified binder improves the rutting resistance of mixture B in

both conditioned and unconditioned states. In general, for the unconditioned samples, lower compaction temperatures exhibit higher cumulative micro strain. This can be due to the lower aging level that took place during the fabrication of the WMA samples at lower temperatures.

Figure 17 presents the relationship between slope of strain and creep loading cycle for a conditioned A-WMA110 incorporating 1% additive. The rate of deformation for creep samples can be quantified in terms of development of strain over creep loading cycles, which is the slope of the creep cumulative strain curve. From Figure 17, the slope of strain reduces when the loading cycle increases. For further investigation, similar graphs were plotted for all conditioned samples and the average slopes was determined over the final 15 minutes of the creep test as shown in Figure 18. From Figure 18, the strain slope of mixtures fabricated using binder A is higher than that of mixtures fabricated using binder B. Also the strain slopes of WMA fabricated using binder B are generally similar to the corresponding values of HMA.

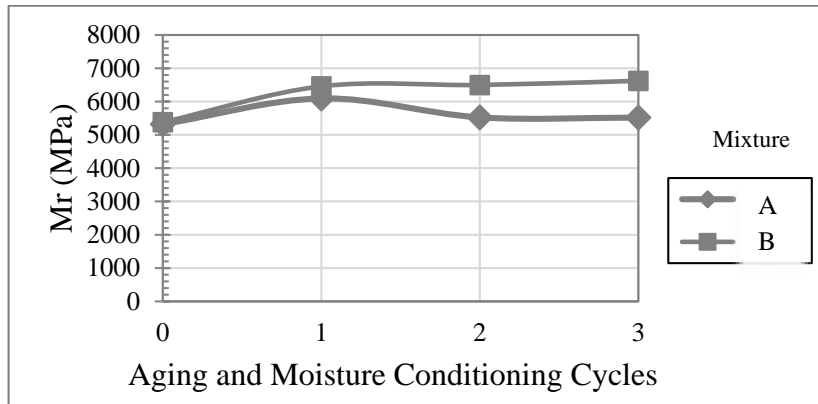


Figure 14. General trend of resilient modulus subjected to various conditioning cycles

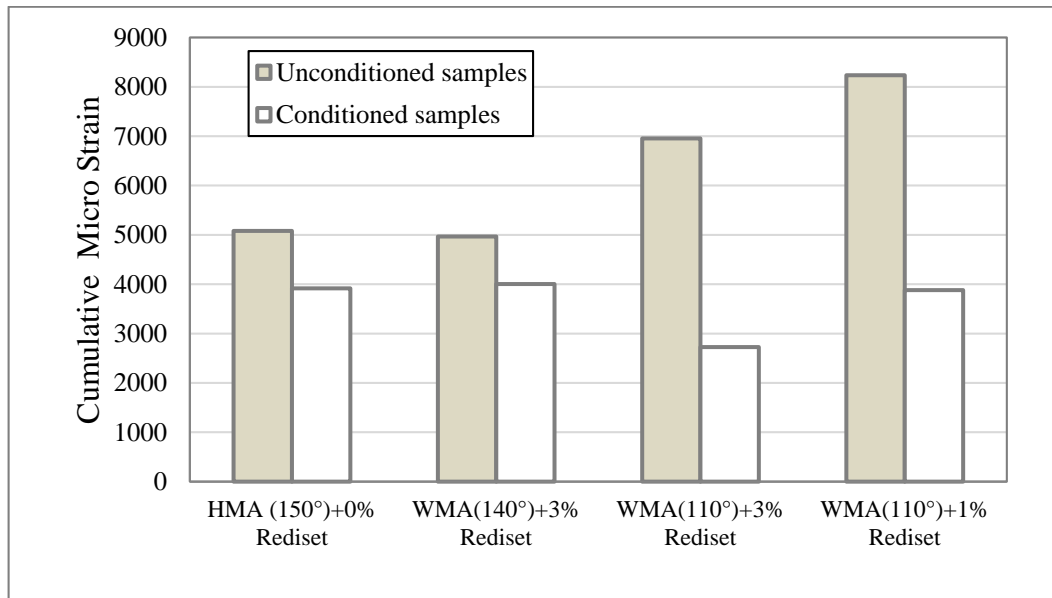


Figure 15. Cumulative micro strain of mixtures fabricated using binder A



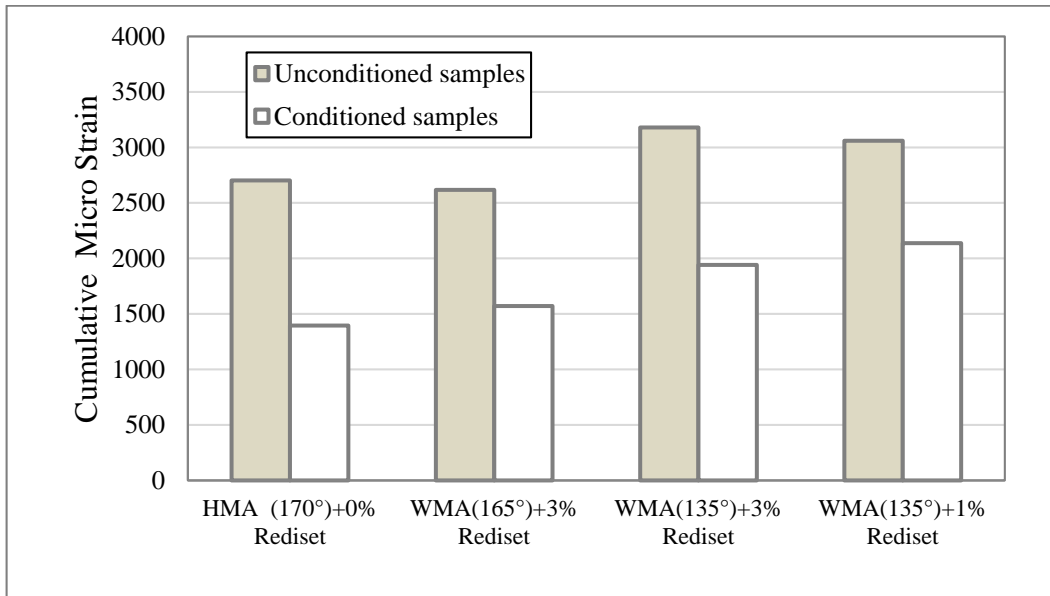


Figure 16. Cumulative micro strain of mixtures fabricated using binder B

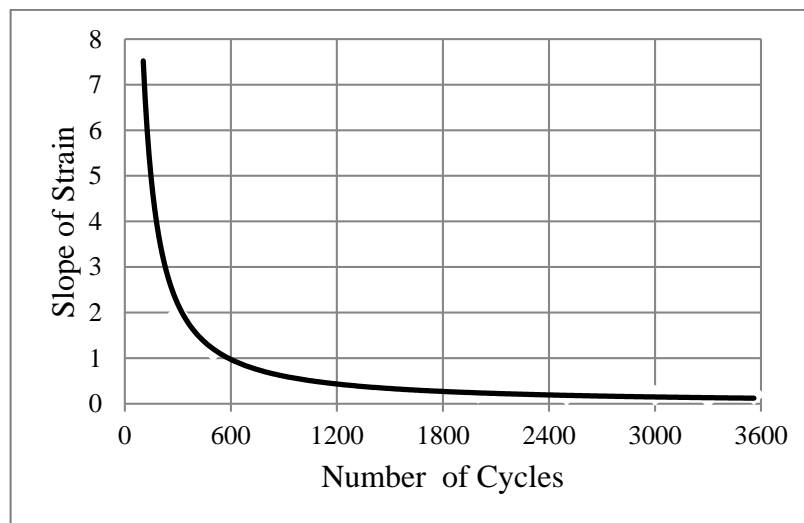


Figure 17. Slope of strain versus number of cycles for A-W110 mixture with 1% Additive

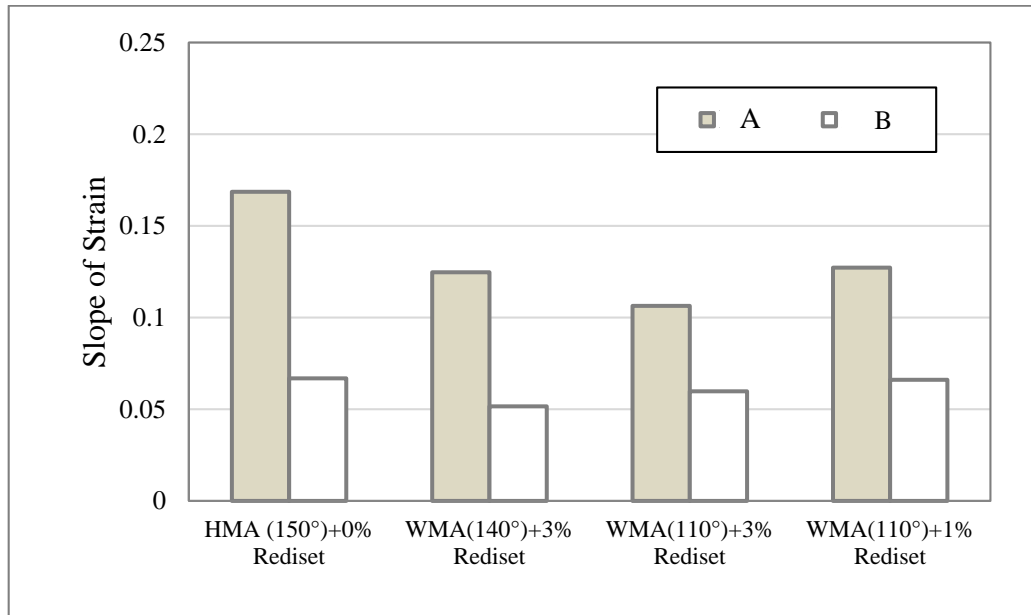


Figure 18. Slope of strain at the last 15 minutes of creep load for conditioned samples

#### 4. Conclusions

This paper investigated the combined effects of aging and moisture conditioning on the stiffness properties of WMA containing Rediset compacted at various temperatures based on the resilient modulus and dynamic creep test results. In addition, the effect of test temperature was investigated. Also, the effect of moisture conditioning method was evaluated for mixtures fabricated by various binders. From the test results, aging and moisture conditioning affect mixture stiffness properties. The effect of aging is to increase the resilient modulus of the asphalt mixtures, while moisture conditioning reduces these values. The type of moisture conditioning and asphalt binder exhibits significant influence on the resilient modulus. Mixtures fabricated by base binder are more susceptible to moisture damage than mixtures fabricated using SBS modified binder. The adverse effects of conditioning via freeze and thaw method is greater than other types of moisture conditioning methods that does not implicate freezing and

thawing. Compaction temperature and test temperature are the most significant factors that affect the stiffness of asphalt mixtures. The resilient modulus of WMA fabricated at higher compaction temperatures are greater than those fabricated at lower compaction temperatures. Also, the resilient modulus reduces when test temperature increases. In most cases, higher Rediset contents increase the resilient modulus of WMA when tested at higher temperatures, while the effect reverses at lower test temperatures. In the dynamic creep test, the combination of aging and moisture conditioning reduce the cumulative micro strain of samples during creep loading regardless of binder type, Rediset content, and compaction temperature. From the creep test results, higher Rediset content improves the permanent deformation properties of unconditioned WMA.

Recently, recycled aggregate has been effectively used in asphalt mixture studies [Kavussi et al., 2019; Kayedi, Hosseini and Mortazavi, 2017; Hamzah, Gungat, and Golchin, 2017; Golchin and Mansourian, 2017]. It is recommended to

evaluate the combined effects of aging and moisture conditioning on the properties of asphalt mixture containing recycled aggregate.

## 5. Acknowledgments

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