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A Comparative Study of Anti-Stripping Additives in Porous Asphalt Mixtures

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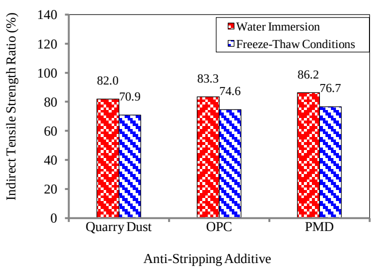
Graphical abstract



Abstract

Presence of water in porous asphalt mixtures detrimentally affected the bonding between binder-aggregate interface and cohesive failure within the binder-filler mastic, making them prone to stripping which contribute to the performance and durability. This paper presents the effect of anti-stripping additives in porous asphalt mixes. In this study, the Marshall specimens were prepared using quarry dust, ordinary Portland Cement (OPC) and Pavement Modifier (PMD) as filler then mixed with 60/70 penetration grade bitumen. The specimens were measured for air voids content and coefficient of permeability and subsequently tested using indirect tensile and Cantabro tests. The moisture sensitivity of porous asphalt was determined based on the ratio of dry and conditioned specimens according to AASHTO T283. The specimens prepared with PMD showed lower air voids content, hence decrease the permeability to give a higher tensile strength and lower abrasion loss compared to specimens prepared with OPC and quarry dust. Based on the results, the PMD filler has a great potential to improve resistance to moisture damage compared to mixes with OPC and specimens prepared with quarry dust fillers.

Keywords: Porous asphalt; stripping; anti-stripping additive; moisture sensitivity; adhesion

1.0 INTRODUCTION

Porous asphalt (PA) is an environmental friendly road material predominantly made up coarse aggregates resulting in an air void exceeding 20%. The interconnected micro voids are created due to higher proportions of coarse aggregates and lower fines content, which allow water to drain quickly through its porous structure. The mix is able to prevent aquaplaning during rainy day thus improves driver visibility, reduces the impact of tire on road pavement and consequently reduces traffic noise [1].

PA has been used extensively worldwide especially in European countries such as Spain, Switzerland, Belgium, Holland, the United Kingdom and the others beside some states in the United States, Japan and Singapore [2]. Mao *et al*., [3] mentioned that 90% of highways in the Netherlands is made of PA. The quest for comfortable driving experience, traffic noise reduction and improving road safety encourage the wide application of PA on road surfaces. In Malaysia, PA was first tried on the Cheras-Beranang Road in 1991. PA is able to reduce traffic accidents and promote road safety, especially during wet weather [4]. In tropical countries like Malaysia, frequent heavy rainfall exposed the PA structures to water induced damages. Increased air voids had exposed pore structure to running water that eroded the binder film, washing the particles and eventually affecting mix properties [5]. Moisture damage is defined as loss of strength or durability in an asphalt mixture due to the effects of moisture measured by the loss of mechanical properties and the strength of aggregate-bitumen bonding [1]. Zeng and Ksaibati [6] found that moisture caused damages to asphalt mixture, weakening the bond between the asphalt and aggregate and consequently enhanced premature deterioration of asphalt pavement.

Nevertheless, the open structure of porous asphalt adversely affects its durability due to high surface area exposed to air and water. The faster oxidation and binder embrittlement of PA compared to the conventional mixes lead to ravelling under traffic shearing stresses, making it rough and undulate [7]. Huber [8], stressed that PA pavements typically failed by ravelling and disintegration when the asphalt binder aged and became brittle. In turn, aggregate particles are dislodged and pavement experience ravels. As reported by Aman *et al*., [9], stripping is the process that results in separation of asphalt binder and aggregate due to the loss of adhesion at the interface of these materials in the presence of water or water vapour, while ravelling is a distress manifestation that is indentified by the dislodgment of aggregate particles from the surface of the mixture. Watson *et al*., [10] recommended the Cantabro test as a standard mix design procedure to indicate mixture resistance to wear or stone loss in an abrasive environment. According to Hamzah *et al*., [11], the Cantabro test is a special test for porous asphalt to evaluate its resistance to particle loss by abrasion and impact forces.

Furthermore, it is used as an important parameter to evaluate bonding properties between aggregate and bitumen.

Aman and Hamzah [1], Aman *et al*., [12], Huang *et al*., [13] and Jahromi [14] had studied the effectiveness of hydrated lime in reducing the moisture-induced damage of the asphalt mixture. The result indicated that specimen incorporated with hydrated lime has effectively reduced moisture damage. This was due to hydrated lime consist of carboxylic acid chemical components absorbed on the aggregate surface in high concentration further enhanced interfacial bonding between aggregate and binder in asphalt mixtures. Further study had been conducted by Aman *et al*., [9] to evaluate the effectiveness of anti-stripping additives namely Ordinary Portland Cement (OPC) and a newly developed anti-stripping agent known as Pavement Modifier (PMD). In their study, specimens incorporating PMD exhibited higher Indirect Tensile Strength (ITS) and better resistance to water sensitivity compared to specimens containing OPC. Furthermore, Aman *et al*., [15] mentioned that PMD containing calcium oxide increases the interaction between the aggregate surface and the bitumen binder improve bonding between the bitumen and the aggregate compared to the hydrated lime containing calcium carbonate. Modified Lottman test [16] was used to evaluate the moisture sensitivity of asphalt concrete mixture.The main purpose of this study was to evaluate the effects of quarry dust, Ordinary Portland Cement (OPC) and a newly developed anti-stripping agent known as Pavement Modifier (PMD) on porous asphalt mixtures. The porous specimens were evaluated on air voids content, indirect tensile test (ITS) and coefficient of permeability PA specimens. The resistance to moisture damage was determined by comparing the ITS of specimens subjected to wet conditions and those tested dry.

2.0 EXPERIMENTAL

2.1 Materials

The crushed granite aggregate produced by Hanson Quarry Sdn. Bhd. Minyak Beku, Batu Pahat was washed, dried and sieved into a selected range of size according to the Standard Specification for Porous Asphalt [17]. Two anti-stripping agents, namely Ordinary Portland Cement (OPC) and a newly developed anti-stripping agent known as Pavement Modifier (PMD) as well as quarry dust, which passing 75 µm were used as mineral filler with specific gravity 2.40 g/cm^3, 2.03 g/cm^3, and 2.80 g/cm^3, respectively. PMD is grayish-black powder was appreciable soluble in water that odourless to slight earthy odour. The modifier composed of Calcium Oxide, C_aO which mainly came in two forms which are Calcium Carbonate (C_aCO_3) and Calcium Hydroxide ($C_a(OH)_2$). Other important components are Silica, (SiO_2) and Magnesium Oxide, (MgO), respectively. A conventional 60/70 bitumen grade was obtained from the Shell Ltd., while the PMD was supplied by NSL Chemicals Sdn Bhd., Ipoh, Malaysia. The results of physical properties of aggregates are shown in Table1. In this study, porous asphalt mix design was prepared with 2% of anti-stripping additives by mass of total aggregates as a part of mineral filler as recommended by PWD [17]. The selected acceptable final combined aggregate gradation is shown in Table 2.

Table 1 Physical properties of crushed granite aggregates

Test Properties	Standard	PWD Requirement	Test results (%)
Flakiness index	BS 812-105.1:1989	Less than 25%	23.1
Aggregate impact value	BS 812-112:1990	Less than 25%	21.9

Table 2 Combined aggregate gradation

Sieve size, mm	14	10	5	2.36	0.075
Percent Passing	100	92.5	17.5	7.5	3

2.2 Binder Content and Asphalt Mixture Design

The mixing and compaction temperatures were determined basedon binder viscosity. The binder viscosity wastested using a Brookfield Rotational Viscometer and conducted according to ASTM D4402 [18] procedures. The Asphalt Institute [19], recommended that the ideal laboratory mixing and compaction temperatures for asphalt mixtures and other hot-mix type using conventional binder are the temperatures at which the binder achieves a viscosity 0.17 ± 0.02 Pa.s and 0.28 ± 0.03 Pa.s, respectively. According to Yildrim *et al*., [20], the viscosities equivalent to 0.275 ± 0.03 Pa.s and 0.550 ± 0.06 Pa.s, respectively, have been used to determine the ideal mixing and compaction temperatures for asphalt mixes using a modified binder.Based on the said criteria, the required mixing and compaction temperatures for bitumen grade 60/70 were 160°C and 150°C, respectively. Subsequently, the design binder content of the porous asphalt mix used was the average of an upper and a lower limit. The upper limit was determined from the binder drainage test based on the British Transport Research Laboratory (TRRL) as described by Daines [21], while the lower limit was determined from the Cantabro test results according to the earlier procedures described by Jimenez and Perez, [22]. The binder content test results obtained represent the lower and upper limit are 4.3% and 5.1%, respectively. Therefore, the 4.7% binder content of the asphalt mixture was used in this investigation.

2.3 Samples Preparation

Bitumen and aggregates were pre-heated for 4 hours in an oven at 160°C. Each specimen was made up of about 1100 g of aggregate batches in addition to asphalt binder. The asphalt mixes were prepared at 4.7% binder content and were blended at their corresponding mixing temperatures. The aggregates and asphalt binder were blended, at their corresponding mixing temperatures. According to the Asphalt Institute [19] procedure, the loose mixes were conditioned in an oven for 2 hours at the compaction temperature to allow the asphalt binder absorption to take place. Then, specimens were compacted in the standard Marshall moulds at 50 blows per face and left to cool down overnight at ambient temperature prior to extrusion.

2.4 Laboratory Tests Procedure

2.4.1 Air Voids

One of the primary functions of PA mixture is to drain surface water through the pavement structure instead of crossing the pavement surface. Hence PA mixes need to provide adequate void structure for satisfactory water drainage [23]. For this study, an air voids analysis was conducted by using CoreLok vacuum-sealing and dimensional methods [24]. The bulk gravity of compacted specimens was evaluated using the CoreLok vacuum-sealing method according to ASTM D3023 [25] procedure. The theoretical maximum density (G_{mm}) of the loose mix was carried out according to the ASTM D2041 [26] procedure. The air voids in the compacted specimens were calculated using Equation (1), derived from ASTM 3203 [25] procedure.

$$Va = 100x\left(1 - \frac{G_{mb}}{G_{mm}}\right) \quad (1)$$

Where:

Va = The air void

G_{mb} = The bulk specific gravity of the compacted specimen

G_{mm} = The theoretical maximum density

2.4.2 Cantabro Test

The resistance to particle losses was analyzed using a Los Angeles abrasion to drum without charge of steel balls and rotated 300 times at 30 rpmand 25ºC. This test was carried out to assess the cohesiveness of the Porous Asphalt mixes. The PA specimens were conditioned in an incubator at a pre-selected temperature for 4 hours before being tested. The test result was expressed as percentage of the weight loss relative to the initial weight, indicating the cohesive properties of the mix. The test method adopted following the procedures described by Jimenez and Perez [22].The percentage of each abrasion loss was calculated based on Equation (2).

$$P = 100x\left(\frac{P_1 - P_2}{P_1}\right) \quad (2)$$

Where:

P = The abrasion loss (%)

P1 = The mass before test (g)

P2 = The mass after test (g)

2.4.3 Coefficient of Permeability

The permeability or hydraulic conductivity of PA mixes was always linked to their ability to conduct water and it is undoubtedly one of the most significant parameters to be taken into account. The coefficient of permeability was examined by using test method adopted from Fwa *et al*., [27] and Cooley *et al.*, [28]. The hydraulic conductivity equipment was fabricated from a cylindrical Perspex tube glued to a thick Perspex base. Water was poured into the Perspex tube and allowed to permeate through the specimen. In this test, a transparent cylindrical tube in which the time for a falling head of water between fixed distances along the tube is measured by a stop watch was recorded [29]. The permeability of the porous specimen can be estimated when a hydraulic gradient is created across the porous specimen. The coefficient of permeability, k will be computed from Equation (3).

$$k = 2.3\left(\frac{aL}{At}\right)\log\left(\frac{h_1}{h_2}\right) \quad (3)$$

Where:

k = The coefficient of permeability (cm/s)

a = The tube cross sectional area (cm2)

A = Specimen cross sectional area (cm)

L = Height of specimen (cm)

t = Time (s)

h1 and h2 = Initial water level at t1 (cm) and final water level at t2 (cm)

2.4.4 Moisture Sensitivity of Porous Asphalt

The testing procedure described herein followed the AASHTO T283 [30] procedures for the determination of water sensitivity of bituminous mixtures. Two subset compacted specimens were prepared for subsequent conditioning and the un-conditioning procedures. The conditioned specimens were applied with pressure vacuum at 6.7 kPa for 10 minutes and the specimens were submerged for another 10 minutes in a water bath, while a same number of specimens were left at 25°C in an incubator for a similar period of time. To determine the effect of the freeze–thaw cycle, the specimens were wrapped with leak proof plastic bags containing 10 ml of distilled water. The plastic bag were placed in a freezer at −18°C for 16 hours, followed by immersion of the specimens in a water bath at 60°C for 24 hours. Upon subjected to wet conditioning, the specimens were pre-conditioned at 25°C in a water bath for four hours before testing for indirect tensile strength according to the ASTM D4123 [31] procedures. The ITS was calculated using Equation (4).

$$ITS = \frac{2000F}{\pi hd} \quad (4)$$

Where:

ITS = Indirect Tensile Strength (kPa)

F = Maximum applied load (N)

h = Specimen thickness (mm)

d = Specimen diameter (mm)

The ITS was also used to evaluate the resistance of the mix to the effects of water, calculated from the ratio of the ITS of moisture-conditioned samples to the ITS of unconditioned samples. Resistance to moisture sensitivity was assessed based on the ITS ratio (ITSR), calculated using Equation (5).

$$\text{ITS Ratio} = \left(\frac{ITS_{wet}}{ITS_{Dry}}\right) x\ (100) \quad (5)$$

Where:

ITS Ratio = The indirect tensile strength ratio (%)

ITS_{Wet}= The average ITS of the wet group (kPa)

ITS_{Dry}= The average ITS of the dry group (kPa)

The laboratory test results of this study were statistically analyzed by using analysis of variance (ANOVA) to determine if the effect of factors were statistically significant at 5% significant level.

3.0 RESULT AND DISCUSSION

3.1 Effect of Anti-Stripping Additives on Bulk Specific Gravity

The bulk specific gravity results of the compacted specimens (G_{mb}) for the porous asphalt incorporating anti-stripping additives are shown in Figure 1. The results indicate that the specimens (G_{mb}) incorporating quarry dust exhibit higher bulk specific gravity compared to Ordinary Portland Cement (OPC) and pavement modifier (PMD) fillers. The individual bar chart shows that the average G_{mb} of the compacted specimens containing quarry dust, OPC and PMD were 1.970 g/cm^3, 1.860 g/cm^3 and 1.840 g/cm^3, respectively. Based on the results, by incorporating 2% of OPC and PMD, the G_{mb} for porous asphalt compacted specimens decreases by 5.6% and 6.1%, correspondingly. According to Aman, [12], PMD contains chemical compounds that reacted with the mixes to increase the aggregate-bitumen bonding and improved the wetting condition compared to OPC and dust quarry, and lead to an increase in densification of the mix and thus resulting higher densities.

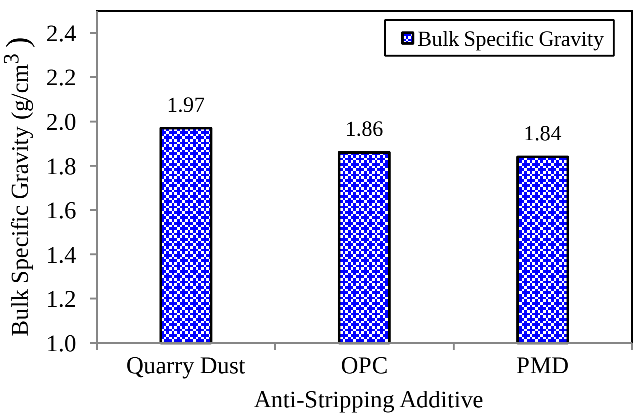


Figure 1 Comparison of bulk specific gravity for compacted mixes

3.2 Effect of Anti-Stripping Additives on Air Voids and Indirect Tensile Strength

Sufficient air voids are indispensable to ensure the drainage capacity of porous asphalt. Figure 2 shows the graphical plot of PA specimens incorporating anti-stripping additives tested for air voids and indirect tensile strength. Based on the result, it can be seen that the porous specimens incorporating PMD exhibit higher Indirect Tensile Strength (ITS) value compared to the specimens prepared with OPC and quarry dust fillers. The result shows an increasing trend of the ITS values as air voids decreasing.

According to Kandhal and Mallick [32], the minimum air void content for porous asphalt is 20% compared to 18% based on Malaysia Public Work Department (PWD) [17] specification. Thus, the specimens of air voids are conforming to the minimum requirement. By incorporating PMD and OPC, the air voids correspondingly decrease by 8.2% and 4.7%, resulting in the increase of ITS by 8.9% and 7.9%, respectively. According to Aman [5], specific gravities of PMD and OPC were 2.032 g/cm^3 and 3.140 g/cm^3, respectively. A high quantity of PMD fills up the interstices and provides contact points between larger aggregate particles when mixed with asphalt binder, consequently reducing the air voids. Thus, enhance the bitumen-aggregate coating resulted in increasing the ITS values [33].

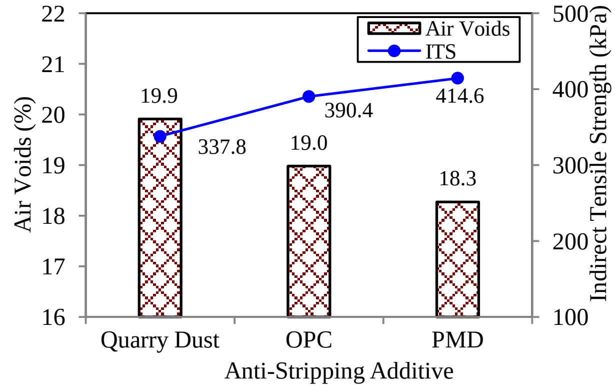


Figure 2 Effect of air voids on ITS for dry PA mixtures

Further analysis was performed on PA specimens incorporating PMD, OPC and quarry dust fillers using a one-way ANOVA to determine the effects of air voids on ITS at 95% confidence level ($\alpha = 0.05$). Table 3 shows that air voids have a significant effect on increasing the ITS value with *p*-value less than 0.05.

Table 3 One-way ANOVA effect air voids on ITS

Source	DF	SS	MS	F	*p*-value
Air Voids	6	2141.28	356.88	44.15	0.022
Error	2	16.17	8.08		
Total	8	2157.45			
R-Sq = 99.25% R-Sq(adj) = 97.00%					

3.3 Effect of Anti-Stripping Additives and Air Voids on Abrasion Loss

Figure 3 shows the abrasion loss decreases as the air voids decrease. The abrasion loss of specimens incorporating PMD is 14.8%, the lowest compared to specimens prepared with OPC and quarry dust where the air voids are 18.7% and 22.6%, respectively. It can be observed that the abrasion loss for specimens prepared with a PMD filler decreased by 34.5% compared to the 17.3% when prepared with OPC. As reported by Hamzah *et al*., [11], PMD particles absorbed polar components of the bitumen, reacted with aggregate properties that added considerable strength to the mixture. Hence, resistance to disintegration had increased. According to Watson *et al*., [10] recommendations, the abrasion loss of PA mixes should not exceed 20% of unaged specimens when conducted at 25°C. Unfortunately, high abrasion loss reduces the resistance of porous mixes to disintegration. Therefore, mixes with PMD filler exhibits better resistance to abrasion loss compared to mixes incorporating quarry dust fillers.

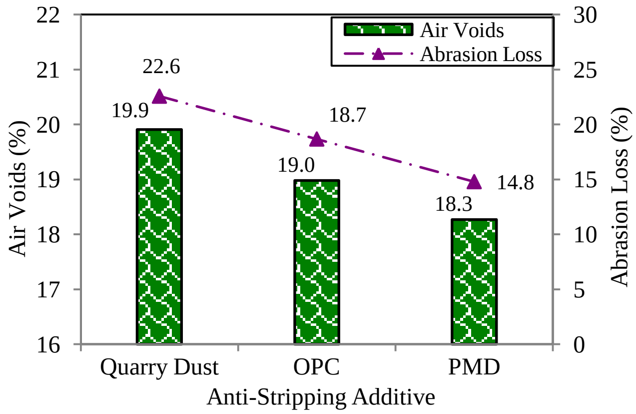


Figure 3 Air voids effect on dry abrasion loss

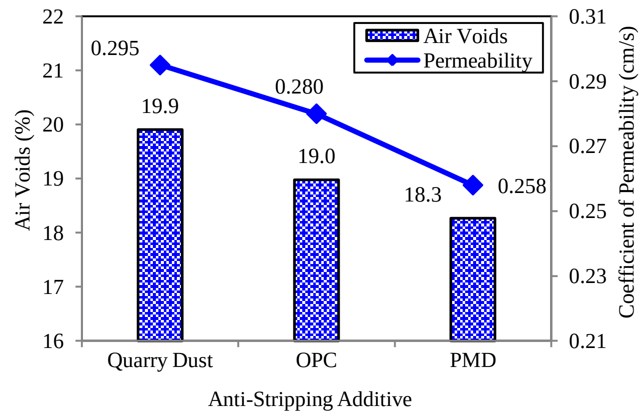


Figure 4 Result of air voids on coefficient of permeability

The experimental data obtained were analyzed using One-way Analysis of variance (ANOVA), the specimens incorporating quarry dust, OPC and PMD fillers at 95% confidence level ($\alpha = 0.05$). Table 4 shows that air voids have a significant effect on abrasion loss value with *p*-value less than 0.05.

Table 4 One-way ANOVA effect air voids on abrasion loss

Source	DF	SS	MS	F	*p*-value
Air voids	6	93.163	15.527	71.81	0.014
Error	2	0.432	0.216		
Total	8	93.596			
R-Sq = 99.54% R-Sq(adj) = 98.15%					

3.4 Effect of Anti-Stripping Additives and Air Voids on Coefficient of Permeability

Figure 4 shows the effects of air voids on coefficient of permeability (*k*) for specimens incorporating quarry dust, OPC and PMD fillers. The bar chart indicates that the *k* value decreases as the air voids decrease. It can be seen that the air voids and *k* values consistently lower for specimens prepared with PMD compared to those specimens prepared with OPC and quarry dust. The slope of the line also shows a general tendency for *k* to decrease at a higher rate as the air voids decrease.

Figure 4 shows by incorporating OPC and PMD, the *k* values increase by 3.0% and 12.5%, respectively. The PMD filler clearly shows a potential to reduce the air voids. Clearly, specimens incorporating PMD exhibits lower permeability compared to those OPC and quarry dust. As reported by Aman *et al*., [1], Liu and Cao [34], the *k* values of PA mix is controlled by the shape and size distribution of aggregates which form the air voids that influence the drainage efficiency of porous asphalt. Mallick et al., [35] recommended a minimum *k* value for porous asphalt at least 0.116 cm/s to provide effective drainage. All mixes in the study exhibit higher *k* values than the recommended minimum value.

Table 5 summarizes the correlation among anti-stripping additive type used, increment of air voids, and increasing values of k in the PA mix. The results analyzed using statistical analysis show that the correlation between anti-stripping additives, air voids and coefficient of permeability resulted in increasing of *k* values are 0.978, 0.977, and 0.970, respectively. It can be seen that the anti-stripping additives, air voids and coefficient of permeability have a significant correlation with *p*-value less than 0.05.

Table 5 Correlation between air voids and anti-stripping on the increment of *k*

		Anti stripping Additive	Air Voids	Coefficient of Permeability (*k*)
Anti stripping Additive	Pearson Correlation	1	-.978	-.977
	Sig. (2-tailed)		0.001	0.001
	N	9	9	9
Air Voids	Pearson Correlation	-.978	1	.970
	Sig. (2-tailed)	0.001		0.001
	N	9	9	9
Coefficient of Permeability (*k*)	Pearson Correlation	-.977	.970	1
	Sig. (2-tailed)	0.001	0.001	
	N	9	9	9
**. Correlation is significant at the 0.01 level (2-tailed).				

The experimental data obtained was statistically analyzed using one-way ANOVA to identify the effects of air voids on permeability at 95% confidence level. Table 6 shows that the air voids have a significant effect on the permeability of porous specimens with *p*-value less than 0.05.

Table 6 One-way ANOVA effect air voids on coefficient of permeability

Source	DF	SS	MS	F	*p*-value
Air voids	6	0.0020969	0.0003495	49.93	0.020
Error	2	0.0000140	0.0000070		
Total	8	0.0021109			
S = 0.002646 R-Sq = 99.34% R-Sq(adj) = 97.35%					

3.5 Moisture Sensitivity of Porous Asphalt

Figure 5 shows the average ITSR for PA incorporating quarry dust, OPC and PMD as filler. The specimens incorporating PMD exhibit higher ITSR and better resistance to water damage compared with the specimen containing quarry dust and OPC. Upon being subjected to the water immersion freeze-thaw conditions, the specimens prepared with quarry dust is more susceptible to water damage. However, due to high air voids, water infiltration into the connected macro pores of PA mixture, loss of cohesion and the failure of the asphalt bond with the aggregate happened resulting in low ITSR values [36]. As reported by Aman and Hamzah [12], PA due to its the open structure exposes a large binder surface area to the oxidative effect of air and damaging effect of water resulting increasing interfacial moisture content, leading to the de-bonding of bitumen films from aggregate surface, which greater affinity of the aggregate from water than for bitumen.

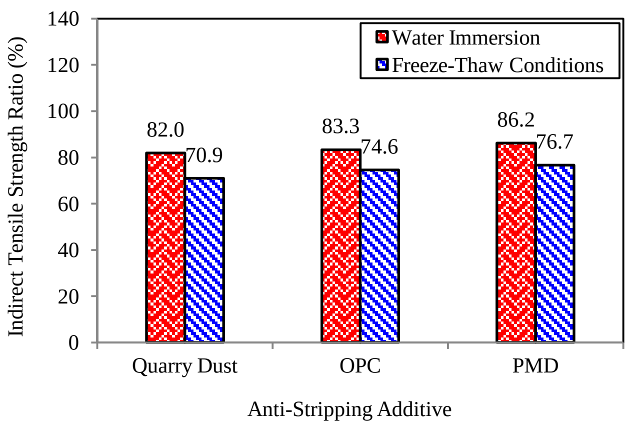


Figure 5 Comparison of ITS Ratio (ITSR) for PA mixes

Based on the Figure 5, the average ITSR value for water immersion specimens incorporating quarry dust, OPC and PMD fillers were 82.0%, 83.3% and 86.2%, respectively, while 70.9%, 74.6% and 76.7% correspondingly for freeze-thaw condition specimens. It can be seen that the PMD improving the moisture resistance caused by the presence of carbonaceous compounds. According to Aman *et al*., [1], anti-stripping additive containing carbonaceous compounds reacting with high polar molecules in asphalt to form insoluble salts that no longer attract water thus increasing bond between aggregate and asphalt. That explain why the PA specimens incorporating PMD have higher resistance to water damage compared with specimens incorporating OPC and quarry dust fillers.

The results are similar to that of Hamzah *et al*., [11], which that porous specimen incorporating PMD can better resist moisture damage due to stripping compared to specimen incorporating hydrated lime. The ITSR for specimens tested for freeze-thaw conditions is constantly lower than water immersion specimens. This might due to the effect of freeze condition where formation of ice crystals fractured thin asphalt binder films bonding with aggregates [37]. Feng *et al*., [38] reported that the freeze–thaw cycle is the effects of temperature changes resulted a change in volume and strength of asphalt mixtures, and will inevitably influence on the durability of asphalt pavement at low temperature. Furthermore, freeze–thaw cycle was used to assess the damage of mixtures caused by effects of water displacement in asphalt film and expansion of water in the cold regions. It can be concluded that specimens incorporating PMD exhibit higher ITSR and better resistance to water damage compared with the specimen containing OPC and quarry dust. The presence of carbonaceous compounds in the PMD has improved the moisture resistance of the specimen.

■4.0 CONCLUSION

Water can damage the porous asphalt mixtures by diffusion in the binder and influence its strength, resulting in a loss of cohesion of the asphalt film. Porous asphalt prepared with quarry dust, OPC and PMD as fillers and also anti-stripping agents were evaluated for their resistance to water sensitivity mix. From this study, porous specimens incorporating PMD exhibit higher ITS, better resistance to water damage. However, lower air voids, consequently decreased the coefficient of permeability and abrasion loss compared to mixes incorporating OPC and quarry dust. It can be seen that porous specimens conditioned with freeze–thaw exhibit lower ITS ratio compared to the specimen conditioned with the water immersion method. Porous specimens incorporating PMD as filler can better resist to moisture damage and improve resistance to disintegration compared to those specimens incorporating OPC and quarry dust. Therefore, mixes with PMD filler can provide better anti-stripping action compared to OPC and quarry dust fillers to enhance the porous mix performance.

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