Moisture damage evaluation of asphalt-aggregate constituents and warm mix asphalt using imaging techniques and tensile tests

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Abstract. Warm Mix Asphalt (WMA) is more susceptible to adhesive failures at the asphalt-aggregate interface than Hot Mix Asphalt (HMA) due to its lower production temperature. This paper presents an innovative approach to quantify the adhesive failures of asphalt-aggregate constituents and mixtures in direct and indirect tensions, respectively. Advanced imaging techniques were utilized to compute the specimens percentage adhesive failure. A PG-64 bitumen was the conventional binder used. Hydrated Lime (HL) and Pavement Modifier (PMD) were used as anti-stripping fillers, while Evotherm (EV) was incorporated as the surfactant-WMA additive. Three moisture conditioning levels were performed namely; unconditioned, 1 freeze-thaw (F-T) and 3 F-T cycles prior to testing. The specimens percentage adhesive failure increased, while tensile strength reduced with F-T cycle. PMD specimens exhibited slightly lower percentage adhesive failure than HL specimens. The percentage failure further reduced with the incorporation of EV. The effects of incorporating EV were more pronounced when combined with PMD as shown by the higher tensile strength and lower percentage failure than HL-EV. Limestone specimens showed superior moisture resistance than granite in moist condition. The high percentage broken aggregate on the fractured surfaces of tested asphalt mixtures was found to be more related to aggregate orientation than shape.

1. Introduction
The destructive effects of moisture can adversely affect mixture performance and functionality. This is particularly true when granite aggregates are used in the mixture since such siliceous aggregates are known to be hydrophilic. Inadequate drying of aggregates due to the lower production temperature of WMA contributes to adhesive failures at the binder-aggregate interface [1]. Infiltration of moisture into asphalt pavements results in two failure mechanisms, namely adhesive and cohesive failures. Adhesive failure takes place when binder film strips away from the aggregate surfaces, while cohesive failure is caused by softening of the asphalt mastics [2]. The asphalt binder and aggregate bond strength is an important parameter to evaluate the binder ability to resist moisture damage. A test method that can effectively assess the effects of water in both adhesive and cohesive failures in an asphalt-aggregate system can lead to a better comprehension of the mixtures moisture sensitivity [3]. According to Canestrari et al. (2010), a repeatable, reliable and practical method to investigate the adhesive and cohesive properties of asphalt-aggregate systems is based on the Pneumatic Adhesion Tensile Testing Instrument (PATTI) [4]. However, a standard procedure for evaluating moisture damage at the asphalt-aggregate interface is still not available.
This study investigated the adhesive strength of various asphalt constituents and mixtures in relation to its mechanical strength using direct and indirect tensions, respectively. Adhesive failures attributed to moisture conditionings were investigated. Compacted asphalt mixtures were first subjected to indirect tensile strength (ITS) test, followed by examination of the fractured surface using 3-D image analysis. On the other hand, asphalt constituent test specimens were tested using the PATTI test and specimen fractured surface was examined using 2-D image analysis. The 2-D imaging technique used was strictly monoscopic with images of specimens taken from merely one viewpoint. This study attempts to overcome this shortcoming by instead employing the 3-D imaging technique. This gives a more precise quantification of adhesive failure. In Malaysia, qualitative measurement is still carried out based on visual inspection using the naked eye. Such quantification is very subjective in nature and varies with different observers. With the introduction of 3-D imaging technique, it may be incorporated into the Malaysian Public Works Department (PWD) specifications to evaluate stripping if it is made mandatory in the near future. Furthermore, preliminary studies were also carried out to evaluate the effects of aggregate shape and orientation upon mixtures fractured surfaces.

2. Methodology

2.1. Materials

The unmodified PG-64 was the binder type used in this investigation. Granite aggregates used in the preparation of all mixtures were supplied by Kuad Sdn. Bhd. in Penang. Limestone boulders were sourced from Pens Industries Sdn. Bhd., Perlis, for aggregate substrate preparation. The adopted median aggregate gradation was in accordance with the Malaysian PWD gradation limits for asphaltic concrete mixture type AC-14 [5]. All mixtures incorporated Pavement Modifier (PMD) as the filler, while asphalt mastics used PMD and Hydrated Lime (HL). The adopted filler to asphalt ratio was F/A = 1. Hence, base binders were added with the same amount of fillers by mass of binder. PMD is a grayish-black powder mineral filler that has been used as anti-stripping additive for asphalt mixtures. According to Hill et al. (2012), the surfactant-WMA (EV) was added at an optimum dosage rate of 0.5% by mass of PG-64 binder [6].

2.2. Specimen preparation

Asphalt mixtures prepared for this investigation included three conditioning types, four mixing and compaction temperatures and one anti-stripping agent as filler. The specimen dimensions were 100 mm in diameter and 63.5 mm in height. The Servopac Gyratory Compactor which better simulates mixture densification in the field was used to compact specimens to 7±1% air voids. The Marshall mixture design ASTM D1559 [7] procedures conforming to PWD specification [5] for mixture type AC-14, were applied to determine the mixtures optimum binder content. The optimum binder contents of base PG-64 binder were 5.0% and 5.2% for HMA and WMA, respectively. The mixing and compaction temperatures of all asphalt mixtures are listed in table 1. A total of 48 asphalt-aggregate test specimens were also prepared, including three conditioning types, two aggregate and filler types. For preparation of asphalt mastics, binders and fillers were preheated to 160°C prior to blending using the high shear mixer for 30 min.

| Mixture                 | Mixing Temperature (°C) | Compaction Temperature (°C) |
|-------------------------|-------------------------|-----------------------------|
| HMA                     | 160                     | 150                         |
| WMA Control (0% Additive)| 140                     | 130                         |
| WMA (0.5% Additive)     | 120-140                 | 110-130                     |

Table 1. Mixing and compaction temperatures of asphalt mixtures.
2.3. Laboratory moisture conditioning

Moisture conditioning was conducted in accordance with ASTM D4867 [8] procedures. The only modification made was the addition of Sodium Carbonate (Na$_2$CO$_3$) to the distilled water at a concentration of 6.62 gm per liter to accelerate stripping within the asphalt specimens [9]. Investigation was carried out on three sets of specimens; unconditioned, 1 freeze-thaw (1 F-T) cycle and 3 F-T cycles. Prior to heating the asphalt mastics and aggregates for specimen preparation, silicon cuts as shown in figure 1 were glued to the substrate surface. The use of silicon cut provided lateral confinement to the asphalt mastics during preparation and thawing at 60°C. Moisture conditioned specimens were placed in water inside the ALVS chamber for 30 min at 35°C prior to F-T cycle.

![Figure 1. Silicon cuts.](image)

Figures 2(a) and (b) show the asphalt binder and mastics specimens, respectively after exposure to F-T cycle. An interesting observation pertaining to the moisture-damage mechanism was made in this study where moisture penetrated into the asphalt-aggregate interface via holes on the asphalt film. The generated holes started from the top, open surface of asphalt specimens during conditioning at 60°C in a submerged water condition. The holes were observed to be cylindrical and randomly distributed. The holes became visible within approximately 2 h after conditioning and the holes diameters varied from microscopic to more than 1 mm. The holes eventually reached the bottom of asphalt film. After reaching the interface through holes, moisture started to replace the asphalt film from the substrate surface, and adhesive failure or stripping began to take place. The process started with dewetting of asphalt film from substrate, followed by spreading of moisture on the substrate. Figure 2 also shows that more holes were developed on the binder specimen compared to asphalt mastics.

![Figure 2. Formation of holes on asphalt-aggregate specimens after moisture conditioning.](image)

2.4. Test methods

The Indirect Tensile Strength (ITS) test was employed to evaluate mixtures moisture susceptibility according to ASTM D4867 [8] procedures. Test temperature for all mixtures was set at 15°C. Such a low temperature stiffened the specimens and easily disintegrated when tested until failure [10]. The PATTI with modified pull stub as shown in figure 3 was used to record the maximum tensile stress required to separate the asphalt mastics from aggregate substrate. The asphalt film thickness is the
space between the pull-off stub and aggregate surface, in this case equivalent to 0.8 mm. Failure within specimen occurred once tensile strength exceeded the bond strength at the pull-off stub and substrate interface, or the asphalt mastics cohesive strength.

![Figure 3. PATTI instrument with modified stub [11].](image)

3. Imaging technique

Images of specimen fractured surfaces were taken after the test for image analysis. Imaging technique in 3-D was used to compute the percentages of adhesive failure and broken aggregates of asphalt mixtures, while 2-D imaging technique was carried out on fractured surfaces of asphalt constituent test specimens.

Imaging technique in 3-D was introduced to more precisely quantify the amount of binder stripping from the aggregate surfaces. Prior to 3-D image analysis, ordinary 2-D photos had to be first captured, merged and converted to a 3-D model using the 123-D Catch software. Autodesk 123-D Catch software was used to merge the ordinary 2-D images into a 3-D model. A minimum of 20 photos were captured for each specimen at various angles from the horizontal axis. Figure 4 shows the transformation of 2-D images, taken at different angles, into a 3-D model. The final assembled 3-D models were then saved and exported into CloudCompare for 3-D image analysis.

![Figure 4. Conversion of ordinary 2-D images into a 3-D model.](image)

Figure 5(a) demonstrates one of the 3-D models imported from 123-D Catch. Prior to analysis, this model had to be first cropped or segmented, leaving only the fractured surface of specimen as depicted in figure 5(b). This model was then converted to scalar fields for statistical computations. Similar to 2-D image analysis, the multidimensional domain of the model, in red, green and blue (RGB) was reduced to lower dimensions, consisting of only one or two component axes. Conversion
to grayscales yielded models with merely one band or intensity. Binder covered areas were represented by low gray values, while higher intensities were associated with stripped and broken aggregate surfaces. Figures 6(a) and (b) show the conversion of the segmented fractured surface of the original 3-D model into grayscales. Classification of 2-D images and 3-D models was carried out by means of thresholding. The number of classes used in this software was by default, 255. Threshold range values for stripped and broken aggregate surfaces were obtained via the trial and error method by narrowing the number of classes between 0 and 255. Figure 6(c) shows the classification of the model into stripped and broken aggregate areas. Figure 7 shows the original images of PG-64 asphalt mastics over granite aggregate substrate taken after testing specimens using PATTI test in 3 F-T condition. These images were analyzed using the Earth Resource Development Assessment System (ERDAS) software. Figure 8 presents the classified images that clearly show the adhesive failure over aggregate substrate. The statistical tool included in this software will conveniently display the amount of pixels that corresponded to each of the threshold range value selected. These values were then used to quantify the percentages adhesive failure and broken aggregates.

Figure 5. A 3-D model imported from 123-D catch.

Figure 6. Classification of the segmented fractured surface of 3-D model.

Figure 7. Original images of PG-64 asphalt mastics on granite substrates after 3 F-T cycles.
4. Studies on broken aggregates
All tested ITS test specimens were preheated in the oven at 80°C for two hours. Broken aggregates observed on the specimen fractured surfaces were extracted. Each tested ITS test specimen consisted of two broken parts with symmetrical fractured surfaces. Photographs of broken aggregate orientation were immediately taken to measure the orientation angle between aggregate longitudinal axis and fractured plane. The ImageJ software was utilized for this purpose. Only aggregates with orientation angle equal to or less than 80° were regarded as having orientation issues. Figure 9 shows the schematic diagram of broken aggregate orientation with respect to fractured plane. All extracted aggregates were stored in individual plastic bags and left to cool at room temperature. The aggregates were glued together and weighed to obtain the total extracted aggregate mass. Aggregate shape was examined using the proportional calliper according to ASTM D4791 [12] procedures. The mass and percentage of elongated and flat aggregates were determined.

5. Results and discussion
The image analysis results are used to determine the amount of pixels that corresponds to the total fractured surface, stripped and broken aggregate areas. For computation of results, failures attributed to adhesion and broken aggregates are expressed in percentage, while ITS is in MPa. The pull-off strength of PATTI test is expressed in kPa.

5.1. Effects of moisture conditioning on asphalt mastics adhesive failure
Figure 10(a) shows the percentage adhesive failure of unconditioned and conditioned asphalt mastics on granite and limestone substrates using the pull-off tensile test. In unconditioned state, there is no clear relationship in terms of percentage adhesive failure between specimens of different aggregate types, filler types and EV contents. The aggregate type shows insignificant effects on percentage adhesive failure of unconditioned specimens. In addition, cohesive failure is generally observed in tested unconditioned specimens. In the absence of water, the asphalt-aggregate adhesive bond is higher than the asphalt film inner cohesion. From figure 10(a), the percentage adhesive failure of all PG-64 specimens escalates after 1 F-T cycle, regardless of EV content, aggregate and filler types. The highest percentage failure after 1 F-T cycle is recorded by HL-Control with 29.0% adhesive failure, followed by PMD Control with 24.2%. The corresponding HL and PMD specimens incorporating
0.5% EV exhibit lower percentage adhesive failure than control specimens. This implicates the beneficial effects of adding EV to further enhance the stripping resistance of WMA specimens when subjected to severe moisture conditionings.

Similar trend is also found in specimens using limestone aggregate where specimens added with WMA additive demonstrate lower percentage adhesive failure than control specimens. The lowest percentage failure is shown by PMD-EV with only 18.0% failure, followed by HL-EV with 20.5% failure. After 3 F-T cycles, the highest failure is still recorded by HL-Control, followed by HL-EV, PMD-Control and the lowest by PMD-EV. Specimen HL-Control registers 47.6% and 44.8% failures using granite and limestone substrates, respectively. Specimens incorporating EV still exhibit lower percentage adhesive failure than the corresponding control specimens after 3 F-T cycles. However, when comparing between filler types, asphalt mastics using PMD exhibit higher resistance to moisture damage than HL shown by the lower percentage adhesive failure. In addition, the effects of using EV are more significant when used in combination with PMD. This is evidenced from the lower percentage adhesive failure of PMD-EV specimens compared to HL-EV. Limestone specimens exhibit lower percentage adhesive failure after moisture conditionings compared to specimens using granite aggregate. These findings are in agreement with Kanitpong and Bahia (2005) [13].

5.2. Effects of moisture conditioning on asphalt mastics bond strength

Figure 10(b) shows the pull-off strength of PG-64 mastics using both aggregate types. The results show no obvious trend in terms of dry specimen bond strength using different aggregate and filler types. The pull-off strength of PG-64 specimens reduces more significantly after 3 F-T cycles than after 1 F-T cycle. Specimens using PMD exhibit slightly higher pull-off strength than HL specimens after moisture conditionings. Moreover, the effects of incorporating EV are more significant when used in conjunction with PMD, as shown by the higher strength in PMD-EV than HL-EV. Specimens incorporating EV demonstrate higher pull-off strength compared to control specimens, regardless of filler type. After 3 F-T cycles, the PMD-EV and HL-EV specimens exhibit the highest strength values. Similarly, limestone which has better affinity towards conditioned asphalt mastics shows higher pull-off strength than specimens using granite aggregate. The percentage adhesive failure results described in Section 5.1 show that adhesive failure increases with increasing freeze-thaw cycle. Hence, the specimen pull-off strength is inversely proportional to the percentage adhesive failure in moist conditions.

5.3. Effects of moisture conditioning on mixture indirect tensile strength

Figure 11(a) shows the ITS test results of PG-64 mixtures. The ITS of all mixtures decreases with F-T cycle. The reduction in ITS is more significant after 3 F-T cycles compared to after 1 F-T cycle and in
dry condition. The ITS of all WMA is found to be lower than HMA, regardless of conditioning level. This implicates the higher moisture damage susceptibility of WMA due to their lower production temperatures. When comparing all WMA, WMA with 0% additive exhibits the lowest ITS. This finding can again be substantiated by the absence of warm mix additive to help improve its adhesive strength. Similar to the PATTI test results, the ITS is also found to be inversely proportional to percentage adhesive failure. This finding is also in agreement with Hamzah et al. (2014) [14]. From figure 11(b), almost all PG-64 mixtures meet the minimum 80% indirect tensile strength ratio (ITSR) limit except for WMA produced at the lowest mixing temperature of 120°C after 1 F-T cycle. After 3 F-T cycles, all PG-64 mixtures including HMA fail the test.

![Figure 11](image1.png)

(a) ITS  (b) ITSR

Figure 11. ITS results of fractured specimens (quantitative measurement).

5.4. Effects of moisture conditioning on mixture adhesive failure

Figure 12(a) represents the percentage adhesive failure of PG-64 mixtures, quantified using 3-D imaging technique. The percentage adhesive failure escalates with the number of F-T cycles. The percentage adhesive failure of dry specimens for all PG-64 mixtures, produced at different mixing temperatures, is similar. However, WMA prepared at 140°C with 0% additive, 130°C and 120°C, exhibit the highest failure with respect to adhesion after 1 F-T cycle. This may be attributed to the effects of lower production temperature, resulting in WMA more susceptible to adhesive failure due to water infiltration.

![Figure 12](image2.png)

(a) Adhesive failure  (b) Broken aggregates

Figure 12. Percentage failure results of fractured surfaces (quantitative measurement).

As for WMA with 0% additive (WMA Control), this may be caused by the absence of warm mix additive to further enhance the mixture adhesive properties. The WMA (with additive) produced at 140°C shows comparable performance with HMA even after exposure to 1 F-T cycle. After 3 F-T
cycles, the percentage adhesive failure of HMA using PG-64 binder is still lower than the corresponding WMA produced at different mixing temperatures. As for WMA, the percentage adhesive failure is relatively equivalent to one another after 3 F-T cycles.

5.5. Shape and orientation analysis on broken aggregates

Figure 12(b) shows the percentage broken aggregate quantified using 3-D imaging technique. These broken aggregates are assumed to be caused by fractures during compaction or due to the indirect tensile force applied onto the specimen. The percentage broken aggregate failures show no obvious trends when mixtures were moisture conditioned. From the investigation carried out in Section 4, the high percentage broken aggregate in tested specimens is found to be more related to aggregate orientation rather than shape. Aggregates with orientation angles equal to or less than 80° account for more than 90% of the total extracted aggregate mass, while elongated and flat aggregates represent more than 40% of the total mass. Aggregates with orientation issue are subjected to flexures or bending stresses during testing and may break easily. In addition, elongated and flat aggregates are less desirable as they could affect pavement durability.

6. Conclusions

The percentage adhesive failure of asphalt-aggregate test specimens escalated, while pull-off strength reduced with F-T cycle. Specimens incorporating PMD exhibited higher moisture resistance than HL specimens. Incorporation of EV further reduced the percentage adhesive failure of all specimens. Limestone which showed better affinity towards asphalt mastics in moist condition exhibited lower percentage adhesive failure than granite specimens. The use of 3-D imaging technique was necessary for a more precise quantification of adhesive failure. The mixture ITS reduced with the number of F-T cycles. The asphalt constituent and mixture test specimens incorporating EV exhibited comparable, if not better, moisture resistance than the control specimen. The high percentage broken aggregate in tested specimens was found to be more related to aggregate orientation rather than shape.

7. References

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