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Araştırma Makalesi / Research Article

Evaluation of the Combined Effects of Long-Term Aging And Moisture Damage on the Performance of Asphalt Mixture Incorporating Warm Mix Additive

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Abstract

Infiltration of moisture into the Warm Mix Asphalt (WMA) mixture is one of the primary factors that potentially compromises pavement structural integrity. This paper evaluates the effectiveness of a warm mix additive as an antistripping agent in WMA. In this study, to simulate field environmental conditions in the laboratory, asphalt mixture specimens were first exposed to long-term aging and moisture damage (simultaneously). Different aspects of WMA and Hot Mix Asphalt (HMA) performance including compactability, workability, tensile and shear strengths were then studied and compared. A 3D image analysis was performed to precisely quantify the percentage of failure contributed by adhesion on the fractured surface of the tested specimens. The test results showed that WMA samples were not only more workable and compactable compared to HMA but also exhibited superior resistance toward

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moisture damage over HMA even after experiencing severe moisture conditioning. Such trend was also observed based on higher strength and lower adhesion failure of WMA compared to HMA, regardless of test type. The tensile and shear stresses results indicated that utilization of cubical aggregates in asphalt mixtures can improve mixture performance. Moreover, the 3D image analysis results showed that the cubical aggregates utilized to prepare modified WMA exhibited lower adhesion failure which could be correlated to the effectiveness of the WMA additive.

Keywords: *Warm mix additive, Cubical aggregates, Moisture conditioning, Long-term aging, Imaging technique.*

Ilık Karışım Katkısı Katılan Asfalt Karışımının Performansına Uzun Süreli Yaşlanma ve Nem Zararının Birleştirilmiş Etkilerinin Değerlendirilmesi

Öz

Ilık Karışım Asfalt (WMA) karışımına nemin sızması, kaplamanın yapısal bütünlüğünü potansiyel olarak tehlikeye atan birincil faktörlerden biridir. Bu makale, ılık karışım katkı maddesinin WMA'da soyulma önleyici bir madde olarak etkinliğini değerlendirmektedir. Bu çalışmada, laboratuvarda saha ortam koşullarını simüle etmek için, asfalt karışım numuneleri önce uzun süreli yaşlanma ve nem hasarına (eşzamanlı olarak) maruz bırakılmıştır. Daha sonra sıkıştırılabilirlik, işlenebilirlik, çekme ve kesme dayanımları dahil olmak üzere WMA ve Sıcak Karışım Asfalt (HMA) performansının farklı yönleri incelendi ve karşılaştırıldı. Test edilen numunelerin kırık yüzeyindeki yapışmanın neden olduğu bozulma yüzdesini kesin olarak ölçmek için bir 3D görüntü analizi yapıldı. Test sonuçları, WMA numunelerinin HMA'ya kıyasla yalnızca daha fazla işlenebilir ve sıkıştırılabilir olduğunu değil, aynı zamanda şiddetli nem koşullandırmasına maruz kaldıktan sonra bile HMA'ya göre nem hasarına karşı üstün direnç sergilediğini gösterdi. Bu eğilim, test türünden bağımsız olarak, HMA'ya kıyasla WMA'nın daha yüksek mukavemeti ve daha düşük yapışma bozulmasına dayalı olarak da gözlendi. Çekme ve kayma gerilmeleri sonuçları, asfalt karışımlarda kübik agrega kullanımının karışım performansını iyileştirebileceğini göstermiştir. Ayrıca, 3D görüntü analizi sonuçları, modifiye WMA'yı hazırlamak için kullanılan kübik agregaların, WMA katkı maddesinin etkinliği ile ilişkilendirilebilecek daha düşük yapışma bozulması sergilediğini gösterdi.

Anahtar kelimeler: *Ilık karışım katkı maddesi, Kübik agregalar, Nem şartlandırması, Uzun süreli yaşlandırma, Görüntüleme tekniği.*

1. Introduction

Warm Mix Asphalt (WMA) has recently gained popularity among road construction industries due to their lower mixing and compaction temperatures compared to Hot Mix Asphalt (HMA) (Barraj, F., et al., 2022). This results in reduction of greenhouse gas emissions and energy consumption. Despite the beneficial impacts, WMAs are susceptible to moisture damage as ramification of lower mixing and compaction temperatures leading to incomplete drying, hence the presence of trapped moisture within the aggregate particles. According to Hicks (1991), the two main mechanisms associated with moisture damage are adhesion failure due to presence of water at the interface between mixture constituents which facilitate the removal of binder film from the aggregate surface, and of cohesion failure due to the changes in asphalt mastics or mortar softening point in the presence of moisture. Copeland et al. (2007) later on recognized aggregate degradation as the third mechanism in which moisture degrades the bituminous mixtures. Wen et al. (2016) suggested that the addition of an antistripping agent in WMA can considerably improve the stripping inflection point due to moisture damage. One of the recently developed WMA additives is ZycoTherm. This additive can reduce the mixture compaction temperatures to approximately 110˚C. Rohith and Ranjitha (2013) reported compatibility of ZycoTherm with both unmodified and modified binders due to its insignificant influence on the binder properties and grade. Sharanappanavar (2013) also found lower mixing and compaction temperatures of WMA mixtures modified using ZycoTherm, It was also stated that such additives can potentially act as an anti-stripping agent to enhance the moisture resistance of asphaltic mixtures.

In reality, asphalt pavements are subjected to several distresses such as moisture damage and long-term aging. The aging increases the mixture stiffness and brittleness, particularly at low temperatures (Hamzah et al., 2015). Similarly Menapace et al. (2015) informed that although aging exhibited negligible impacts on the microstructure morphology of WMA binders, such effects could considerably influence the asphalt mechanical properties. Bairgi et al. (2018) found the beneficial impacts of densification and long-term field aging on WMA rutting and stripping characteristics. According to Izadi et al. (2018), although aging increased the fracture energy and failure resistance of both WMA and HMA, long-term aging significantly reduced the mixtures' fatigue life. However, the detrimental effects of aging on the mechanical properties of WMA were found to be lower compared to the corresponding values of HMA. Arefin et al. (2018) found that binder type plays a crucial role on the effects of aging on both WMA and HMA. Valentová et al. (2016) reported the effects of aging on mixtures' moisture susceptibility in terms of Indirect Tensile Strength Ratio (ITSR), containing either only regular paving grade bitumen or bituminous binder with combination of anti-stripping agents or WMA additives. From their study, the additive initially showed reduced ITSR after 5 days of laboratory aging, but improved ratio after 9 days of aging.

The objectives of this study are: to first assess the moisture susceptibility of mixtures incorporating warm mix additive under different circumstances such as simultaneous long-term aging and moisture damage; to measure the proportions of adhesive failure and broken aggregates via 3D imaging technique, and finally to evaluate and compare the compactibility and performance of specimens when normal and cubical aggregates were used to prepare asphalt mixtures. Two types of asphaltic mixtures subjected to various conditions including, unconditioned and simultaneous three freeze-thaw (3 F-T) cycles and long-term aging (LTA) were prepared. The additive was incorporated as the anti-stripping and warm compaction additive in WMA to investigate the effects of lower compaction temperature on the mixtures' moisture damage susceptibility. The performance of asphalt mixtures in terms of tensile and shear strengths was also evaluated.

2 Materials and Methods

2.1 Materials

WMA samples incorporating the warm mix additive with 80/100 penetration grade (PG-64) base binder, normal and geometrically cubical shaped granite aggregates were first prepared in accordance with local specifications for asphalt mixture type AC 14 (JKR 2008). HMA mixtures were also prepared to serve as control samples. Tables 1 to 3 provides the basic properties of raw materials and aggregate gradation. Ordinary Portland Cement (OPC) was the filler type used. As a continuation from a previous study conducted by Kuan (2017), 5.3% optimum binder content was adopted in the preparation of all specimens. To prepare the modified binder, the base binder and high shear mixer mould utilized for wet mixing were preheated at 140˚C in an oven for two hours prior to blending. A warm mix additive, 0.1% by binder mass, was then added to the base binder and premixed homogenously at 1,000 rpm for 10 minutes. The properties of the added additive are tabulated in Table 4. From the Rotational Viscometer test results, the mixing and compaction temperatures for HMA were determined as 160˚C and 150˚C, respectively, while the corresponding values were reduced to 140˚C and 130˚C for the preparation of WMA. Prior to the mixing procedures, the batched aggregates were preheated in an oven for four hours at the target compaction temperature, while the base and modified binders were only pre-heated for two hours at the same temperature to minimise premature aging of binder. The loose mixtures were finally compacted to 7±1% air voids using a gyratory compactor.

Table 1. Granite aggregate properties.

Feature	Measured Values
Specific Gravity (g/cm3)	2,62
Water Absorption Ratio (%)	0,91
Los Angeles Abrasion Loss Value (%)	23,86
Aggregate Crushing Value (%)	19,25
Coarse Aggregate Angularity (%)	49,51
Flat and Elongated (%)	23,3

Table 2. Binder PG-64 properties.

Feature	Measured Values
Penetration at 25°C, 100 g, 5 s, (0.1 mm)	85,8
Softening Point (°C)	45
Ductility at 25°C (cm)	>100
Flash and Fire Point (°C)	331-340
Solubility (%)	99,52
Specific Gravity (g/cm3)	1,03

Table 3. Aggregate gradation for mix type AC14 (JKR, 2008)

Sieve Sizes (mm)	20	14	10	5	3,35	1,18	0,425	0,15	0,075
Lower-Upper Limits	100	90-100	76-86	50-62	40-54	18-34	12-24	6-14	4-8
Passing (%)	100	95	81	56	47	26	18	10	6

Table 4. Properties of the warm mix additive

Criteria	Descriptions
Form	Liquid
Color	Pale yellow
Flash Point (°C)	>80
Density (g/ml)	1.01
Freezing Point (°C)	5
Solubility	Miscible in water
pH Value	10% solubility in water neutral or slightly acidic
Viscosity (CPS)	100-500

2.2 Mixtures Conditioning Methods

In addition to unconditioned samples (control), some of the compacted specimens were long-term aged and moisture conditioned to simulate the field conditions. The SHRP-A-383 (Bell et al., 1994) procedures were modified where compacted samples were exposed to ultraviolet light at 85˚C for five days in a forced-draft oven to prepare the long-term aged specimens. To accelerate the adverse effects of field water intrusion in asphalt pavements, the aged specimens were then fully immersed in a vacuum saturator filled with sodium carbonate solution at 6.62 gm/litre concentration for moisture conditioning following ASTM D4867 (ASTM, 2006) procedures. A saturation level of 55% to 80% was achieved by vacuuming compacted specimens in the desiccator for 15 minutes. The vacuum saturation procedures were repeated when the degree of saturation was less than 55%, while the specimens were considered as damaged and discarded when the degree of saturation was more than 80%. Specimens were then freezed at -18 ± 2˚C for at least 15 hours, followed by immersion in water bath at 60˚C for 24 hours as one cycle. The above procedure was repeated for three cycles. For ease of reference, the mixtures were designated based on their constituents and conditioning methods as exemplified in Table 5.

Table 5. Designation of tested mixtures

Mixture Type	Aggregate Type	Conditioning	Mixtures Designation
Hot Mix Asphalt	Normal	Unconditioned	HNU
		Conditioned	HNC
	Cubical	Unconditioned	HCU
		Conditioned	HCC
Warm Mix Asphalt	Normal	Unconditioned	WNU
		Conditioned	WNC
	Cubical	Unconditioned	WCU
		Conditioned	WCC

2.3 Determination of Compaction Energy and Workability Indices

The Compaction Energy Index (CEI) indicates the consumed energy by the roller during execution in order to compact loose asphalt mixtures to the desired in-situ density. The CEI was obtained from the maximum specific gravity (G_{mm}) values from the 8th gyration to 92% of Gmm. The Gmm value of the 8th gyration was used to mimic the compaction effort by the paver during construction, while the selection of 92% Gmm was based on the current state of practice where HMA mat was initially roller-compacted to 92% Gmm, and subsequently compacted under traffic loading. The CEI euquals the area under the curve between the 8th gyration and 92% Gmm as shown in Figure 1. Although lower CEI is generally desirable, mixtures with very low CEI value might result in a tender pavements which should be avoided (Mahmoud and Bahia, 2004).

Moreover, the mixture workability was calculated based on Leeds Workability Method (Cabrera, 1991). The Leeds method is based on the relationship between mixture air voids and the corresponding compaction energy input applied by the gyratory compactor. A higher Workability Index (WI) indicates mixtures that are easier to compact (Dessouky et al., 2012). It should be

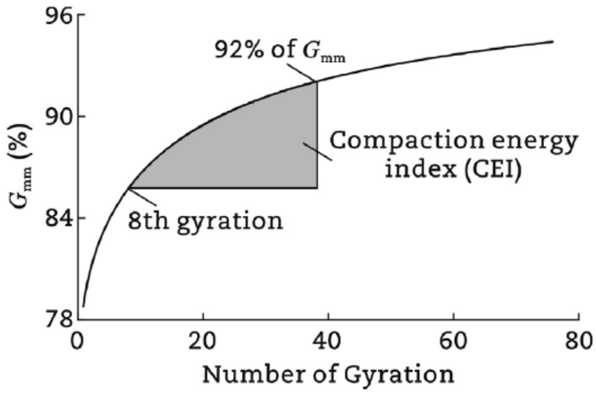


Figure 1. Illustration of the compaction energy index (Mahmoud and Bahia, 2004)

informed that in order to minimizing compaction effort lower CEI and higher WI mixtures are more desirable.

2.4 Leutner Shear Test

The Leutner shear test is typically used to determine the pavement layers bonding condition. In this study, the test was conducted to determine the effects of aggregate shape and warm mix additive on the shear strength of asphalt specimens. In the test, the samples were first pre-conditioned at 10˚C in an incubator for four hours prior to testing. The conditioned specimens were placed in the Leutner shear frame with interchangeable clamping and loading devices, and properly aligned with the shear axis as shown schematically in Figure 2. A constant loading rate of 50.8 mm/min was then applied until the specimens were sheared into two parts and the maximum shear force was obtained. Displacement recordings allowed the relationship between shear load versus displacement to be plotted. The Leutner shear strength was calculated using Equation (1). The Leutner shear strength ratio as an aging index was also computed as the strength ratio of conditioned to unconditioned specimens.

$$\sigma_s = F_{max}/A \quad (1)$$

where, σ_s is the shear strength (MPa), F_{max} represents the maximum shear force (kN), A is the specimen cross sectional area (m^2).

2.5 Semi-Circular Bending Test

The Semi-Circular Bending (SCB) test is typically used to characterize mixtures' fracture properties (Omranian et al., 2017). The test was carried out in accordance with AASHTO TP 124 (AASHTO, 2016) procedures to measure the tensile strength of asphalt mixtures. Semi-circular specimens with a notch at the center of flat side were first prepared. The specimens were conditioned at 10˚C in an incubator for four hours prior to testing. A SHIMADZU Universal

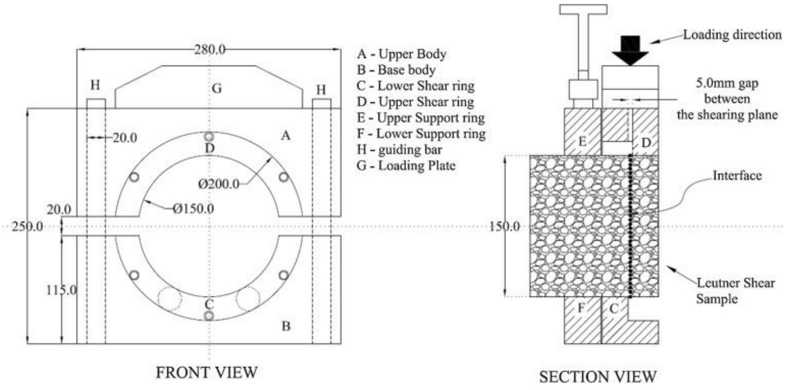


Figure 2. Schematic of leutner shear test (Sudarsanan et al., 2018)

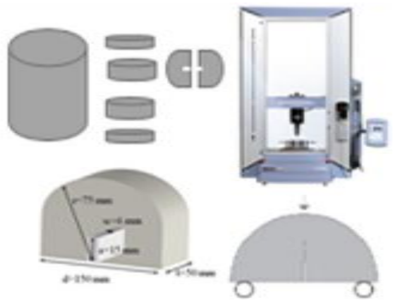
Testing Machine equipped with SCB test setup was employed to perform the test. Two roller supports were set at 120 ± 0,1 mm distance apart. A semi-circular specimen was placed on the roller supports and the load cell of 100 kN was aligned with the notch at the centre. The load was then applied at a constant rate of 50.8 mm/min until the specimen split into two. Figure 3 presents a schematic sketch of specimens and their preparation, testing apparatus as well as the split samples. The maximum tensile strength was calculated using Equation 2. The tensile strength ratio was also computed as the strength ratio of conditioned to unconditioned specimens.

$$\sigma_{max} = 4{,}253F_{max}/Dt \qquad (2)$$

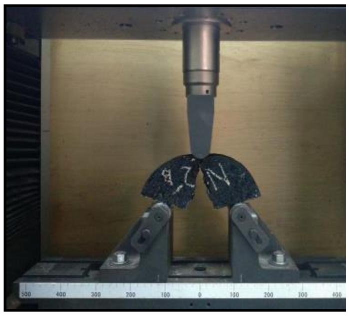
where, F_{max} is the maximum force (N), D equals the specimen diameter (mm), and t is the specimen thickness (mm). In total, three replicates for each tested mixture were evaluated.

2.6 Imaging Technique

Upon close visual examination, three distinct colours can be observed on the fractured surfaces of the tested specimens. These colours were related to failures caused by adhesion (brownish), cohesion (black) and broken aggregates (white). A 3D image analysis technique was carried out to measure the percentages of adhesion and cohesion failures as well as broken aggregates due to moisture damage. The 2D images of the fractured surface of the tested samples were initially captured using a high-resolution optical device. At least 20 images at equally spaced intervals



(a) Schematic of Semi-Circular Bending Test (Omranian et al., 2018a)



(b) Split Sample

Figure 3. SCB test

were taken for each specimen. Figure 4 shows the schematic image capturing procedures. The conventional 2D photos were converted into a 3D model using the Autodesk ReCap Photo software. The completed 3D models were then saved and exported to CloudCompare software for 3D image analysis. Following the study conducted by Teh and Hamzah (2019), the 3D models were first converted into grey scales to reduce the model multidimensional domain to lower dimensions comprising only one or two component axes. For classification of the model, the threshold range values for adhesive failures and broken aggregates were determined by limiting the number of segments between 0 and 255. Accordingly, lower band values reperesents binder areas, while higher intensities shows the stripped and broken aggregates. The number of pixel point clouds attributed to broken aggregates, adhesive and cohesive failures was analysed and determined in CloudCompare. The calculated pixels by the software were then used to measure the porion of adhesion and cohesion failures as well as broken aggregates. For ease of differentiating the composition of each specimen, white colour indicates the composition of broken aggregates, while red and black colours visualize the adhesive and cohesive failures, respectively. Figures 5a and b show the original 3-D model and classified model, respectively as obtained from CloudCompare software.

3. Results and Discussion

3.1 Compaction Energy and Workability Indices

Figures 6a and b show the CEI and WI of unconditioned asphalt mixtures produced with normal and cubical aggregates, respectively. The results presented in Figure 6a indicate that the CEI of HNU is considerably higher than WNU, while the difference between the corresponding values drops for HCU and WCU. The discrepancy between CEIs' of HNU and WNU implies that HMA requires extra energy for mixture compaction to achieve the desired density during road construction.

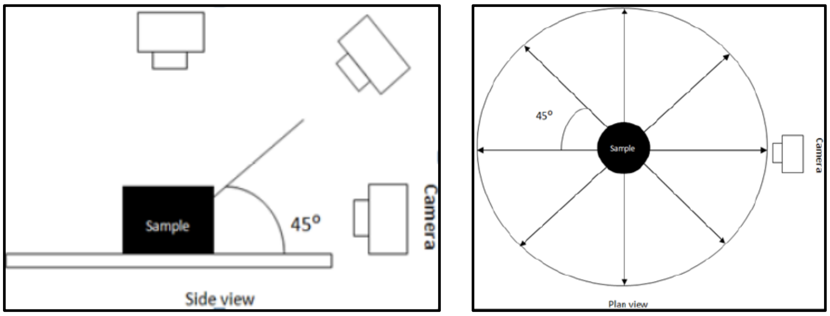
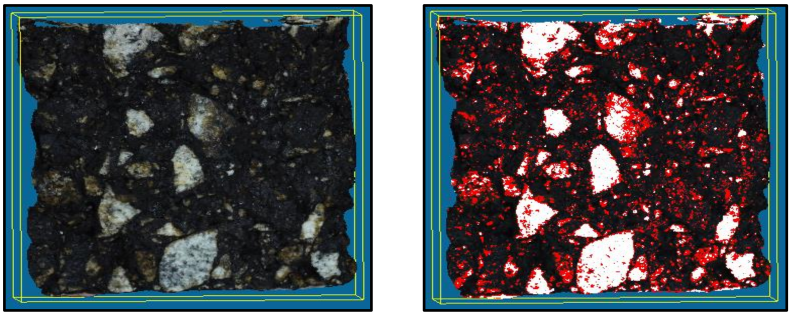


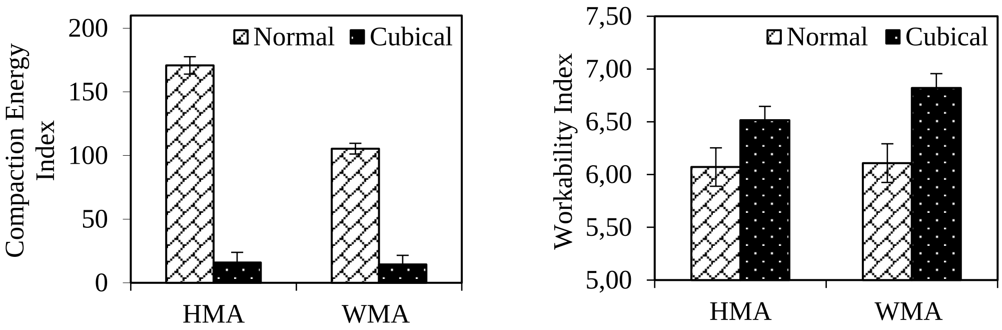
Figure 4. Schematic of the image capturing of the specimens' fractured surface



(a) Original 3D Model (b) Classification of 3D Model

Figure 5. Image analysis using cloud compare

This finding is in agreement with the study conducted by Omranian et al. (2018b), where such behaviours were attributed to the beneficial impacts of warm mix additives on the CEI. In addition, the mixtures incorporating cubical aggregates exhibit lower CEI than mixtures produced with normal aggregates. This finding can be correlated to the shape of cubical aggregates that possesses higher homogeneity degree with visible edges and corners faces for dense packing and lower air voids. The difference between the CEI of HCU and WCU is noticeably lower when compared to similar HNU and WNU values. It indicates that cubical aggregates significantly reduce the CEI, hence, the impacts of mixture type on the corresponding value can be ignored. The result in Figure 6b indicates that the WI of HNU and HCU is lower compared to the corresponding values of WNU and WCU, respectively. Despite the CEI, the difference between WI is more obvious for mixtures produced using cubical aggregates. It indicates that mixtures containing warm mix additive are more workable. In addition, mixtures prepared with cubical aggregates exhibits higher WI compared to mixtures produced using normal aggregates, which indicates improved workability of mixtures with cubical aggregates. The difference between the WI of mixtures with normal aggregates is extremely lower compared to the corresponding values of mixtures produced with cubical aggregates. It implies that mixture type has a more significant impact on mixtures containing cubical shape aggregates.



(a) Compaction Energy Index (b) Workability Index

Figure 6. Results of mixture compactability indices

3.2 Shear Strength

Figures 7a and b illustrate the results of mixtures' shear strength and their ratio obtained from Leutner shear strength test, respectively. Figure 7a shows the higher shear strength of WMA over HMA for both conditioned and unconditioned samples. This outcome proves the effectiveness of the added warm mix additive that enhances the mixtures shear strength. It can also be correlated to the mixtures internal friction increment due to the warm mix additive. However, similar to the study conducted by Bennert *et al*. (2010), who detected increase in shear rate of binders incorporating Rediset as a warm mix additive that led to changes in internal friction of mixtures particles, further analysis should be carried out to substantiate such inferences. Moreover, the incorporation of cubical aggregates promotes shear strength for both HMA and WMA based on the increase in corresponding values at about 10 ± 1% for all samples. This may be attributed to the cubical aggregates that contribute to enhanced shear stress resistance over the flaky and elongated shapes of normal aggregates. This implicates the beneficial impacts of cubical aggregates on the shear strength of mixtures. Figure 7a also shows that conditioning of mixtures (aging and moisturizing) decreases the shear strength, whereby the corresponding values reduce by almost 8 ± 1% for all samples. It can be concluded that aggregate shape exhibits a more significant effect on shear strength compared to aging conditions based on the higher percentage of aggregate effects on shear strength. Figure 7b compares the shear strength ratio of samples which also ranks the aging resistance of the specimens. The highest ratio is related to WCs followed by HCs, HNs and WNs. It implies that although the differences are small (the maximum discrepancy is 1.22% which can be neglected), aging is less severe for mixtures produced using cubical aggregates. This can be attributed to the lower air voids in mixtures containing cubical aggregates which reduce the destructive impacts of moisture and aging on the samples. Figure 7b also shows that the least aging effects are related to WMA with normal aggregates, attributed to the minor undesirable effects of the added warm mix additive (due to low additive dosage) that reduces the mixture resistance against moisture damage and aging. However, such inferences require further analysis since WMA with cubical aggregates exhibits lower susceptibility to moisture and aging damage compared to HMA produced with cubical aggregates, which can be correlated to the interaction of cubical aggregates with warm mix additive that enhances the mixtures aging resistance.

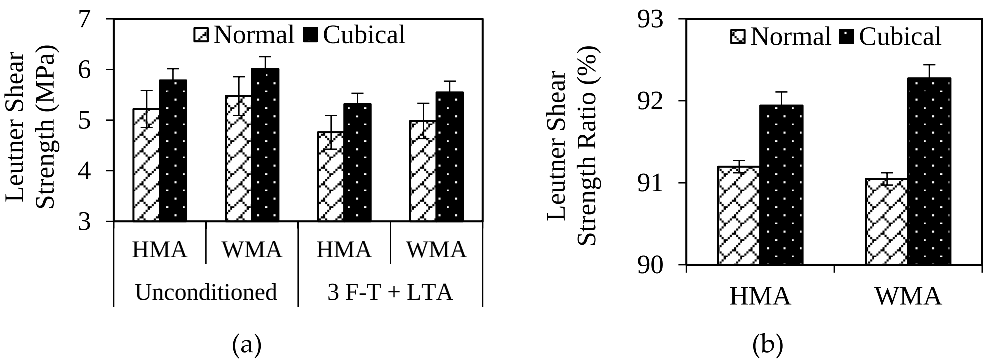


Figure 7. Results of Leutner shear strength and ratio

3.3 Tensile Strength

The fracture behaviour of samples in terms of tensile strength and their ratio is presented in Figures 8a and b, respectively. From Figure 8a, WCU and HNC respectively exhibits the maximum and minimum tensile strength. This trend is similar to a study conducted by Yang *et al.* (2017) who reported warm mix additive (Evotherm®) positive impacts on the tensile strength, moisture damage resistance, and fatigue performance of crumb rubber modified mixture. The results also show that there is a minor favourable impact of cubical aggregates on the shear strength, while aging noticeably deteriorates the mixture fracture resistance, where the tensile strength is reduced by approximately 7,5 ± 0,5% for all mixtures after conditioning. Figure 8b shows the tensile strength ratio which associates with the difference between the aging resistance of mixtures. The highest tensile strength ratio is related to WCs followed by WNs, HCs, and HNs. Although the differences in results are not considerable (the maximum discrepancy is 0,864%), aging is less severe for WMA. It indicates the positive impacts of warm mix additive on the mixtures resistance against the damages caused by moisture and aging conditioning. This finding is further explored using imaging technique. Figure 8b shows that the highest aging impacts are related to HMA with normal aggregates as reflected in the lowest tensile strength ratio. This certifies both cubical aggregate and warm mix additive constructive impacts to reduce the moisture and aging resistance of mixtures. The effects of cubical aggregates on the tensile strength ratio can be directly correlated to such mixtures lower air voids. This finding is in agreement with the study conducted by Isacsson and Zeng (1998), where higher air voids resulted in higher aging rate and consequently reduced the mixtures fracture resistance.

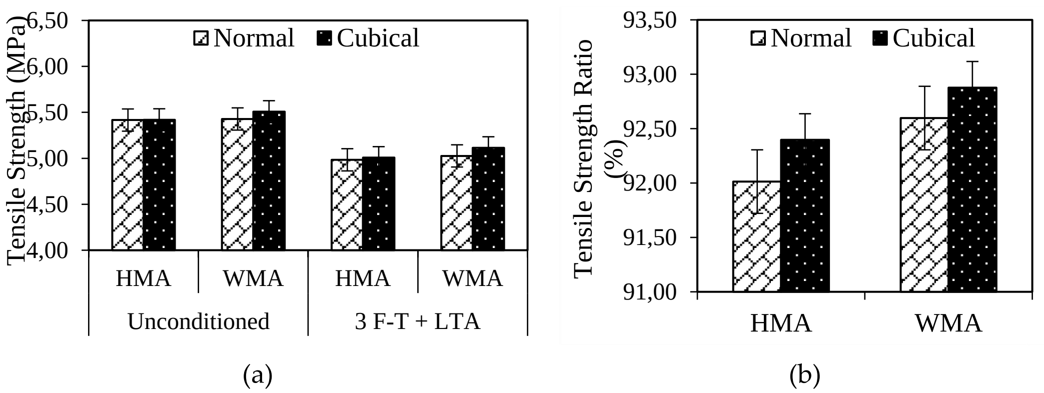
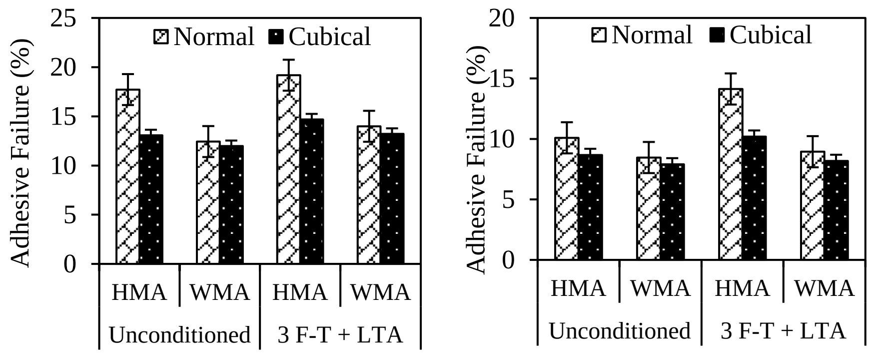


Figure 8. Results of tensile strength and ratio

3.4 Image Analysis

Image analysis was conducted on the fractured surfaces of samples to quantify the percentages of adhesive and cohesive failures as well as broken aggregates. Out of the three, this paper only presents the adhesive failure and broken aggregates results as shown in Figures 9 to 10. Cohesive failure can be easily calculated by deducting adhesive failure and broken aggregates summation from 100%. The results of image analysis reperesenting adhesive failure of specimens tested by Leutner shear and SCB tests are illustrated in Figures 9a and b, respectively. These figures clearly show that conditioning of samples increases the adhesive failure which can be associated with the destructive impacts of moisture damage and aging that weaken the adhesive bond between binder and aggregates, and consequently deteriorate the mixtures performance. The results also indicate that the incorporation of cubical aggregates reduces the adhesive failure of all mixtures. For instance, adhesive failure of HNUs tested using Leutner shear and SCB tests are 17,72% and 10.09%, respectively, while the corresponding values for HCUs decrease to 13,28% and 8,67%, respectively. This finding can be correlated to the variations in mixtures air voids and aggregate interlock based on the changes in aggregates geometrical shape. However, using either conventional methods or advanced technologies such as utilization of X-ray computed tomography to scan and determine the mixtures' internal structures is recommended to prove such inferences. In addition, WMAs exhibit better performance in terms of adhesive failure compared to HMAs. This finding confirms the beneficial impacts of the added warm mix additive on mixtures to reduce the adverse impacts of moisture damage and aging. Although the trend of variation in mixtures adhesive failure remains unchanged for both tests, the samples subjected to shear test exhibit higher adhesive failure compared to those studied through tensile strength test. For instance, adhesive failures of WCU and WCC tested using Leutner shear test are 11.98% and 13.22%, respectively, while the corresponding values are 10.19% and 8.18%, respectively, for SCB tested samples. It shows that adhesion plays a crucial role in mixture shear strength. Hence, incorporation of the warm mix additive as an antistripping agent is recommended for pavement that requires higher shear strength and locations that experience heavy rainfall to reduce pavement distresses due to moisture damage.



(a) Leutner Shear Test (b) Semi-Circular Bending Test

Figure 9. Adhesive failure of samples subjected to different performance tests

The percentages of the specimens' broken aggregates tested by Leutner shear and SCB tests are depicted in Figures 10a and b, respectively. The results show that the proportion of broken aggregates increases after conditioning which can be attributed to the destructive impacts of moisture and aging damages on the aggregates. In addition, lower percentages of broken aggregates are observed for samples produced using cubical shaped aggregates. Although the differences between broken aggregates for WNC and WCC when tested using Leutner shear as well as HNU and HCU when tested by SCB are very small, the lower percentage of broken cubical aggregates can be correlated to their better interlock and lower proportion of flaky and elongated aggregates compared to normal aggregates. These figures also indicate that the proportion of broken aggregates varies by mixture type, conditioning and test variation. For instance, in the case of samples subjected to the Leutner shear test, HCU exhibits slightly lower broken aggregates compared to WCU, while the corresponding value is higher for HCU over WCU when the SCB test was performed. An opposite trend can be observed in the case of HCC and WCC. Although no specific trend can be detected in the percentage of broken aggregates, the differences between proportions of broken aggregates for HMAs and WMAs at similar conditions are very low when Leutner shear test was conducted, and which can even be neglected. It can therefore be inferred that the use of warm mix additive may not exhibit substantial impacts on the shear strength when the mixtures incorporate cubical aggregate. Such inference can be interpreted as the dominant impacts of aggregates on mixtures over warm mix additive. Moreover, the results indicate that the mixture has higher broken aggregates when tested by Leutner shear test compared to SCB test. For instance, the percentages of broken aggregates for HNU and WNU are 8.30% and 10.77%, respectively, when subjected to shear strength test, while the corresponding values are 7.56% and 8.08%, respectively, on SCB tested samples. It indicates that aggregates with higher cohesive strength should be incorporated when the mixtures are exposed to extreme shear distresses.

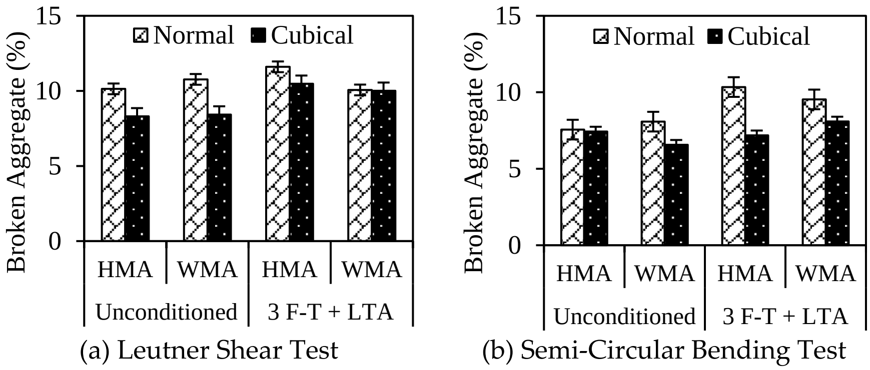


Figure 10. Broken aggregates of samples tested using different performance tests

4. Conclusions

Moisture damage susceptibility has always been a concern in asphalt mixes as the intrusion of water in asphalt pavement would eventually lead to pavement distresses such as stripping and ravelling. The effectiveness and impacts of the added warm mix additive as an anti-stripping agent and a warm mix asphalt compaction additive on the mixtures moisture damage were investigated in this study. The effects of aggregate shape on the mixtures engineering properties were also studied in terms of tensile and shear strengths, aggregate degradation after applied loadings and moisture susceptibility. The findings conclusions are as follows:

1. The WMA was more workable and easier to be compacted to the desired density as compared to HMA even at a lower compaction temperature, as reflected in the lower CEI and higher WI.
2. The WMA samples subjected to that exposed to simultaneous long-term aging and moisture damage exhibited better behaviour in terms of tensile and shear strength ratios compared to HMA. This proved the effectiveness of incorporating warm mix additive to reduce moisture damage in asphalt mixtures.
3. Mixtures incorporating cubical aggregates exhibited higher tensile and shear strengths than those produced with normal aggregates which implied cubical aggregates superior fracture resistance when subjected to applied loads.
4. The adhesive failure of WMA incorporating cubical aggregates was lower than HMA. This implicated that the utilization of warm mix additive and cubical aggregates enhanced the mixtures moisture damage resistance.
5. The percentage of broken aggregates was found to be independent of moisture conditioning and mixture type since no specific trends were observed. The higher percentage of broken aggregates was found in mixtures incorporating normal aggregates compared to those containing cubical aggregates due to higher proportion of flaky and elongated aggregates.

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