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To cite this article: Muhammad Rafiq Kakar *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **236** 012013

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Analyzing the stripping potential of warm mix asphalt using imaging technique

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Abstract. In asphalt mixtures, stripping occurs when the bond between the asphalt and the aggregate is broken due to the intrusion of water within the asphalt aggregate interface. Warm mix asphalt (WMA) is a technology that allows significant reduction in mixing and compaction temperatures of conventional hot mix asphalt. However, WMA is susceptible to moisture damage due to its lower production temperature. This can cause adhesive failure, hence stripping of asphalt binder from the aggregates. In this study, direct tensile strength (DTS) and indirect tensile strength (ITS) tests were applied to fracture the mixture specimen. Imaging technique was applied on the fractured faces of asphalt mixture to quantify the adhesive failure susceptibility due to the destructive effects of moisture. The results showed that adhesive failure increased with the number of freeze and thaw cycles and mixtures prepared with PG-76 binder exhibited lower adhesive failure compared to PG-64 binder. From fractured ITS samples, most of broken aggregates were found located in the vicinity where the indirect tensile load was applied. On the other hand, high adhesive failure was obtained at the center portion where maximum tensile stresses were developed. The image analysis method employed in this work has proven to be very effective to analyze the deterioration of asphalt mixtures subjected to moisture conditioning.

1. Introduction

Moisture is a major concern in asphalt pavements and it can exert adverse effects on the performance of hot mix asphalt (HMA) [1,2]. In the case of WMA, mixing at low temperature might result in insufficient drying of the aggregates, which in turn adversely affects the adhesion between aggregates and asphalt binder [3,4]. According to Lottman [5], two typical mechanisms of moisture damage are:

- i. Loss of adhesion due to moisture at the asphalt aggregate interface, stripping away the asphalt film
- ii. Loss of cohesion due to softening of the mastics.



The adhesion between asphalt and aggregate can be classified based on chemical reaction, surface energy, molecular orientation, and mechanical adhesion [6]. These can be influenced by factors such as surface tension of the asphalt binder and aggregate, chemical composition of asphalt and aggregate, asphalt viscosity, surface texture of the aggregate, aggregate porosity, aggregate cleanliness and aggregate moisture content and asphalt binder temperature at the time of mixing [7]. Lytton et al. [8] measured the thickness of asphalt film during which the failure from adhesion to cohesion takes place. They identified that thin films asphalt mixtures fail in tension (adhesive bond failure), while failures within the mastic in thick films asphalt mixtures are due to cohesive failure. Another study by Kim et al. [9] showed that moisture damage is strongly influenced due to the cohesive and adhesive bond failure. Stripping in asphalt mixtures can occur when the bond between asphalt binder and aggregate is broken due to the intrusion of water within the binder aggregate interface. Moisture can disrupt the bonds between asphalt aggregate by means of molecular diffusion through asphalt film and has the potential to extend towards the aggregate surface [10]. Stripping mechanisms can occur in the form of detachment, displacement, spontaneous emulsification, pore pressure, hydraulic scour, pH instability, and the effects of the environment on bitumen aggregate material systems [11,12]. Stripping can also increase due to variations in temperature, freeze thaw cycles, and wetting-drying cycles. Stripping of asphalt mixtures is a phenomenon resulting from moisture damage and is more likely to take place in the context of WMA. Furthermore, the water nature to which the mix is exposed (salt content, pH) also affects the stripping of asphalt mixture [13]. Fillers such as hydrated lime, Ordinary Portland Cement, and many other liquid anti stripping agents have been used in HMA to mitigate stripping of asphalt binder from aggregate [14].

Presently, the water sensitivity of asphalt pavements are studied using relatively simple tests that can be divided into two groups. Firstly, tests conducted on loose mix to determine aggregate coating properties during water immersion or in boiling water (qualitative measurement). Secondly, tests conducted on compacted mixes to evaluate the retained strength or stiffness or more commonly, the mechanical properties (quantitative measurement). Unfortunately, these tests were not very effective as they evaluate the adhesive failure via visual inspection [15]. The use of mechanical test to measure strength followed by imaging technique to quantify the percent amount of adhesive failure is more convenient to achieve both quantitative and qualitative measurements. Such a technique can enable testing of parameters using only one material in addition to saving time and cost involved in the preparation and testing of loose mix. Compared to visual inspection the use of imaging technique is more precise, as the human vision is relatively poor at differentiating between the perceived brightness and color features of the failure plan [16]. Image analysis software has been widely used worldwide in a variety of applications. Salem et al. [17] described that imaging methods have been well-recognized to be very effective in analyzing deterioration status of concrete structures. This paper evaluates the adhesion behavior of asphalt mixtures related to its mechanical strength both in direct tension and indirect tension when subjected to moisture conditioning. In asphalt technology, moisture susceptibility testing of loose and compacted asphalt mixtures are carried out in a qualitative and quantitative manner. To address the above stated parameters, a novel method using image analysis technique was adopted which fractured the specimen in direct tensile and indirect tensile followed by examining the fractured surface. With this method, a more precise quantification is expected compared to the conventional method of visual inspection.

2. Materials and method

Two conventional asphalt binders, PG-64 and PG-76 (polymer modified binder), were used in this study. The asphalt binders were transported from Shell Bitumen Singapore to the laboratory in sealed containers to minimize the effects of oxidation and premature binder aging. Surfactant based WMA additive results in a significant improvement on the production conditions of sustainable asphalt mixtures. Cecabase RT 975 additive is consumed in a very limited amount of 0.2 to 0.5% by weight of the binder [18]. This additive, which is liquid at room temperature, can be easily mixed with the hot asphalt binder before the asphalt mixture production.

2.1 Filler

Mineral fillers are fine particles of mineral material that exhibit specific characteristics, helpful in the design and construction of asphalt pavements. The typical proportions are 94 to 96% aggregate comprising 6% of mineral filler, 4 to 6% asphalt binder by weight. To investigate the effects of filler as anti-stripping agent in asphalt mixture, ordinary Portland cement (OPC) and pavement modifier (PMD) were used. PMD is a greyish-black powder mineral filler developed in Malaysia used as anti-stripping agent. The addition of approximately 5% of PMD by aggregate weight, act as mineral filler in hot mix asphalt surface course mixes.

2.2 Specimen preparation

All specimens were prepared according to the Asphalt Institute manual (MS-2) (Asphalt Institute, 2001). The hot binder and aggregate were mixed together at 160°C, 180°C and compacted at 150°C, 170°C for PG-64 and PG-76 binders, respectively. PG-64 and PG-76 WMA mixtures were prepared at mixing temperatures shown in Table 1 and relatively 10°C lower temperatures were used for compaction of each WMA mixtures. The specimens tested in this study were 100 mm diameter and 120 mm in height for direct tension test (DTT) and 100 mm diameter and 63.5 mm height for indirect tensile strength (ITS). The samples were compacted to the desired heights by using the Servopac Gyrotory Compactor. The air voids of the specimens were kept at $7 \pm 1\%$ and the specimen heights at 120 ± 0.5 mm. Since Cecabase RT 975 content has no effect on the optimum binder contents. In addition, the supplier recommends 0.3% Cecabase RT 975 and this value was adopted to test the DTT and ITS specimens. In Table 5, the specimens are designated according to their type (H for HMA and W for WMA), filler type (O for OPC and P for PMD) and their mixing temperature for example (180 for 180°C). Therefore, specimen HP160 denotes a HMA incorporating PMD filler mixed at 160°C.

The optimum binder content (OBC) utilized in the preparation of both DTT and ITS specimens are 4.5 and 5.2%, respectively. For mix design, the target air voids of all the specimens were $4 \pm 0.1\%$. This showed that OBC for the WMA was found to be independent of the amount of additive used.

Table 1. Mixture designation (DTT and ITS).

Mixture Type	Filler Type	Mixing Temperature (°C)		Designation	
		PG-64	PG-76	PG-64	PG-76
HMA	OPC	160	180	HO160	HO180
HMA	PMD	160	180	HP160	HP180
WMA	OPC	140	170	WO140	WO170
WMA	OPC	130	160	WO130	WO160
WMA	OPC	120	150	WO120	WO150
WMA	PMD	140	170	WP140	WP170
WMA	PMD	130	160	WP130	WP160
WMA	PMD	120	150	WP120	WP150

The DTT specimen end faces were cleaned and dried out at room temperature. To avoid non-uniform stress concentration due to eccentricity, special care was taken while gluing samples to ensure flat end faces. The specimens were glued with specially designed tensile test molds which utilized a low temperature high adhesive strength epoxy resin. The Araldite high performance epoxy adhesive was used to glue the specimen with the capping mold. After gluing, the specimens were kept at room temperature for 24 h to allow strong bond between the molding cap and specimen to develop [15].

2.3 Laboratory moisture conditioning

The moisture conditioning was performed to evaluate the effects of accelerated water conditioning employing the freezing-thawing cycle on compacted asphalt mixtures as described in the previous study by Hamzah et al. [15]. The conditioning of all the compacted specimens was done according to

ASTM D4867 (2006) procedures with the only modification of using distilled water with addition of Na_2CO_3 at 6.62 gm. Water with Na_2CO_3 was used to increase the pH value so as to enhance the stripping rate or damage inside asphalt specimens [19]. The specimens were immersed in the solution and vacuumed for 15 min to achieve saturation levels between 55% and 80%. For the next step, these specimens were exposed to freezing condition at -18 ± 3 °C for 16 h and thawing at 60°C for 24 h as one cycle. Three sets of specimens; unconditioned dry, conditioned 1 freeze thaw cycle and 3 freeze thaw cycles were prepared and set aside. The conditioned DTT specimens were left for 24 h before gluing them to perform the test. Finally, the effects of conditioning on HMA and WMA stripping were evaluated using imaging technique on the fractured faces of DTT and ITS specimens [15].

2.4 Imaging technique

Images of DTT and ITS fractured specimens were obtained using a high-resolution optical device and were then processed by means of Environment for Visualizing Images (ENVI) software (Exelis Visual Information Solutions). Optical imaging is a simple and economic way as it can acquire information (images) of a component without direct contact (non-destructive type). It is also an area scanning method, capable of instantaneous recording of a two-dimensional image of an object. Once the live images are taken, appropriate image processing reveals potential characteristics and changes in image under investigation [15]. The Region of Interest (ROI) tool given by ENVI was used to classify the area marked as brown and white tinctures on the specimen images. The selected brown and white regions were identified as stripping/failure due to adhesion and failure within the aggregates/broken aggregates, respectively. More details on the process of imaging technique can be found in Hamzah et al. [15].

3. Results and discussion

In this paper, for the purpose of comparing results of ITS test with DTT, the results of DTT were obtained from the authors already published work elsewhere Hamzah et al. [15]. The following sections will describe the results of percent adhesive failure, tensile strength (direct and indirect) broken aggregates, and statistical analysis and correlations obtained from the results of DTT and ITS tests.

3.1 Effects of moisture conditioning on adhesive failure of DTT samples

The image analysis provides measurements of failure plan in terms of area in square meters. However, for analysis of the results, failures caused by adhesion and broken aggregates are expressed in percentage, while strength values obtained from DTT are expressed in Mega Pascal.

The adhesive failure results of both PG-64 and PG-76 mixtures at different conditioning cycles are respectively presented in Figures 1(a) and (b). The results show that the number of freeze-thaw cycles influences the percent amount of adhesive failure showing that with the increase in F-T cycles the percent adhesive failure increases. It was also observed that the percent adhesive failure due to moisture conditioning (F-T cycles) was higher in PG-64 compared to PG-76 mixtures. The PG-64 and PG-76 WMA mixtures show high resistance against moisture damage at 1 F-T cycle compared to HMA. However, this trend was reversed after 3 F-T cycles. Mix WO130 and WO120 exhibit the highest percentage adhesive failure after 1 and 3 F-T cycles. This might be due to the influence of lower mixing temperature, where WMA's are thought to be more prone to adhesive failure at higher F-T cycles.

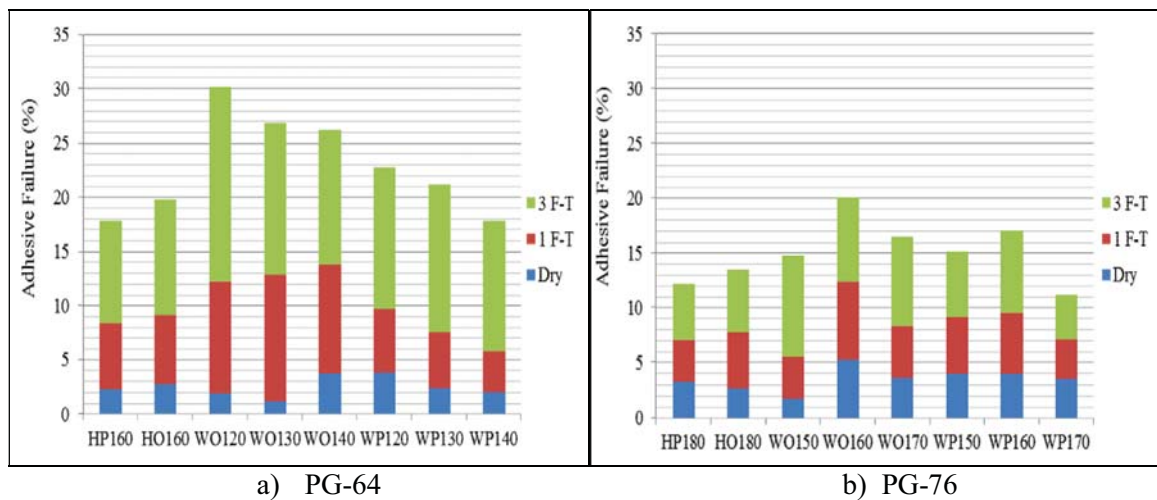


Figure 1. Percent adhesive failure on fractured surfaces of DTT specimens.

3.2 Failures due to broken aggregates on DTT samples

Figures 2(a) and (b) shows the percent area of failure due to broken aggregates quantified using imaging technique. Interestingly, these broken aggregates appeared on the fractured surface of every specimen after the test. These broken aggregates are thought to be due to the influence of compaction, as it is believed that some micro cracks are developed in aggregates during compaction. Therefore, when the specimen was subjected to tensile load, these aggregates can be easily split and appeared on the fractured plan. The results illustrates that the percent broken aggregates do not exhibit a specific trend and are not dependent on the moisture conditioning (F-T cycles).

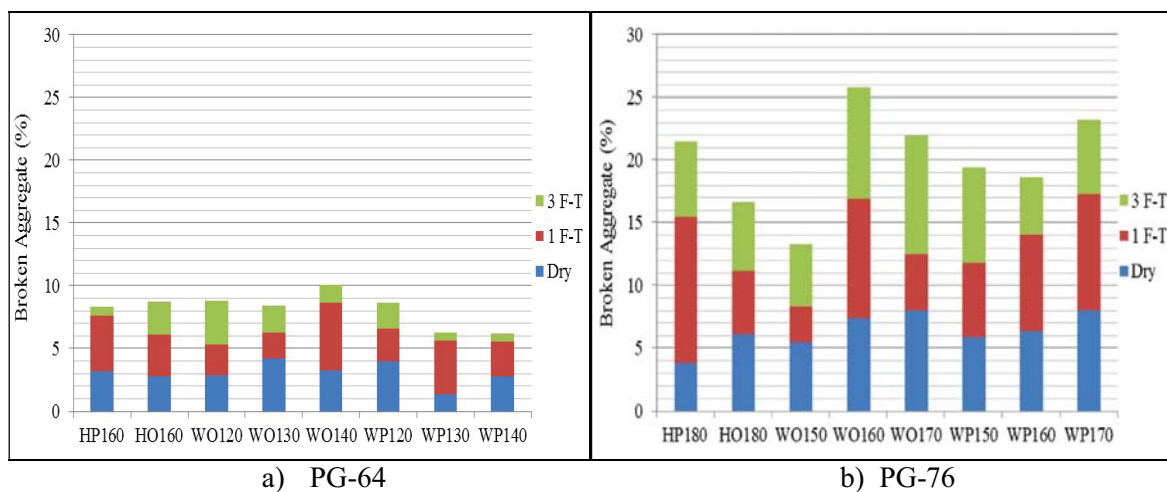


Figure 2. Percent broken aggregate on fractured surfaces of DTT specimens.

3.3 Effects of moisture conditioning on direct tensile strength

The direct tensile strength (DTS) results of both PG-64 and PG-76 mixtures at different F-T cycles are presented in Figures 3(a) and (b). The result illustrates that the mixtures DTS decreases with the increase in F-T cycles. This reduction in DTS is more noticeable after 3 F-T cycles. The reduction in DTS after 1 and 3 F-T cycles for HMA modified with PMD filler remain higher however, mixture WP150 exhibits the lowest DTS after 3 F-T cycles. Overall the DTS of PG-76 WMA remains higher when compared to PG-64. Considering the DTS results of PG-76 mixtures, it is evident that the OPC as a filler improved the DTS of HMA and WMA when compared with PMD filler after F-T cycles.

More detailed discussion on the results of percent adhesive failure, broken aggregates and direct tensile strength can be found elsewhere Hamzah et al. [15].

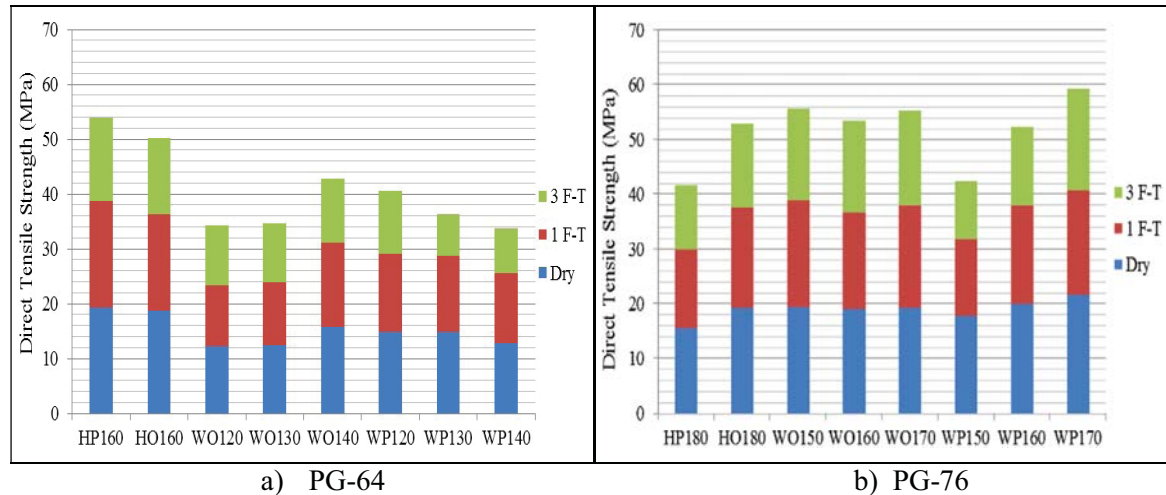


Figure 3. Direct tensile strength of fractured surfaces.

3.4 Statistical analysis on the results of percent adhesive failure after DTT

A two-way ANOVA at 95% confidence level ($\alpha = 0.05$) was conducted to analyze the effects of percent adhesive failure on asphalt mixtures. Tables 2 to 6 represent the statistical analysis on the limited results obtained. Table 2 shows that the freeze-thaw (F-T) conditioning on PG-64 mixtures significantly affects the percent adhesive failure, while mixing temperature and type of anti-stripping agent (ASA) have no significant effect on the percent adhesive failure. Similarly, Table 3 shows that the F-T conditioning on PG-76 mixture significantly affects the percent adhesive failure, while mixing temperature and anti-stripping agent have no significant effect on the percent adhesive failure.

A paired t-test was run to analyze the mean difference between percent adhesive failures of mixtures prepared with PG-64 and PG-76 binders. Tables 4 to 6 show a significant difference in the mean values of the percent adhesive failure between the mixtures in dry, 1 F-T and 3 F-T conditions. The mean values of the percent adhesive failure in PG-76 mixtures were lower than that of PG-64 mixtures after 1 F-T and 3 F-T cycles. Therefore, mixtures prepared with PG-76 binders are more resistant to moisture damage compared to PG-64. However, in dry conditions, the mean value of the percent adhesive failure for PG-64 remained lower than PG-76 mixtures.

Table 2. Two-way ANOVA on effects of percent adhesive failure (PG 64 Mixture).

Source	DF	SS	MS	F	<i>p</i> -value	Significant
F-T condition	2	435.2517	217.6259	50.66292	< 0.05	Yes
Temperature and ASA	7	47.86365	6.837664	1.591797	0.217265	No
Error	14	60.1379	4.295564			
Total	23	543.2533				

Table 3. Two-way ANOVA on effects of percent adhesive failure (PG 76 Mixture).

Source	DF	SS	MS	F	<i>p</i> -value	Significant
F-T condition	2	41.55308	20.77654	15.12766	< 0.05	Yes
Temperature and ASA	7	18.8185	2.688357	1.957427	0.134913	No
Error	14	19.22779	1.373414			
Total	23	79.59936				

Table 4. t-Test: Paired two sample for means (DTT, Dry).

Dry Mixture	PG-64	PG-76
Mean	2.51	6.7125
Variance	0.796542857	3.032764286
Observations	8	8
Hypothesized Mean Difference		0
DF		7
P(T<=t) two-tail		< 0.05

Table 5. t-Test: Paired two sample for means (DTT, 1 F-T).

1 F-T Mixture	PG-64	PG-76
Mean	7.4075	4.85625
Variance	8.181335714	1.300055357
Observations	8	8
Hypothesized Mean Difference		0
DF		7
P(T<=t) two-tail		< 0.05

Table 6. t-Test: Paired two sample for means (DTT, 3 F-T).

3 F-T Mixture	PG-64	PG-76
Mean	12.935	3.5025
Variance	6.450914286	1.102364286
Observations	8	8
Hypothesized Mean Difference		0
DF		7
P(T<=t) two-tail		< 0.05

3.5 Indirect tensile strength test

The indirect tensile strength test was used as a standard moisture test to evaluate moisture susceptibility of mixtures according to ASTM D4867 [20]. The moisture conditioning procedure for indirect tensile strength test samples was similar to DTT specimens, as described in Section 2.3. Figures 4 and 5 shows the original and transformed ITS test specimens, respectively. These images were captured for the adhesive failure evaluation using imaging technique. It can be observed in Figures 4(a) and 4(c) that most of the broken aggregates were found in the vicinity of ITS load

application. These observations are more visible in the transformed images obtained as shown in Figures 5(a) and (c).

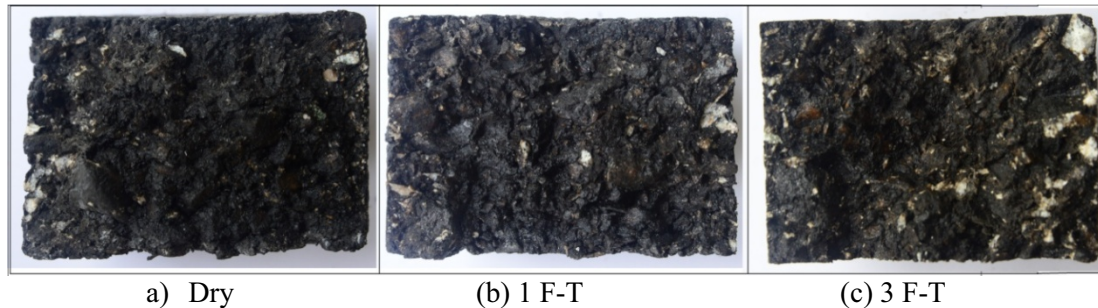


Figure 4. ITS original images of WO150 fractured surfaces.

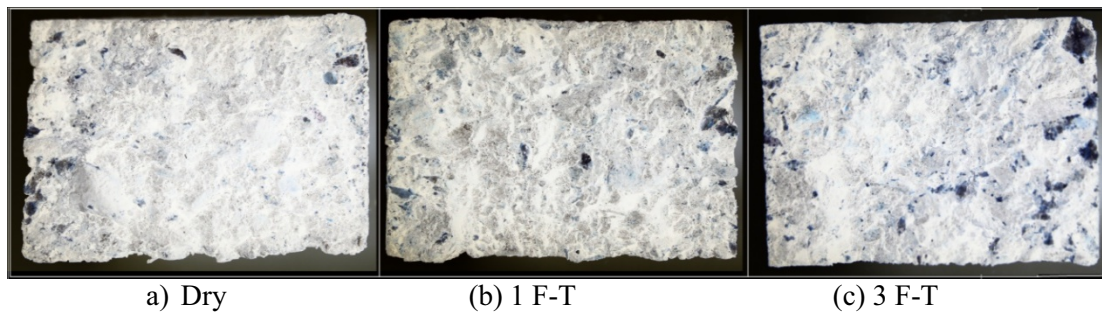


Figure 5. ITS transformed images of WO150 fractured surfaces.

3.6 Effects of moisture conditioning on adhesive failure using ITS

Figure 6 represents the percent adhesive failure quantified using image analysis on the fractured faces of mixtures after being subjected to indirect tensile strength test. The results, shown in Figure 6(a), illustrate that the percent adhesive failure of PG-64 mixture increases with F-T cycles. Mixture HP160 and mix WO120, respectively exhibits the lowest and highest percent adhesive failure. The percent adhesive failure of WMA is higher than HMA. The results further show that the overall percent adhesive failure quantified in ITS specimens are lower compared to the percentage failure obtained in mixtures tested using direct tensile.

Figure 6(b) shows the percent adhesive failure of PG-76 mixtures. The percent adhesive failure increases when the mixtures are exposed to F-T moisture conditioning. The PG-76 mixtures follow similar trends compared to mixtures prepared with PG-64 binder. Similarly, mixture HP160 exhibits the lowest percent adhesive failure, while the highest percent adhesive failure is observed in mixture WO120. The overall percent adhesive failure of PG-64 mixtures is higher than mixtures prepared with PG-76 binders. These results show similar trends compared to DTT results.

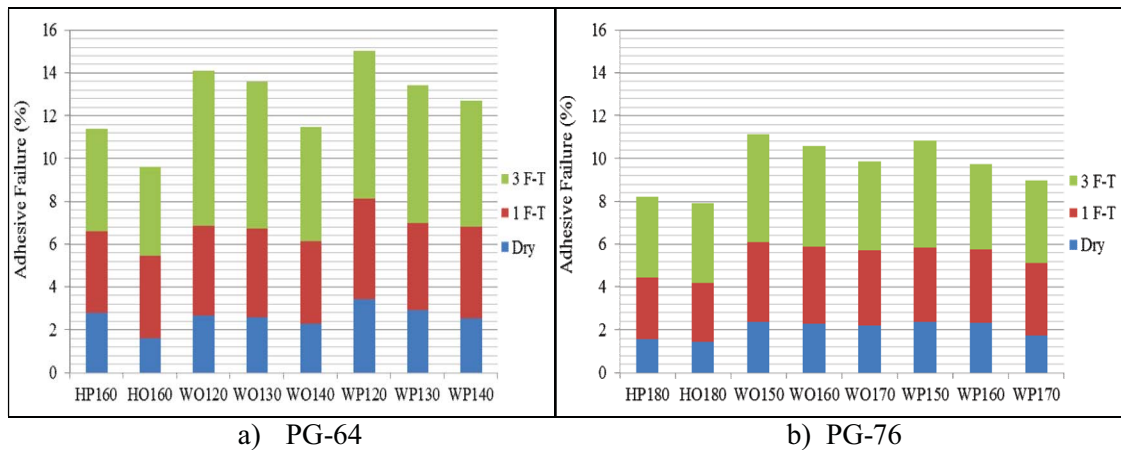


Figure 6. Percent adhesive failure on fractured surfaces of ITS specimens.

3.7 Failures due to broken aggregate using ITS test

Figures 7(a) and (b) presents the percent of broken aggregates on the fractured faces of mixtures tested using indirect tension tests. Similar to the results of DTT specimens, the broken aggregate on the fractured faces were assumed to be caused by fractures developed during the compaction process or due to the indirect tensile force applied on the specimen. The percent broken aggregate failure shows no trends when mixtures were moisture conditioned. However, the comparative result of PG-76 and PG-64 mixtures show the higher failures are observed in the former.

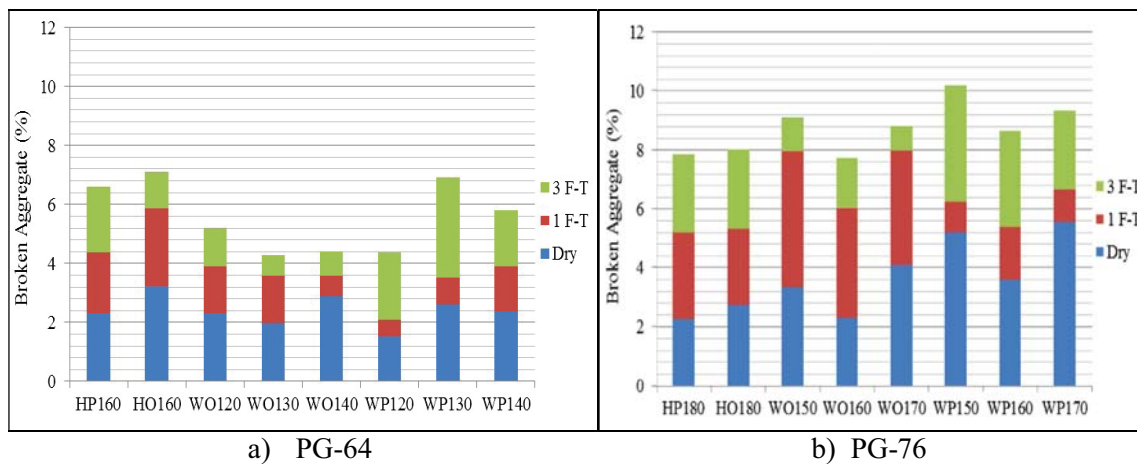


Figure 7. Percent broken aggregate on fractured surfaces of ITS specimens.

3.8 Effects of moisture conditioning on ITS

The indirect tensile strength results of PG-64 and PG-76 mixtures are shown in Figures 8(a) and (b). The results show that the ITS decreases when the samples are subjected to F-T moisture conditioning. HP160 mixture exhibits the highest strength in dry conditions, while the lowest strength is observed for mixture WO120 after being subjected to 3 F-T cycles. Similar trends are observed for mixtures prepared with PG-76 binder. The overall strength of PG-76 mixtures is slightly higher than PG-64 mixtures. This trend is similar with specimens tested for direct tensile strength.

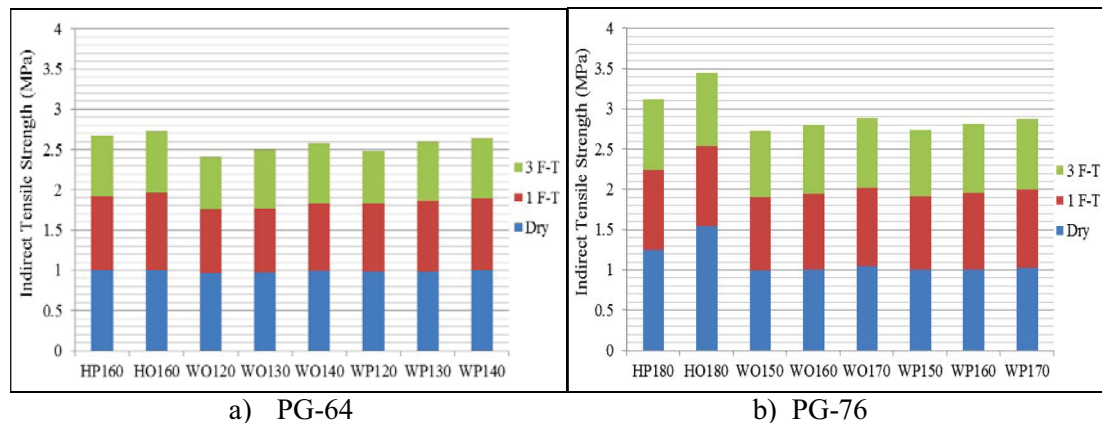


Figure 8. Indirect tensile strength of fractured surfaces.

3.9 Statistical analysis on indirect tensile test results

Tables 7 to 11 show the statistical analysis on the results of the indirect tensile test. A two-way ANOVA at 95% confidence level ($\alpha = 0.05$) was carried out to analyze the effects of the percent adhesive failure. Table 7 shows that F-T conditioning, mixing temperature and ASA on PG-64 mixtures significantly affect the percent adhesive failure. Similarly, Table 8 shows that the F-T conditioning, mixing temperature and ASA on PG-76 mixtures significantly affects the percent adhesive failure.

A paired t-test was carried out to analyze the mean difference between the percent adhesive failures of mixtures tested for ITS. Tables 9 to 11 show a significant difference in the mean values between the mixtures subjected to dry, 1 F-T and 3 F-T conditions. The mean percent adhesive failures of PG-76 mixtures are lower than PG-64 mixtures after dry, 1 F-T and 3 F-T cycles. The results also show that PG-76 mixtures are more resistant to moisture damage compared to PG-64 mixtures.

Table 7. Two-way ANOVA on effect of percent adhesive failure (PG-64 Mixture).

Source	DF	SS	MS	F	<i>p</i> -value	Significant
F-T condition	2	44.99065	22.49533	79.03236	< 0.05	Yes
Temperature and ASA	7	7.179337	1.02562	3.603288	< 0.05	Yes
Error	14	3.984881	0.284634			
Total	23	56.15487				

Table 8. Two-way ANOVA on effect of percent adhesive failure (PG-76 Mixture).

Source	DF	SS	MS	F	<i>p</i> -value	Significant
F-T condition	2	20.26369	10.13184	207.6009	< 0.05	Yes
Temperature and ASA	7	3.348172	0.47831	9.80055	< 0.05	Yes
Error	14	0.683262	0.048804			
Total	23	24.29512				

Table 9. t-Test: Paired two sample for means (ITS, Dry).

Dry Mixture	PG-64	PG-76
Mean	2.596	2.037
Variance	0.28133442	0.158715889
Observations	8	8
Hypothesized Mean Difference		0
DF		7
P(T<=t) two-tail		< 0.05

Table 10. t-Test: Paired two sample for means (ITS, 1 F-T).

1 F-T Mixture	PG-64	PG-76
Mean	4.1259	3.3464
Variance	0.088146462	0.115922518
Observations	8	8
Hypothesized Mean Difference		0
DF		7
P(T<=t) two-tail		< 0.05

Table 11. t-Test: Paired two sample for means (ITS, 3 F-T).

3 F-T Mixture	PG-64	PG-76
Mean	5.9460	4.2775
Variance	1.225407447	0.301280745
Observations	8	8
Hypothesized Mean Difference		0
DF		7
P(T<=t) two-tail		< 0.05

4. Conclusions

The image analysis method employed in this work has proven to be very effective to analyze the deterioration of asphalt mixtures subjected to moisture conditioning. Optical imaging is a simple and economic way to acquire information in the form of images without direct contact (non-destructive type). It is also an area scanning method, capable of instantaneous recording of two-dimensional images of an object, which is very applicable. In this research, a novel method using imaging technique to evaluate moisture damage responsible for stripping in HMA and WMA in terms of adhesive failure quantification. The percent failure due to adhesion showed that PG-76 mixtures exhibited higher resistance to moisture damage compared to PG-64 mixtures. In addition, the adhesive failure increased when the mixtures were subjected to F-T cycles. Because the percent adhesive failure in PG-76 mixture was lower therefore, it facilitated the failure along the cracks that were already induced during compaction. However, PG-64 mixtures exhibited a higher percent adhesive failure, which resulted in lower aggregate breakage. Therefore, the failures due to broken aggregates in the PG-76 mixtures were higher than PG-64 mixtures. The DTS results of PG-64 and PG-76 mixtures showed that a higher percentage failure due to adhesion corresponded to lower DTS of HMA and WMA after F-T cycles. From fractured ITS samples, most of broken aggregates were found located in

the vicinity where the indirect tensile load was applied. On the other hand, high adhesive failure was obtained at the center portion where maximum tensile stresses were developed. The ITS test results showed similar trends as observed for DTT specimens. However, the overall percent adhesive failures were lower compared to DTT results, which showed the effectiveness of the DTT method.

Acknowledgments

The authors would like to acknowledge the Malaysian Ministry of Higher Education through the Fundamental Research Grant Scheme (FRGS grant number 203/PAWAM/6071277) that enabled this paper to be written.

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