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Effect of various filler types on the properties of porous asphalt mixture

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Abstract. The open structure of porous asphalt exposes a large surface area to the effects of air and water, which accelerates the oxidation rate and affects the coating properties of the binder. These factors may influence the adhesive strength of the binder-aggregate and lead to cohesive failure within the binder film, contributing to aggregate stripping and moisture damage. The addition of fillers in asphalt mixtures has been identified to stiffen the asphalt binder and improve mixture strength. This study investigates the effect of various filler types (hydrated lime, cement, and diatomite) on the properties of porous asphalt. Compacted samples of porous asphalt were prepared using Superpave gyratory compactor at the target air void content of 21%. Each sample was incorporated with 2% of filler and polymer-modified binder of PG76. The morphology and chemical composition of fillers were investigated with a field emission scanning electron microscope (FESEM) and energy dispersive X-ray (EDX) analysis. The properties of porous asphalt were evaluated in terms of permeability, abrasion loss, resilient modulus, and indirect tensile strength. All mixtures were found to show high permeability rates. Mixtures with hydrated lime exhibited lower abrasion loss compared to mixtures with cement and diatomite. The use of diatomite increases the resistance of the mixtures to rutting and moisture damage compared to other fillers as shown by the enhanced resilient modulus and indirect tensile strength.

1. Introduction

Porous asphalt has been used widely due to its ability to allow rainwater to drain quickly from the pavement surface through its pore structure. Given this ability, porous asphalt is utilized in wearing courses with approximately 50 mm thickness and placed over the impermeable asphalt surface as a possible solution for road safety improvements in wet conditions and for the reduction of traffic noise. In terms of safety benefits during rain events, porous asphalt was acknowledged to reduce splash and spray because of rapid dry surfaces and minimize the risk of hydroplaning and wet skidding, thereby improving night visibility [1]. Porous asphalt is designed with open-graded aggregate gradations that consist of a large proportion of coarse aggregates with a limited amount of fine aggregates to create larger quantities of interconnected voids of more than 18%, to allow water to penetrate through the voids [2,3].

Despite its safety and environmental benefits, the performance and service life of porous asphalt can be affected by its poor structural durability. The life of a porous surface is expected to be shorter than that of a conventional asphalt surface because of the deterioration by runoff, air infiltration, subsequent stripping and oxidation, and hardening of the binder [4]. 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 caused by the inappropriate gradation and low density in porous asphalt mixture, which results in a lower performance than normal dense-grade mixture [1]. Moreover, the open structure that facilitates water drainage exposes the pores of porous asphalt to air, water, and clogging materials that erode the binder film and eventually affects the strength of the binder-aggregate bonding [5]. In tropical countries such as Malaysia, which experiences frequent high rainfall intensity, porous structures are subjected to water-induced problems. In addition, issues of high traffic impact stress due to rapid development in infrastructure and road construction exert a profound effect on the durability of the porous asphalt layer, thereby worsening the deterioration of the asphalt pavement. These factors cause loss of bonding in the binder–aggregate system as a result of adhesive and cohesive failures in the porous asphalt, leading to stripping. In turn, stripping contributes to a decline in the performance and service life of the pavement. Stripping failure is defined as the separation or detachment of the aggregate and asphalt binder because of the loss of adhesion between these two materials usually in the presence of moisture; such failure is typically accompanied by gradual loss of strength over the years, which causes distress manifestations including ravelling, rutting, shoving, corrugation, and cracking [6].

The utilization of filler in the asphalt mixture has long been recognized by asphalt-paving technologists. Despite the small proportion it represents in the mixture, the use of filler is proven essential in improving the performance of asphalt mixtures to various distresses. The presence of filler can positively affect the overall mixture performance including strength, stability, workability, resilient modulus, resistance to moisture, resistance to permanent deformation, and aging characteristics [7,8]. The indirect tensile strength test by Huang *et al*. [9] showed that the said strength of the asphalt mixture increases as the filler content rises. This result is in agreement with the findings of Ahmed *et al*. [10], where higher filler content improves the mixture tensile strength. This higher tensile strength implies that mixtures with filler are capable of withstanding larger tensile stress before failure [11]. Another study revealed that the results for resilient modulus also indicated that mixtures with filler show higher resilient modulus values, which leads to stiffer mixtures with superior load-spread capacity and greater resistance to fatigue cracking and permanent deformation [7, 12].

Hydrated lime is the most commonly used additive in asphalt mixtures. It is known as an active filler that provides good adhesive bonding at the binder–aggregate interface, which effectively controls water sensitivity and resists stripping [13,14]. Li *et al.* [15] also investigated the use of diatomite as the filler in porous asphalt mixtures. Their study resulted in improved interface adhesion and low-temperature cracking resistance. On this basis, diatomite is considered a potential filler in porous asphalt, and the extension of the study is necessary. Ordinary Portland cement is also a possible additive, but limited research exists regarding the use of cement as filler in asphalt mixtures [14]. Therefore, this study evaluates the effect of different filler types on the properties of porous asphalt through permeability, abrasion loss, resilient modulus, and indirect tensile strength.

2. Experimental

2.1. Materials

The crushed granite aggregate used in this experiment was supplied by Hanson Quarry Products in Kulai, Johor. The gradation limit of the combined aggregate for porous asphalt was selected according to the Standard Specification for Porous Asphalt from JKR specifications [16] (see Figure 1). The aggregate gradation employed for the porous asphalt mixture in this study was Grading B with nominal maximum aggregate size of 14 mm.

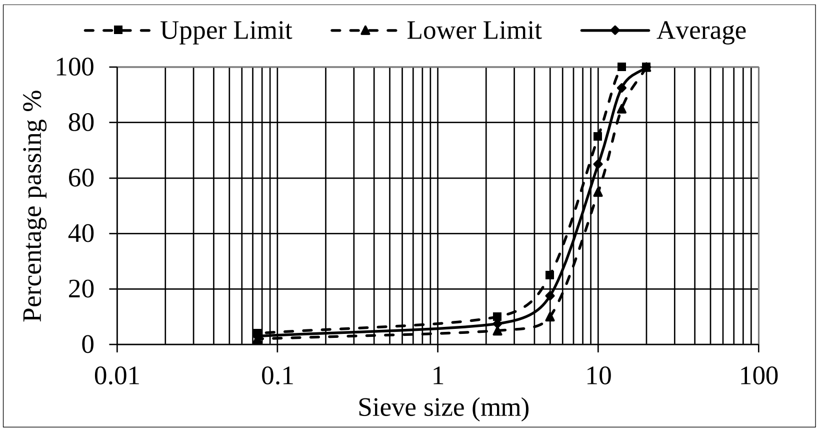


Figure 1. Plotted Malaysian gradation limits for porous asphalt.

The aggregate was tested for specific gravity and water absorption. The polymer modified binder PG76 was used as a binder for the mixture design and sample preparation as per JKR specification [16]. PG76 is highly suitable for the efficient performance of the porous asphalt mixture because it is modified with polymer and exhibits outstanding high viscosity property. The properties for aggregates and the binder utilized in this study are presented in Table 1. Three types of filler were selected for sample preparation: hydrated lime, cement, and diatomite (which passed the 75 µm sieve size). Specific gravities are 2.72 (hydrated lime), 3.2 (cement), and 2.2 (diatomite).

Table 1. Materials properties.

Materials	Properties	Value
Coarse aggregate	Specific Gravity Bulk	2.695
	Water Absorption (%)	0.520
Fine aggregate	Specific Gravity Bulk	2.427
	Water Absorption (%)	2.048
Bitumen PG76	Penetration at 25°C (dmm)	40.6
	Softening point (°C)	70
	Viscosity at 135ºC (Pa. s)	2.8
	Specific gravity	1.030

2.2. Mixture design and sample preparation

The design binder content of the porous asphalt mixture was determined by 1) the average of the upper limit from the binder draindown test, 2) the lower limit from the Cantabro test, and 3) the target air void content of 21%. The 21% air void content was selected to prevent over-compaction on the samples (particularly for those with diatomite filler) such that the number of gyrations obtained would not exceed the maximum compaction of 75 gyrations, as recommended in the Superpave system. The binder draindown test is used to quantify the sufficient bitumen film thickness for coating the aggregate particles, whereas the Cantabro test is applied to evaluate the resistivity of the mixture against stripping or aggregate loss. Therefore, the design binder content used for the mixture prepared with hydrated lime and cement was 5%. The mixture with diatomite filler had the highest design binder content (5.25%) because of its high surface area, high porosity, and the high absorptive capacity of the material, which allows it to adsorb higher amounts of asphalt binder compared to other fillers.

The Superpave gyratory compactor was employed to produce compacted cylindrical samples of 100 mm diameter and an approximate thickness of 50 mm, with 725 g of blended aggregate. The samples were mixed at 180 °C. Then, the loose mixtures were conditioned in an oven for 2 h at the compaction temperature of 170 °C to allow the absorption of the asphalt binder into the aggregate. 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 ascertain the desired number of gyrations. As shown in Figure 2, the number of gyrations to achieve the target of 21% air voids content is 40, 45, and 58 for the mixture with hydrated lime, cement, and diatomite, respectively. All materials were added for 2% by mass of total aggregates as a part of the mineral filler.

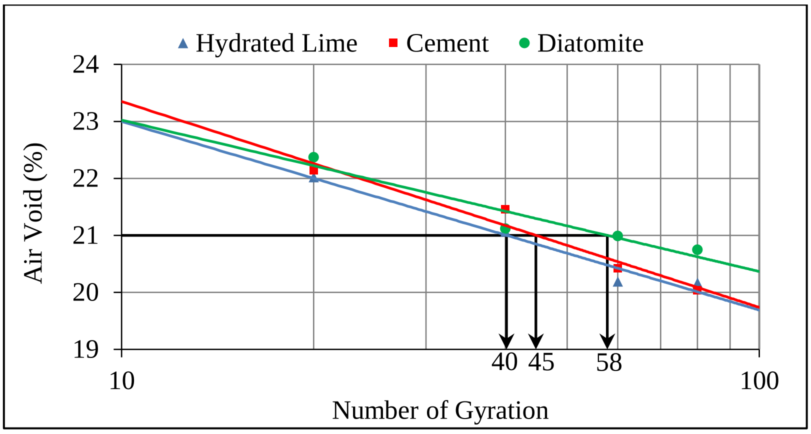


Figure 2. Plot of air void content versus number of gyration.

2.3. Laboratory tests

2.3.1. FESEM and EDX. Filler surface textures were examined using a field emission scanning electron microscope (FESEM). This machine captures surface images with a scan using a high energy beam of electrons in a raster scan pattern. It generates images of the sample at the microscale to enable the characterisation of microstructural properties. The samples of hydrated lime, cement, and diatomite powder were prepared in small quantities and sputtered with an extremely thin layer of carbon or metallic coating to render their surfaces conductive. The information in FESEM images is important for verifying some filler properties, such as specific surface area, particle distribution, and porosity. The chemical compositions of all the three filler types were evaluated quantitatively through energy dispersive X-ray (EDX) analysis and provided in the form of element weight percentage. This analysis was used to map the distribution of specific elements (Al, K, and Na) that characterized the various minerals in the material.

2.3.2. Permeability rate. Permeability tests were performed to determine the relative permeability of the compacted samples of porous asphalt mixtures. The falling head permeameter was used and permeability was measured in terms of the discharge time in seconds, which indicates the time required for a specified volume of water to permeate through a compacted sample. The time needed for the water level to fall between two designated points from 60 to 20 on the graduated cylinder was ascertained. The coefficient of water permeability, k, a product of Darcy's Law equation, was calculated using equation (1).

$$k = \frac{al}{At} ln\left(\frac{h_1}{h_2}\right) \quad (1)$$

where k is the coefficient of water permeability (cm/s), a is the inside cross-sectional area of inlet standpipe (cm^2), l is the thickness of the test sample (cm), A is the cross-sectional area of the test sample (cm^2), t is the average elapsed time of water flow between timing marks (s), h_1 is the hydraulic head on the sample at time t_1 (cm), and h_2 is the hydraulic head on the sample at time t_2 (cm).

2.3.3. Abrasion loss. The Cantabro test was conducted to determine the particle loss of the porous asphalt under abrasion. This test measures the resistance of the compacted samples to stone loss at high frequencies using abrasion machines. Abrasion loss, which was calculated through the percentage of weight loss, indicates the durability of the sample. In this study, the results of abrasion loss were also utilized to determine the design binder content of the porous asphalt with an average loss of mass no more than 15%. The percentage of abrasion loss (L) of each sample was computed using the following equation:

$$L = (M_1 - M_2 / M_1) \times 100 \tag{2}$$

where L is the abrasion loss (%), M_1 is the initial weight of the test sample (g), and M_2 is the final weight of the test sample (g).

2.3.4. Resilient modulus. A resilient modulus test was performed to measure the stiffness modulus of the asphalt mixtures using the repeated-load indirect tension test. The test is a non-destructive assay for investigating the recoverable strain of a mixture under repeated stress. Results with high resilient modulus value indicate that the asphalt mixture is stiff and the recoverable strain from repeated vehicle loads is smaller. With this method, the effect of temperature and load on resilient modulus were examined. In this study, the resilient modulus test was performed according to ASTM D4123 [17]. The assessment was conducted at temperatures of 25, 30, and 35 °C, loading frequencies of 1 Hz, and load duration of 0.1 s as recommended in the JKR specifications [16].

2.3.5. Moisture susceptibility test. The paragraph text follows on from the subsubsection heading but should not be in italic. The modified Lottman test is the most commonly used assay for determining the moisture susceptibility of bituminous mixtures. This test was performed according to AASHTO T283 [18]. Samples of dry and moisture conditioned subsets were fabricated, with each subset consisting of three samples. The dry or control subsets (unconditioned) were left at 25 °C in an incubator for 2 h before testing. The wet subsets (conditioned) were preconditioned using vacuum saturation for approximately 15 min to achieve a saturation level of 55% to 80%. After saturation, the samples were wrapped in leak-proof plastic bags containing 10 ml of water. The samples were then placed in a freezer at a temperature of –18 °C for 16 h, followed by sample immersion in a water bath at 60 °C for 24 h. Prior to indirect tensile testing, the conditioned samples were placed in a water bath at 25 °C for another 2 h. The degree of saturation, S, was determined using the following equation:

$$S = W_{SSD} - W_D / V_a \tag{3}$$

where S is the degree of saturation (%), W_{SSD} is the weight of the saturated surface dry sample after vacuum saturation (g), W_D is the weight of the dry sample (g), and V_a is the volume of air voids in the sample (cm^3). The indirect tensile strength (ITS) test was performed according to ASTM D6931 [19]. A loading rate of 50 mm/min was applied using a Marshall loading machine with steel-loading strips. The maximum load was recorded and the tensile strengths of the asphalt mixtures were calculated using equation (4):

$$ITS = 2000F / \pi hD \tag{4}$$

where ITS is the indirect tensile strength (kPa), F is the maximum load (N), h is the height of the specimen (mm), and D is the diameter of the specimen (mm). The ITS values for unconditioned and conditioned samples were utilized to calculate the tensile strength ratio (TSR). The TSR values indicate the resistance of an asphalt mixture to moisture damage. The ratio is calculated as in equation (5):

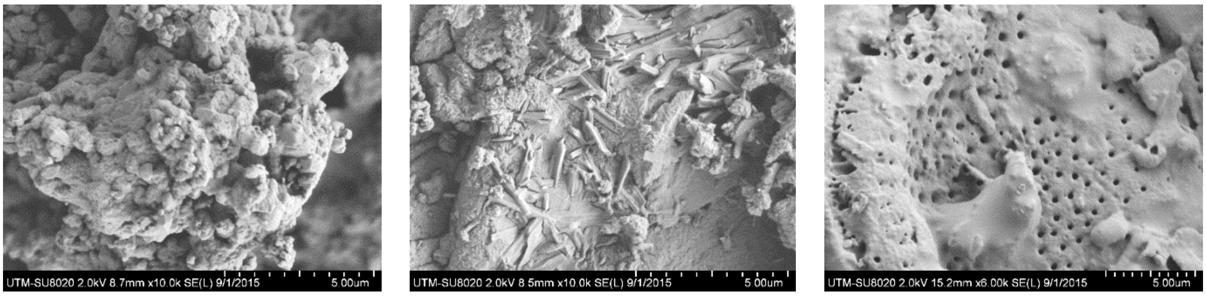
$$TSR = (ITS_{wet} / ITS_{dry}) \times 100, \quad (5)$$

where TSR is the tensile strength ratio (%), ITS_{wet} is the average ITS of the moisture-conditioned subset (kPa), and ITS_{dry} is the average ITS of the dry subset (kPa).

3. Results and discussion

3.1. FESEM and EDX analyses

The surface texture of hydrated lime, cement, and diatomite are compared in Figure 3. The cement texture appears dense and compact. For hydrated lime, the particles exist in a bonded cloud-of-smoke shape. Unlike hydrated lime and cement, the diatomite particle has a porous structure in the form of a single grain. The porous structure of diatomite shows that it has a high surface area that leads to an increase in design binder content due to its elevated adsorptive capacity. These findings can improve drainability and prevent binder draindown. Table 2 presents the chemical composition of the three fillers. Both hydrated lime and cement have high contents of calcium and oxygen that form calcium oxides (CaO). Cement consists mainly of limestone, clay, and gypsum in a high-temperature process. Hydrated lime, or calcium hydroxide ($Ca(OH)_2$), is produced by treating CaO with water. It is well known as a filler that enhances the chemical bonds between the aggregate and binder in asphalt mixtures [20]. Diatomite primarily consists of silica and oxygen in the form of silicon dioxide (SiO_2), which is known for its hardness. According to Cong *et al*. [21], its high silica content and honey-comb silica structure are the most important features of diatomite because they can generate useful characteristics, such as high absorptive capacity, chemical stability and low bulk density.



(a) (b) (c)

Figure 3. FESEM images of (a) hydrated lime at 10000× magnification, (b) cement at 10000× magnification, and (c) diatomite at 6000× magnification.

Table 2. EDX results of fillers.

Element	Hydrated lime (wt. %)	Cement (wt. %)	Diatomite (wt. %)
Al	0.2	1.3	1.4
Au	6.2	8.9	8.9
Ca	43.8	37.8	-
C	12.8	9.1	17.4
F	-	3.0	6.7
Fe	0.4	-	-
Mg	0.8	0.5	0.3
Na	-	-	1.7
O	35.7	33.0	31.8

Si	0.2	6.3	31.9

3.2. Permeability rate
A permeability test was conducted to investigate the ability of a porous asphalt mixture to drain water through its porous structure. Results from the mixtures containing hydrated lime, cement, and diatomite were compared as shown in Figure 4. Based on the outcomes, the permeability rate of the mixture with hydrated lime was higher than that of the mixtures with cement and diatomite. However, all mixtures exhibited higher permeability rates than the recommended minimum *k* value of 0.116 cm/sec for porous asphalt [22]. In addition, the three mixtures exhibited minimal differences from one other. Such small differences might be due to the void distribution and interconnectivity within the mixtures.

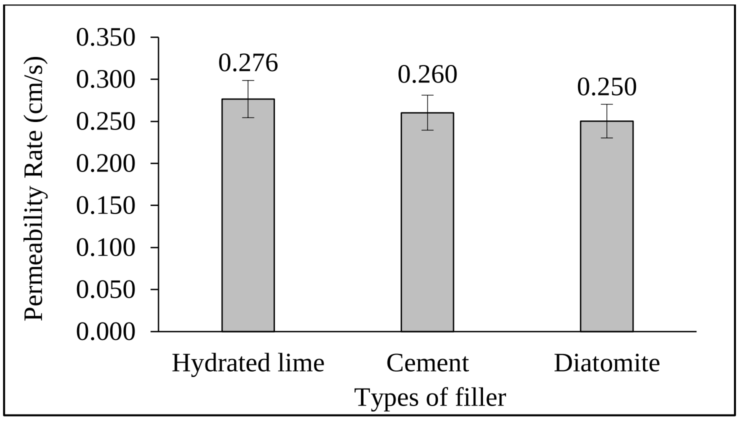


Figure 4. Permeability test result.

3.3. Abrasion loss resistance
Figure 5 presents the results for abrasion loss using the Cantabro test. In this study, the maximum Cantabro particle loss allowed was 25% for unaged porous asphalt mixtures. The abrasion loss of samples prepared with hydrated lime is 21.5%, which is lower than the said loss for samples incorporating cement (33.2%) and diatomite (27.9%). According to Rodriguez-Hernandez *et al*. [23], a lower abrasion loss indicates that the samples possess better cohesion and resistance to ravelling. The current findings demonstrate that the mixture with hydrated lime achieved better results than cement and diatomite, proving that hydrated lime has a good filler property. Given its chemically active nature, which produces a strong physical–chemical interaction with the asphalt binder, hydrated lime is highly effective in enhancing the chemical bonds between the aggregates and the binder in the asphalt mixtures.

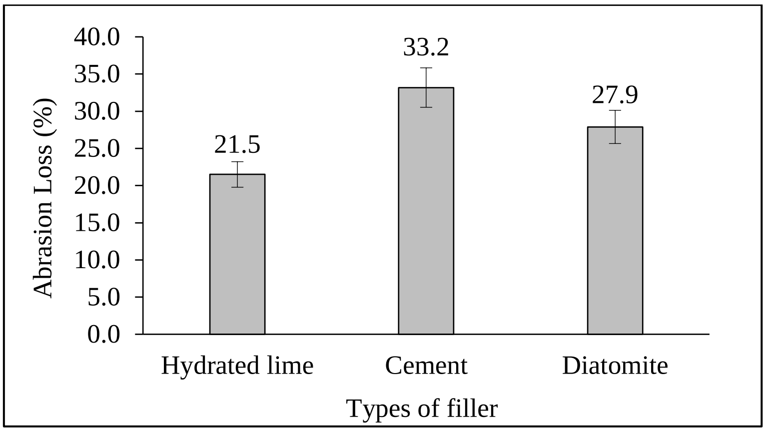


Figure 5. Abrasion loss result.

3.4. Resilient modulus

Results from the resilient modulus tests executed at 25, 30, and 35 °C are shown in Figure 6. The resilient modulus values for all mixture types decreased from 25 °C to 35 °C. According to Faghri *et al*. [24], the material for porous asphalt mixtures is sensitive to temperature. When the temperature increased from 25 °C to 35 °C, the resilient modulus of samples with hydrated lime, cement, and diatomite were reduced by 51%, 64%, and 59%, respectively. The observed significant decrease in resilient modulus at high temperatures is related to the reduced viscosity and softening of asphalt binders, causing the binder to lose its ability to join the aggregates. Therefore, the recoverable strain is increased under applied loads, thereby resulting in lower resilient modulus. According to McDaniel *et al*. [25], the stiffness values of porous asphalt are typically lower than those of dense-graded mixtures given different aggregate gradations. The lack of fine aggregate or mastic in porous asphalt can cause durability problems because the mastic provides strength to the mixture. For porous asphalt, the strength is more dependent on the stone-on-stone contact of the coarse aggregates, which refers to the strong aggregate interlock and good adhesion between aggregates and the polymer-modified binder. Results reveal that, at all test temperatures, the mixture containing diatomite has the highest resilient modulus compared to those with hydrated lime and cement. This finding indicates that mixtures with diatomite are the least susceptible to temperature changes and have the greatest increase in stiffness. Such characteristic is due to the different binder content of mixtures with diatomite, where binder adhesion has a substantial influence on the resilient modulus. As the optimum binder content of diatomite mixtures is slightly higher, the mixture has enough binder content to improve inter-aggregate adhesion and cause a smaller recoverable strain.

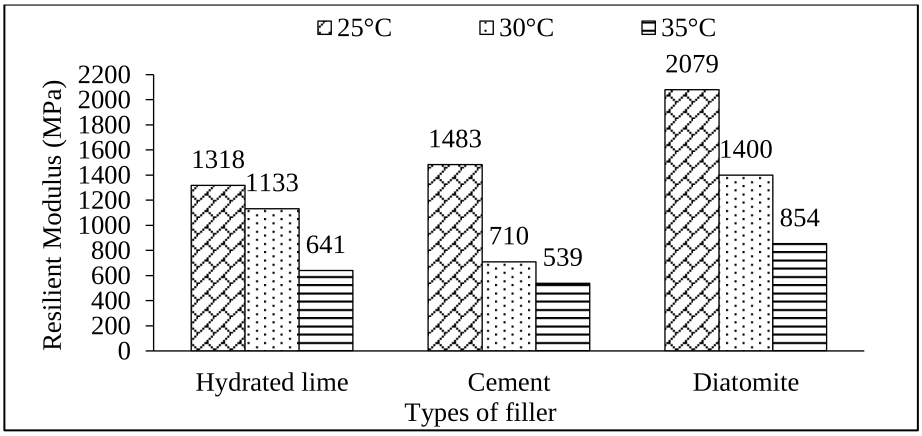


Figure 6. Resilient modulus result.

3.5. *Modified Lottman test*

The ITS and TSR for both unconditioned (dry) and conditioned (wet) samples are shown in Figure 7. As indicated, unconditioned mixtures containing diatomite exhibit the highest tensile strength values. Similar trends were observed for the ITS of conditioned mixtures. Those outcomes suggest that the ITS for conditioned samples is lower than the ITS for unconditioned samples. This observation indicates that deterioration occurred in the mixtures and that moisture conditioning exerts a significant effect on reducing the tensile strength of the mixtures. Samples prepared with diatomite have greater ITS than those prepared with hydrated lime and cement. Therefore, samples incorporating diatomite exhibit greater resistance to moisture damage compared to samples containing hydrated lime and cement. As disclosed in Figure 7, slight differences in TSR values are observed among the mixtures prepared with hydrated lime (88.8%), cement (90.6%), and diatomite (91.9%). The TSR values for mixtures containing diatomite are slightly higher than those of the other two mixtures. However, a minimum requirement of 80% for TSR value was specified for Superpave mix designs in AASHTO T283. Results confirm that all mixtures demonstrate TSR values greater than 80%, indicating that hydrated lime, cement, and diatomite could improve moisture resistance.

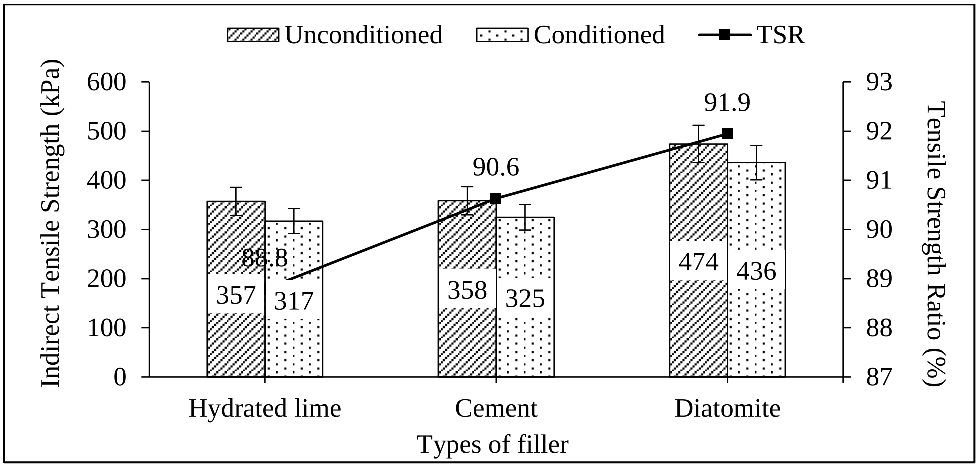


Figure 7. Indirect tensile strength and tensile strength ratio results.

4. Conclusion

Various laboratory tests were performed to evaluate the effects of the three fillers on the properties of porous asphalt. Based on the results, the design binder content and theoretical maximum density for mixtures with diatomite filler were highest, which indicates that diatomite has a stronger adsorption capacity compared to hydrated lime and cement. Mixtures with diatomite resulted in the highest number of gyrations required to obtain the targeted air void content, proving the high porosity of the diatomite structure. Furthermore, the Cantabro test indicates that hydrated lime has better filler properties than cement and diatomite. The lowest abrasion loss from hydrated lime suggests that it provides better cohesion and resistance to ravelling. This feature is due to its strong physical–chemical interaction with asphalt binder. The resilient modulus values were the highest for mixtures containing diatomite at all test temperatures indicating that diatomite improves the stiffness of the porous asphalt mixture more than the mixtures containing hydrated lime and cement. Additionally, the mixture with diatomite shows the highest values for indirect tensile strength and tensile strength ratio. However, the tensile strength ratio for all three mixtures complied with specifications, indicating good resistance to moisture damage. Overall, porous asphalt with diatomite achieved better results in most of the tests, followed closely by the mixtures with hydrated lime, and then by the mixtures with cement.

Acknowledgements
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