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EXPERIMENTAL EVALUATION OF ANTI-STRIPPING ADDITIVES ON POROUS ASPHALT MIXTURES

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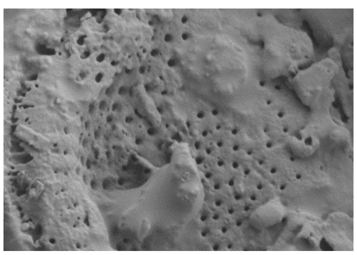
Graphical abstract



Abstract

The open structure of porous asphalt mix influences its strength and durability against air, water and clogging materials. These factors cause loss of adhesion between binder-aggregate interface and loss of cohesion within the binder film. This could lead to stripping problem which contribute to premature failures as well as deterioration in the performance and service life of porous asphalt. Therefore, this study is aimed to evaluate the potential of diatomite as anti-stripping additives in porous asphalt and compared with hydrated lime and Ordinary Portland Cement (OPC). Field Emission Scanning Electron Microscopy (SEM) test and Energy Dispersive X-ray Spectroscopy analysis (EDX) were conducted to investigate the microstructure and chemical composition of the anti-stripping additives. A number of gyratory compacted samples of porous asphalt mixture with Malaysian gradation were prepared. Each sample was incorporated with 2% of anti-stripping additives as filler then mixed with polymer modified bitumen of PG76. The samples were measured for air voids content, permeability rate, resilient modulus and abrasion loss. The results indicate that samples prepared with hydrated lime show higher permeability rate and lower abrasion loss compared to samples with OPC and diatomite. However, the samples prepared with diatomite show enhanced resilient modulus compared to those with hydrated lime and OPC.

Keywords: Porous asphalt, adhesion, anti-stripping additives, hydrated lime, cement, diatomite

1.0 INTRODUCTION

Porous asphalt has been used extensively throughout the world, especially in European countries and some states in the United States of America [1]. Besides, this type of surface layer has also been practiced in several other countries like Japan, Singapore, Australia, New Zealand and South Africa [2]. In Malaysia, the first ever trial of the porous asphalt overlay was constructed in Cheras-Beranang Road in 1991 [3]. The ability of porous asphalt overlay to allow rainwater drain quickly from the pavement surface through its pore structure is the major reason for their adoption in many countries. Due to this ability, porous asphalt is used in wearing courses with approximately 50 mm thick and always laid on top of the existing conventional asphalt surface as a possible solution for road safety improvements in wet conditions and reduction of traffic noise. In terms of safety benefits during rain events, porous asphalt was acknowledged to reduce splash and spray due to rapid dry surfaces, minimize the risk of hydroplaning and wet skidding, thus improves night visibility [4]. In addition, porous asphalt was also considered to be effective in stormwater drainage and pollutant reduction in stormwater runoff.

Porous asphalt also namely porous friction courses (PFC) and open-graded friction courses (OGFC) is designed with open-graded aggregate gradation that consists of a large proportion of coarse aggregates with small amount of fine aggregates to create larger quantities of interconnected voids ranging from 18% to 25%. This is to allow water from the surface to drain quickly through its porous structure and then drained laterally to the edge of the pavement [5-7].

Despite its safety and environmental benefits, the performance and service life of porous asphalt can be affected by the poor structural durability. It can be expected that the life of a porous surface is shorter than a conventional asphalt surface due to deterioration by runoff, air infiltration, subsequent stripping and oxidation, as well as hardening of binder [8]. On the other hand, the open gradation and high air void content lead the porous asphalt mixture to poor durability due to less stone-on-stone contact, which lead to a lower performance than normal dense-graded mixture [4]. Moreover, the open structure that facilitates water drainage had exposed the pores of porous asphalt to air, water and clogging materials that eroded the binder film and eventually affect the strength of the binder-aggregate bonding [3]. Specifically, in tropical countries like Malaysia which experiences frequent high rainfall intensity will expose the porous structures to water induced problems. Also, the issue of high traffic loading gives a profound effect on the durability of porous asphalt layer which enhance the deterioration of the asphalt pavement.

These factors cause loss of bonding in binder-aggregate system as a result of adhesive and cohesive failures in porous asphalt, thus leading to stripping. This could contribute to premature deterioration that decreases the performance and service life of pavement. Stripping failure is defined as the separation or detachment of the aggregate and asphalt binder due to the loss of adhesion between these two materials. This is usually occur in the presence of moisture, typically accompanied by gradual loss of strength over the years, which causes distress manifestations like raveling, rutting, shoving, corrugation and cracking [9-10]. In other words, it can be defined as the dislodgement of aggregate particles from the surface of the pavement, which is associated with moisture sensitivity, binder aging, binder content and binder type [11-12].

In recent years, improving the durability of porous asphalt mixture due to stripping problem has been the interest of many studies, resulting in better materials and mix designs. Nevertheless, this matter can be counteracted by using higher binder grades or modified binder as well as the use of additive to enhance the performance of porous asphalt mixtures [4]. Many studies have proven that the use of binder modifier such as polymer and rubber could improve the performance of the pavements and bring greater adhesion between aggregate and asphalt binder. Besides, previous studies also show that incorporating anti-stripping agent can positively affect the overall mixture performance by improving the aggregate-binder bonding and minimizing moisture-related problem [13]. Hydrated lime is the most commonly used anti-stripping agents in asphalt pavements to improve adhesive effects and reduces the water-induced problem of the asphalt mixture [14]. This is due to the characteristics of hydrated lime which reacts with aggregate to inhibit the formation of water-soluble soap and replace with insoluble salts that no longer attract water [15]. Hence, the interfacial bonding between aggregate and binder will be enhanced and make the asphalt mix stiffer as well as resistance to stripping failure. Ordinary Portland Cement (OPC) also one of the anti-stripping additives but there is a limited research regarding the use of OPC as anti-stripping additive in asphalt mixtures [16].

Diatomaceous earth or diatomite is a kind of non-metallic mineral material mainly composed of the skeletons of microscopic single celled aquatic plants called diatoms. The skeletons are high in natural amorphous silica content (SiO_2), a very durable substance [17]. Diatom skeletons are highly porous, light in weight, low density, chemically stable and inert [18], high absorptive capacity and insulating ability [19], and also as coating and high viscosity additives. The use of diatomite in asphalt binder has shown the improvement on the physical and rheological properties of modified asphalt. Cong *et al.* [20] indicated that the diatomite modified asphalt binder improved the viscosity and resistance to deformation at high temperature. In addition, Li *et al.* [21] investigated the use of diatomite as the filler in porous asphalt mixtures and resulted in better interface adhesion, particle loss resistance, moisture damage resistance, rutting resistance and low temperature cracking resistance. Therefore, an investigation was carried out to evaluate the potential of diatomite as anti-stripping agent on porous asphalt mixtures and compared with other types of anti-stripping additives i.e. hydrated lime and Ordinary Portland Cement (OPC). In this study, the microstructure and chemical composition of the anti-stripping additives were studied using Scanning Electron Microscopy (SEM) test and Energy Dispersive X-ray Spectroscopy analysis (EDX). In addition, the performance of porous asphalt mixture with different anti-stripping additives was evaluated through permeability rate, resilient modulus and Cantabro tests.

2.0 EXPERIMENTAL PROGRAM

2.1 Materials Properties

The crushed granite aggregate used in this study was supplied by Hanson Quarry Products located in Kulai, Johor. The gradation limit of Grading B (nominal maximum aggregate size of 14 mm) for porous asphalt was selected according to the Standard Specification from Malaysia Public Works Department [22], as shown in Figure 1.

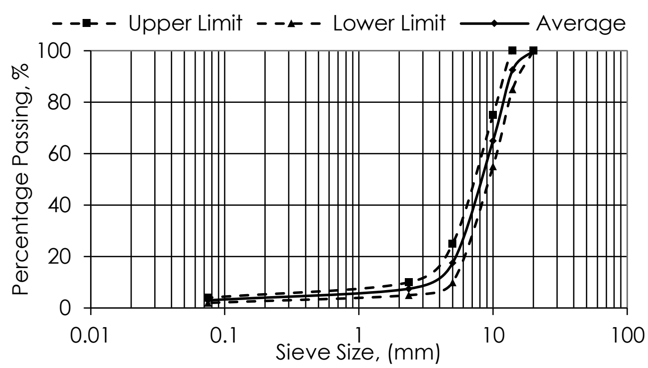


Figure 1 Malaysian gradation limits for porous asphalt mixtures, Grading B

The specific gravity and water absorption test was conducted for coarse and fine aggregate respectively. Polymer modified binder, PG76 was used as a binder for the mix design and sample preparation [22]. PG76 is very suitable to be used for efficient performance of porous asphalt mix as it is modified with polymer and exhibits outstanding high viscosity property. The properties for aggregates and binder used in this study are summarised in Table 1.

Table 1 Materials Properties

Properties	Value
Coarse Aggregate	
Specific Gravity Bulk	2.695
Specific Gravity Saturated Surface Dry (SSD)	2.709
Specific Gravity Apparent	2.733
Water Absorption (%)	0.520
Fine Aggregate	
Specific Gravity Bulk	2.427
Specific Gravity Saturated Surface Dry (SSD)	2.477
Specific Gravity Apparent	2.554
Water Absorption (%)	2.048
Bitumen PG76	
Viscosity at 135°C	2.8 Pa.s
Penetration at 25°C	38.6 mm
Softening Point	60°C
Specific Gravity at 25°C	1.030g/cm^3

Three types of anti-stripping additives used were hydrated lime, Ordinary Portland Cement (OPC) and diatomite, which passing 75 µm sieve size. Diatomite was supplied by I-Chem Solution Sdn Bhd, Selangor, Malaysia, and its physical properties are shown in Table 2. From EDX analysis, the new material of diatomite contains a high content of silica (SiO_2) and other components such as aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3).

Table 2 Properties of diatomite

Properties	Value
Color	White
PH	9-10
Specific gravity	2.1-2.3
Bulk density	0.35

2.2 Mixture Design and Sample Preparation

The optimum binder content of the porous asphalt mix was determined by the average of the upper limit from the binder draindown test and lower limit from the Cantabro test results as well as the target air void content of 21±1%. The binder draindown test is used to quantify the sufficient quantity of bitumen film thickness to coat the aggregate particles. While Cantabro test is used to evaluate the mixture's resistivity against stripping or aggregate loss. The binder content used for mixture with hydrated lime and OPC was 5% and 5.25% used for mixture with diatomite. The samples were mixed at the temperature of 180°C and compacted using the Superpave gyratory compactor. The machine was set at a loading pressure of 600 kPa and an external angle of gyration of 1.25. A few compaction trials were conducted at various numbers of gyrations i.e. 20, 40, 60 and 80 to determine the desired number of gyrations. As shown in Figure 2, the number of gyration to achieve the target of 21% air voids content is 40 gyrations for hydrated lime, 45 gyrations for OPC and 58 gyrations for diatomite. A total of 2% of anti-stripping additives by mass of aggregates was added to the sample as part of mineral filler.

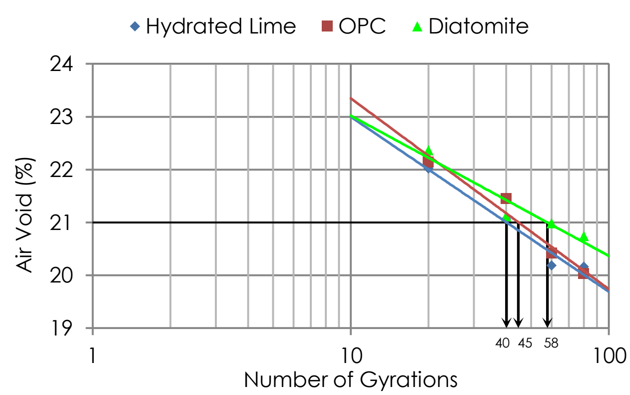


Figure 2 Plot of air voids and gyration number

2.3 Laboratory Tests

2.3.1 Scanning Electron Microscope (SEM)

The investigation on the surface texture of the anti-stripping additives was conducted using Scanning Electron Microscope (SEM). The SEM gives images of the sample surface by scanning it with a high energy beam of electrons in a raster scan pattern. In addition, the test generates an image of the sample at the micro-scale in order to study their microstructural properties. The samples of hydrated lime, OPC and diatomite powder were prepared in a small quantity and sputtered with an extremely thin layer of carbon or metallic coating to make the surfaces conducting.

2.3.2 Cantabro Test

Cantabro test was conducted to determine the abrasion loss of the porous asphalt mixtures. This test measures the resistance of compacted samples to stone loss at high frequency. The abrasion loss was calculated by the percentage of weight loss which indicated the durability of the samples. For this study, the Cantabro test result was also used to determine the design binder content of porous asphalt with the average loss of mass should not be more than 15%. The Cantabro test was conducted according to the apparatus and procedures outlined in JKR/SPJ/2008. The percentage of abrasion loss (L) was calculated using Equation 1:

$$L = \frac{M_1 - M_2}{M_1} \times 100 \quad (1)$$

where,
L = Cantabro Loss, %,
M_1 = Initial weight of test sample,
M_2 = Final weight of test sample.

2.3.3 Coefficient of Permeability

Permeability test was carried out to determine the relative permeability of compacted samples of porous asphalt mixes. The method used was a falling head permeability test using a flexible wall permeameter and the permeability was measured in terms of its discharge time in seconds, which indicate the time taken for a specified volume of water to permeate through a compacted sample. The permeability test was performed at ambient room temperature of 25°C. The coefficient of water permeability, *k*, was a product of Darcy's Law equation and it was calculated using Equation 2:

$$k = \frac{al}{At} \ln\left(\frac{h_1}{h_2}\right) \quad (2)$$

where,
k = Coefficient of water permeability, cm/s,
a = Tube cross-sectional area, cm^2,
l = Thickness of the test sample, cm,
A = Sample cross-sectional area, cm^2,
T = Time, s,
h_1 = Initial water level at time t_1, cm, and
h_2 = Final water level at time t_2, cm.

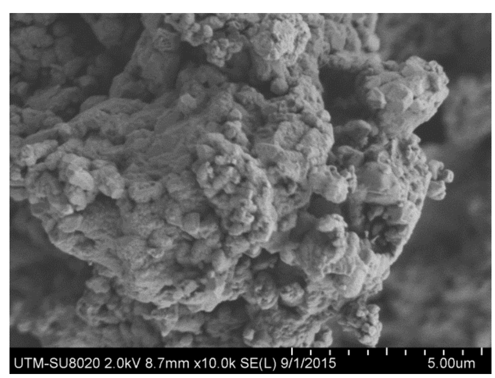
2.3.4 Resilient Modulus Test

The Resilient Modulus Test was performed in accordance with ASTM D4123. Resilient modulus is a non-destructive test which measures the material stiffness under different conditions such as temperature or moisture, density and load level. It can also be defined as the ratio of the applied cyclic stress to the recoverable (elastic) strain after many cycles of repeated loading. The test was conducted at temperature of 25°C (± 1°C), at a loading frequency of 0.5 and 1 Hz for each test temperature as well as the load duration of 0.1s. The test was conducted by applying compressive loads with a haversine waveform. The load was applied vertically in the vertical diametric plane of a cylindrical sample. The total resilient modulus was automatically computed from the machine using the total recoverable deformation, which includes both the instantaneous recoverable and the time dependent continuing recoverable deformation during the unloading and rest-period portion of one cycle.

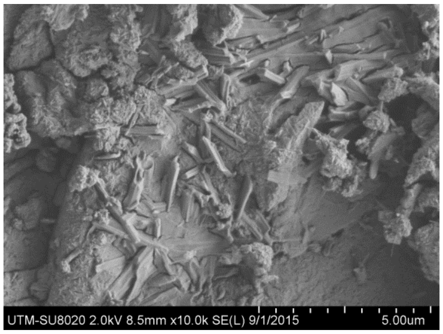
3.0 RESULT AND DISCUSSION

3.1 SEM Analysis

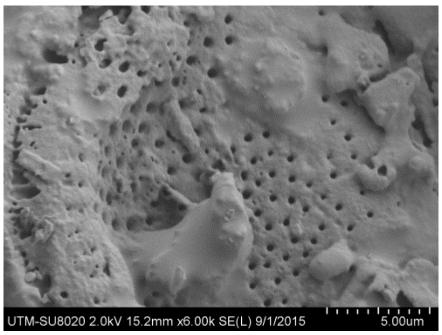
The comparison of the macro texture between hydrated lime, OPC and diatomite is shown in Figure 3. From the figure, it can be seen that these three types of additives are very different to each other. The figure shows that the particle of hydrated lime exists like a cloud-of-smoke shape that bonded together. For OPC, the texture appears to be more dense and compact with its minerals attached to each other. Unlike hydrated lime and OPC, the particle of diatomite presents the microscopic porous structure which can be seen clearly as a single grain structure. The microscopic porous structure of diatomite shows that it has high surface area which led to the increase in binder content due to its high absorptive capacity.



(a)



(b)



(c)

Figure 3 SEM image at magnification of 5.00 μm for (a) hydrated lime, (b) OPC and (c) diatomite

3.2 Abrasion Loss Resistance

The resistance to abrasion loss was analyzed using a Cantabro test. This test was carried out to assess the bonding properties between aggregate and bitumen. The result for abrasion loss is shown in Figure 4. From the results, it can be observed that the abrasion loss of samples prepared with hydrated lime is 21.5% which is the lowest compared to the samples with OPC and diatomite where the abrasion loss are 33.2% and 27.9% respectively. Liu *et al*., [11] recommended that the abrasion loss of porous asphalt should not exceed 20% for unconditioned samples when conducted at 25°C. Unfortunately, all the mixtures show high abrasion loss of more than 20%. However, the mixture with hydrated lime shows better results than others. This proves that hydrated lime has a good property as filler that enhances chemical bonding between aggregate and binder in asphalt mixtures.

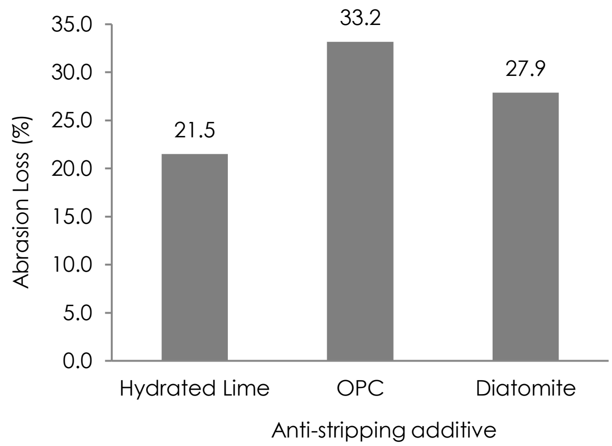


Figure 4 Abrasion Loss result

3.3 Permeability Rate

The permeability test was conducted to investigate the ability of the porous asphalt mixture to drain water through its porous structure. The results were compared between the mixtures containing hydrated lime, OPC and diatomite as shown in Figure 5. Based on the results, it was found that the coefficient of permeability for mixtures with hydrated lime is the highest compared to the mixtures with OPC and diatomite. However, all the mixes still exhibit higher rate value of permeability than the recommended minimum *k* value of 0.116 cm/sec for porous asphalt [23]. The lowest permeability rate for diatomite is might be caused by the higher binder content which reduces the permeability due to the replacement of the air voids by the excess binder [24].

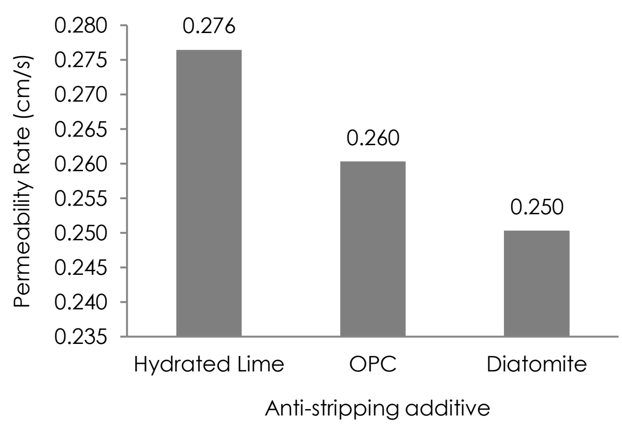


Figure 5 Permeability result

3.4 Resilient Modulus

The Resilient Modulus test was conducted at a temperature of 25°C by applying repetitive compressive loads in a haversine waveform on the sample. This test was carried out to evaluate the stiffness of porous asphalt mixtures, which refers to the ability of the mixture to recover after releasing load. Figure 6 shows the results obtained from the resilient modulus test at 25°C, 30°C and 35°C. It can be seen that the resilient modulus value for all types of anti-stripping additives decreases as the temperature increased from 25°C to 35°C. The results indicate that the mixture with diatomite has the highest resilient modulus compared to the mixtures with hydrated lime and OPC when tested at 25°C. As temperature increases, the resilient modulus shows a reduction for all types of anti-stripping additives. Therefore, it can be concluded that the mixtures of diatomite enhances the stiffness of the porous asphalt mixtures compared with the mixture containing hydrated lime and OPC.

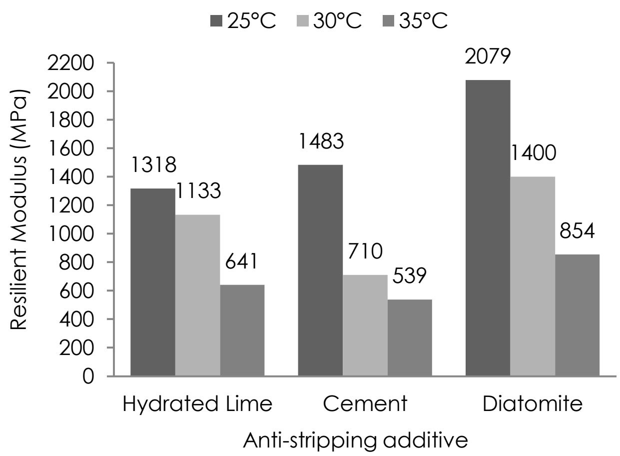


Figure 6 Resilient Modulus result

4.0 CONCLUSION

From the study, it can be concluded that the porous samples incorporating diatomite exhibit higher resilient modulus, which indicates that the mixes have better resistance to deformation. However, the coefficient of permeability decreases compared to mixes incorporating hydrated lime and Ordinary Portland Cement (OPC). Besides, the use of diatomite also shows a high abrasion loss which indicates that diatomite does not give significant effect on the adhesion bonding. The use of OPC also shows very low resistance to abrasion loss compared to the mixture with hydrated lime and diatomite.

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