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Determining the properties of semi-flexible pavement using waste tire rubber powder and natural zeolite

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HIGHLIGHTS

- The use of WTR and natural zeolite on SFP mixtures was investigated.
- The WTR amount added in porous asphalt mixtures affected the mechanical properties of SFP.
- The addition of natural zeolite on grouting mortar improved the mechanical properties of SFP.
- The addition of natural zeolite on grouting mortar improved the durability of SFP.
- The coefficient of permeability of SFP increased with the increase in zeolite content.

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ABSTRACT

The small amount of bitumen contained in semi-flexible pavement (SFP) causes the peeling of the aggregate grains, therefore, it is necessary to include some additives such as waste tire rubber (WTR) to increase the adhesion. Moreover, natural zeolite contains a high amount of silica and this makes it suitable as a replacement for cement in SFP filling mortar. This research was, therefore, aimed at determining the compressive strength, flexural strength, drying shrinkage, permeability, durability, and the stress-strain relationship of semi-flexible pavement (SFP) using waste tire rubber (WTR) powder as an additive material and natural zeolite as cement replacement. The porous asphalt mix was designed in accordance with the optimum asphalt proportion and open-graded aggregate as specified in the 2010 Indonesian Bina Marga Standards and 2014 Australian Asphalt Pavement Association (AAPA), respectively. The process involved the addition of WTR powder on liquid asphalt at 3%, 4%, and 5% before the porous asphalt was mixed. This was followed by conducting a Marshall test on the specimens to determine if they satisfied the Bina Marga Standards. The porous asphalt specimens were grouted by cement mortar with the cement content replaced by 0%, 5%, 15%, and 25% natural zeolite (w/w) to produce SFP after which the properties of SFP were tested after 14 days. The results showed the best properties were obtained at 5% tire rubber powder and 15% zeolite content.

1. Introduction

There are several disadvantages associated with the asphalt concrete mixture due to its low compressive and flexural strength, stability, and permeability [1]. However, these parameters tend to reduce the durability of the mixture due to climatic influences and repetitive loads [2,3]. Moreover, asphalt concrete pavement with continuous gradation also reduces the permeability and affects the traffic comfort of the puddle length due to slip [3,4]. Setyawan [5,6], however, reported using the right type of asphalt concrete is one of the best ways to achieve quality pavement. On the other hand, porous asphalt contains a small amount of bitumen which has the ability to peel off the aggregates and this means it is necessary to include some additives such as waste tire rubber (WTR) to increase the adhesion between the asphalt and the aggregate. Furthermore, the service period of a pavement increased when appropriate additives are administered in the asphalt binder [7,8].

Semi-flexible pavement (SFP) consists of porous asphalt which is a mixture of asphalt matrix with open-graded aggregate void ratios of 20–30% grouted with selected cement mortar to overcome inherent problems [9–11]. Its quality is, however, influenced by

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several factors such as aggregate properties, gradation, mixed stiffness, quality, and content of cement mortar [12,13]. Cement mortar is a mixture of cement, sand, and water at certain mix proportion while the main chemical composition of natural zeolite is silica which makes it applicable as a replacement for cement in the production of the mortar. The inclusion of this zeolite at certain contents makes the mortar denser and increases its strength.

The addition of WTR powder to the asphalt binding material tends to improve its properties by increasing its resistance to permanent deformation, reducing fatigue damage and potential for thermal cracking, lowering the thickness of the pavement structure, and decreasing the possibility of reflective cracking [14–16]. Cement mortar acts as a cavity-filling material in manufacturing SFP by injecting the porous asphalt cavities to ensure more rigidity and, with the use of appropriate composition for the Void in the Mix (VIM), it has also been reported to have the ability to produce a good pavement with maximum strength [17,18]. However, it needs to possess a low viscosity close to water to achieve sufficient strength [19]. In addition, the binding materials of the mortar should be modified to ensure high quality, increase stiffness value, and stability with further effects on the SFP performance, especially the flexibility and stability [20,21].

Over recent years, the use of WTR as additive in asphalt mixtures has been extensively researched [22–25]. A theoretical model to design WTR asphalt mixtures and its validation by experimental tests has been also conducted [26]. Many aspects of the WTR on properties of asphalt mixtures have been studied such as durability, stability, damage resistance and fatigue behavior [27–33]. However, the effect of WTR with additional natural zeolite as a partial substitution for cement mortar in the porous asphalt is not fully understood yet. Further, very limited research and literature can be found where the effect of WTR with additional natural zeolite on the performance of SFP has been reported.

The purpose of this study, therefore, was to increase the performance of SFP mixtures with additional WTR using natural zeolite as a partial replacement of cement in the mortar grouted into the porous asphalt cavities. The performances evaluated include the compressive/flexural strength, drying shrinkage, permeability, durability, and stress/strain relationship. In addition, optimum proportions of WTR and natural zeolite were used.

2. Materials and methods

2.1. Materials

The materials used for the production of the porous asphalt include coarse and fine aggregates, asphalt, and WTR powder while the grouting material was made from the use of mortar containing cement, natural zeolite, and fine aggregates. It is important to note that the WTR powder was applied as an additive while natural zeolite substituted some portion of the cement.

The coarse aggregates were open-graded rocks with a maximum grain size of 19 mm in accordance with AAPA 2004 specifications [34] and obtained from the stone crusher industry in Aceh Utara District, Indonesia while the fine aggregates were river sands with a maximum diameter of 4.75 mm from Sawang River in Aceh Utara District. The physical properties of these aggregates are shown in Table 1 while the gradation of the mixed ones is presented in Fig. 1.

Table 1
Physical properties of the coarse and fine aggregates.

Physical properties	Coarse Aggregate	Fine Aggregate
Bulk density (kg/m^3)	2340	2521
Apparent specific gravity	2.467	2.598
Absorption (%)	1.937	1.890

The 60/70 penetration asphalt made by PT Pertamina with a specific gravity of 1.00, softening point over 48 °C, and flash point at 232 °C was used while the WTR powder applied is commercially available with the size lesser than 4.75 mm as shown in the particle-size distribution in Fig. 2. Moreover, the cement used was the Portland Cement type II made by PT Semen Andalas Indonesia with a specific gravity of 3.16 while the natural zeolite was obtained from Ujong Pancu Village, Aceh Besar Regency, Indonesia, mashed and sieved to ensure it passed through sieve #200. The powder obtained was activated using 30% hydrochloric acid (HCl), washed with distilled water, and dried at room temperature before it was used. The chemical composition of the activated zeolite powder was examined using an XRF test and the results are shown in Table 2. It is important to note that the size of the zeolite powder ranged between 0.36 μm to 43.09 μm as indicated in the particle-size distribution in Fig. 3.

2.2. Determination of optimum asphalt content (OAC)

The optimum asphalt content (OAC) was determined through the use of Bina Marga Standard (2010) [35]. This involved the production of specimens in the form of a cylinder with a diameter of 102 mm and a height of 64 cm and the contents of the asphalt varied at 3%, 3.5%, 4%, 4.5% and 5% with three specimens made for each content for Marshall testing. These values were used because the usual content is in the range of 3% to 5% [36]. Meanwhile, the experimental work was conducted carefully to ensure uniformity since the specimens were limited at 3 for each asphalt content and the coefficient of variance of the test results did not exceed 10%. Moreover, the Marshal specimens which are a mixture of 60/70 penetration asphalt and aggregate was conducted based on ASTM D6927 [37] and the average results for all the specimens and the AAPA 2004 requirements are shown in Table 3**.** This table shows the asphalt contents which are in line with the AAPA requirements are 3% and 3.5% and due to the effectiveness of asphalt pavement stability for high content of asphalt, an OAC of 3.5% was selected for this study.

2.3. The production of the porous asphalt specimens

The porous asphalt specimens were made using the 3.5% OAC after which the WTR powder was added using 3%, 4%, and 5% of the asphalt weight to obtain 3 different mixtures. The asphalt was heated up to 160 °C and the proposed content of the WTR powder was added, stirred evenly, and heated for approximately

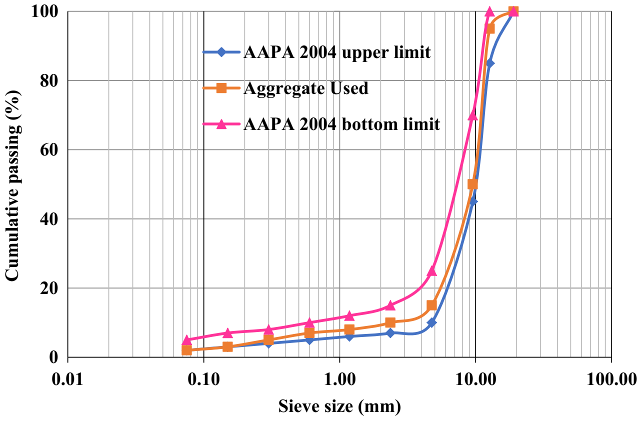

Fig. 1. Mixed aggregate gradation.

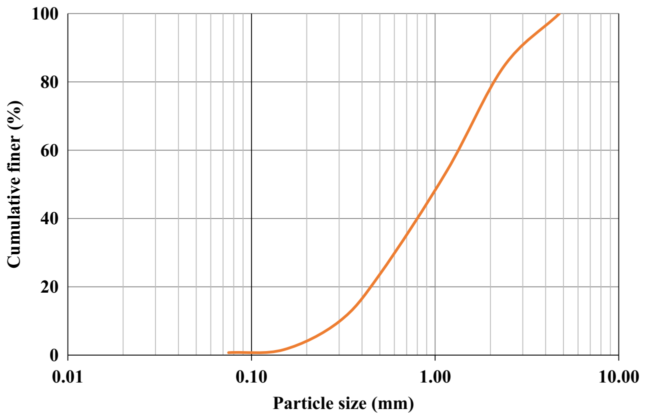

Fig. 2. Particle size distribution of WTR powder.

Table 2
The composition of the chemical compounds of natural zeolite.

The oxide	Percent (%)
S_iO_2	46.57
Al_2O_3	16.58
Fe_2O_3	10.21
CaO	8.77
MgO	4.81
Na_2O_3	2.97
K_2O	0.87
MnO	0.14
TiO_2	0.83
P_2O_5	0.14
Loss of ignition	7.75

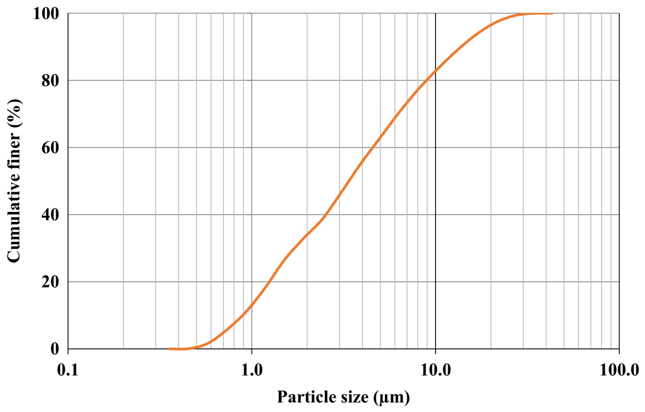

Fig. 3. Particle size distribution of zeolite powder.

5 min. Moreover, the aggregate was heated at 170 °C, added to the asphalt and WTR mixture, and stirred for approximately 15 min at a continuous heat of 160 °C after which the mixture was poured into a mold and compacted at 140 °C. The specimens for the compressive strength, drying shrinkage, and stress–strain relationship tests were cylinders with 102 mm diameter and 64 mm high while those for the flexural test were 65 mm × 75 mm × 300 mm blocks. However, 12 samples were made for each test and WTR content and the mold was opened after one day.

2.4. Grouting mortar into the test specimens

After 3 days of production, the mortar was grouted into the specimen. The mortar was first produced through the even mixture of cement, fine sand, and water. It is important to state that the cement and fine sand were mixed at a ratio of 1:2 based on volume while sufficient water was added to ensure the mixture was not too thick nor too runny. Moreover, the fluidity was evaluated using a hydraulic mortar test which involved the passage of the mixture through the funnel of the test equipment for 5 to 10 s to determine if its flow rate fulfilled the requirements of the Road Engineering Association of Malaysia (REAM SP5) [38]. This standard was employed due to the absence of adequate requirement on flow of SFP grouting mortar in Indonesia. Four different mortar mixtures were made and these include the replacement of cement by the activated natural zeolite at 0%, 5%, 15%, and 25% of cement weight, respectively. Grouting the mortar with the specimen started with the insertion of the mortar into a provided container after which the specimen was added and vibrated using a portable mortar vibrator to make mortar enter the cavity of the porous asphalt specimen. Furthermore, for each different zeolite content, 3 SFP specimens were obtained and treated through open exposure at room temperature.

Fig. 4. Compression test.

Table 3
Marshall testing results for the determination of OAC.

Marshall Parameter	Asphalt Content (%)					AAPA (2004) Requirements
	3.0	3.5	4.0	4.5	5.0	
Stability (kg)	503	512	470	362	356	≥ 500
Flow (mm)	3.97	5.60	4.00	5.78	5.53	2–6
Void in the mix, VIM (%)	24.95	24.70	22.64	18.43	13.88	18–25

Fig. 5. Flexural test.

2.5. Mechanical properties test of the SFP specimens

The mechanical properties of SFP specimens were tested 14 days after the grouting. The compressive strength test was conducted using a compression testing machine with 2000 kN capacity, and the process involved introducing a load on the cylindrical specimen up to when it fractured according to ASTM D1074 standards [39] as shown in Fig. 4. Moreover, the flexural test was conducted using a machine with 100 kN capacity, and the process involved the placement of the specimen on two supports after which a two-point load was introduced until it broke (Fig. 5). The stress-strain relationship was tested using the same method with the compressive strength, but during the loading process, the increase in the load was measured using a load cell while the shortening observed with the specimens was evaluated through the use of 2 CDP-100 type transducers (Fig. 6). Furthermore, the strain was calculated based on the average value recorded from the two transducers. Unlike the compressive strength tests, a compression testing machine with 1000 kN capacity was used.

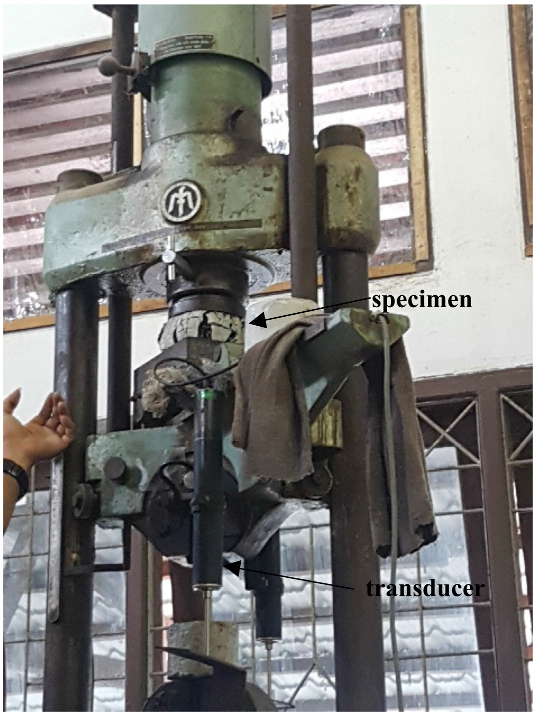

Fig. 6. Stress-strain test.

2.6. Drying shrinkage test

Drying shrinkage of the SFP was tested by immersing the grouted specimens for 24 h in the water, wiped after removal and the length of the specimens was measured after which the specimens were stored in a storage room for 14 days and the length of the specimens was measured again afterward. The value of the drying shrinkage was calculated by comparing the reduction and the original length of the specimen in percentage.

3. Test results and discussion

3.1. Compressive strength

The average compressive strength for the SFP from each of the 3 variations of WTR and natural zeolite was plotted in Fig. 7. The results showed that there was a significantly increase of compressive strength with the increase in the zeolite content from 0 to 15% while slightly decrease at percentage of 25%. The increase in the compressive strengths at 10% and 15% were reported to be caused by the presence of zeolite in the mortar which made it denser after hardening compared to the composition without the mineral. This is associated with the reaction of the silica (SiO_2) in zeolites with the calcium hydroxide ($Ca\ (OH)_2$) which is a by-product of the hydration process of cement in a mortar to form calcium silicate hydrate. This, therefore, led to the increase in the density and compressive strength of mortar, and consequently, for the SFP. However, at 25% zeolite, the amount of SiO_2 in the mixture exceeded the requirement for the reaction leaving some of it unreacted and this weakened the compressive strength of the mortar and the SFP as a consequence. Furthermore, the figure also shows the highest value of compressive strength was recorded at 5% WTR and 15% zeolite.

3.2. Flexural strength

The average flexural strength value of the SFP for each variation of WTR and natural zeolite was plotted in Fig. 8. The results showed 5% WTR has the highest value for all the mixture except for 25% zeolite. As with the compressive strength, the substitution of the cement with natural zeolite by up to 15% increased the flexural strength of the SFP but the value decreased at 25%. The highest value was also observed with 5% WTR and 15% natural zeolite.

3.3. Drying shrinkage

The average drying shrinkage value of the SFP for each variation of WTR and natural zeolite was plotted in Fig. 9. The results showed the SFP with mortar containing zeolite has a smaller drying shrinkage value compared to those with ordinary sand and cement and this was associated with the high density of the specimen with the mineral. However, in contrast to compressive and flexural strengths, at 15% zeolite, 5% WTR showed a poor performance compared to 3% and 4% as observed with their higher values. Moreover, the smallest value was obtained with 4% WTR and 15% zeolite but this was not very different from the value obtained for 5% WTR. For the other mixtures of 0%, 5% and 25% zeolite, 5% WTR was observed to have a smaller value compared to 3% and 4% which showed better performance. However, 5% and 15% zeolite were recorded to have the smallest values at 5% WTR with an insignificant variation. However, the drying shrinkage is not an important factor compared to compressive and flexural strengths. Therefore, even though the drying shrinkage value at 5% WTR and 15% natural zeolite was greater, based on compressive strength and flexural strength data, the mixture of SFP with 5% WTR showed the best performance compared to 3% and 4%.

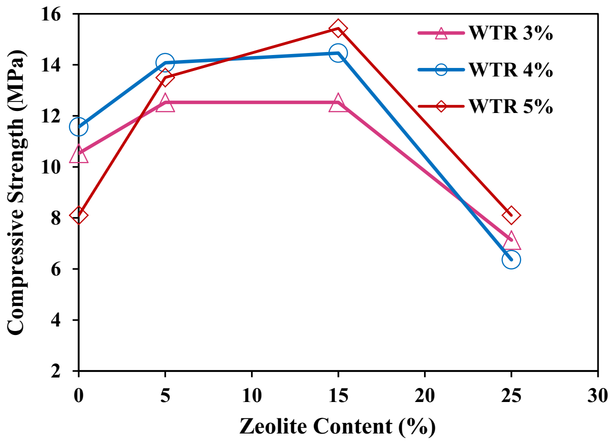

Fig. 7. Compressive strength of SFP.

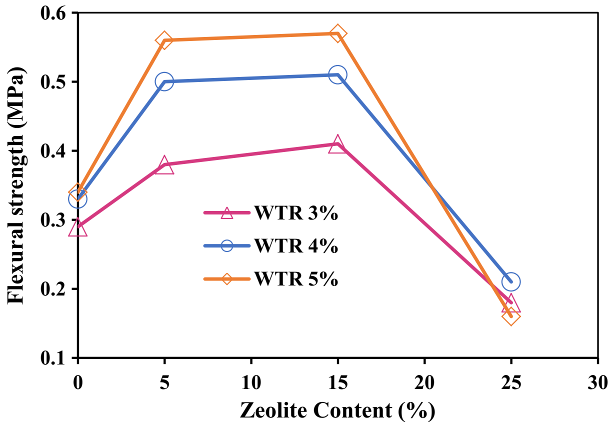

Fig. 8. Flexural strength of SFP.

3.4. Stress-strain relationship

The stress-strain relationship of the SFP at 3%, 4%, and 5% WTR are shown in Figs. 10–12, respectively. Due to the use of load control (deformation control is not applicable in the test equipment), only the stress-strain curve in the ascending branch was successfully recorded. After the maximum load, the specimen was immediately destroyed without any record of the values from the descending branch. Moreover, the shape of the curve for all the variations was discovered to be almost the same. At the beginning of the loading until the stress reached 14% to 20% of the maximum stress, the relationship was linearly elastic after which the stiffness of the SFP decreased from the initial value. This shows a micro-crack started after the SFP was loaded up to 14% and 20% of the compressive strength and after this percentage was exceeded, the relationship was discovered to be linear up to maximum stress with a lower stiffness. It is importance to note that for 5% WTR and 15% zeolite which has the highest compressive and flexural strengths, the relationship was almost linear from the beginning of the loading until the maximum strength. This, therefore, means there was no cracking during the loading process at 5% WTR and 15% zeolite up to when the maximum load was reached.

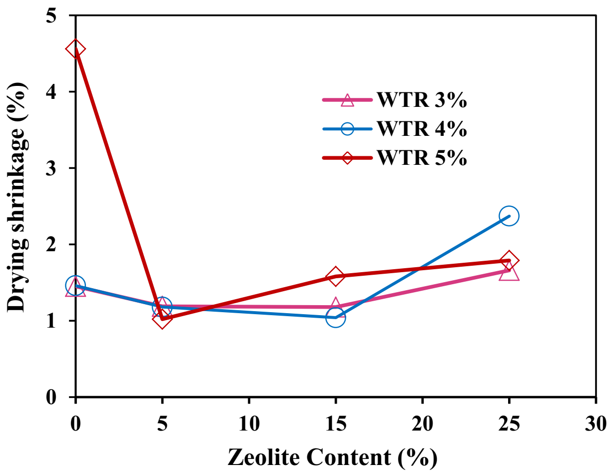

Fig. 9. Drying shrinkage of SFP.

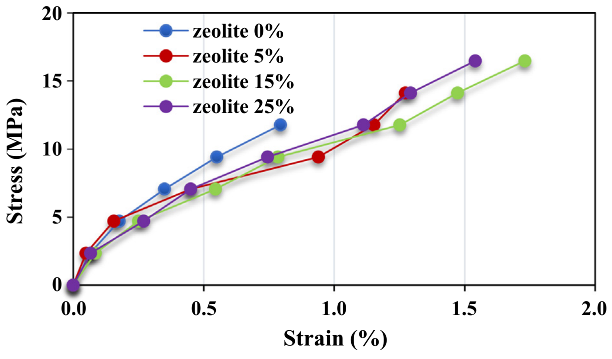

Fig. 10. Stress-strain relationship of SFP with an additional 3% WTR.

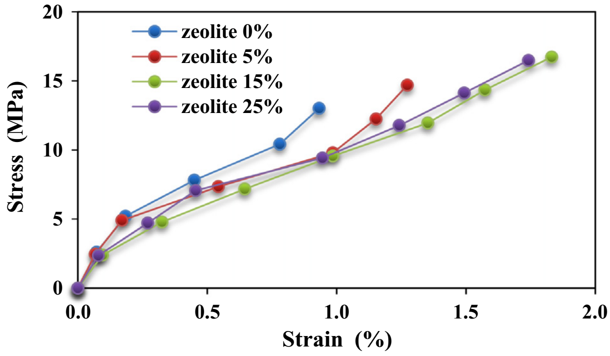

Fig. 11. Stress-strain relationship of SFP with an additional 4% WTR.

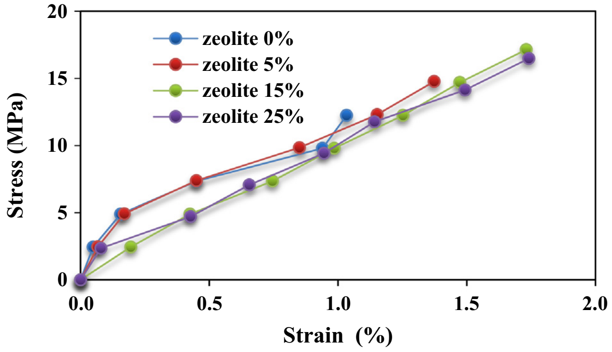

Fig. 12. Stress-strain relationship with an additional 5% WTR.

3.5. Initial modulus of elasticity

The initial modulus of elasticity was calculated from the stress-strain relationship data. This involved comparing the stress and strain under linear conditions to obtain the magnitude of the elastic modulus for all the variations as shown in Fig. 13. The results showed the lowest values were obtained at 15% zeolite and this means greater deformation was experienced at this mixture compared to others at the beginning of loading.

3.6. Modulus of elasticity after crack

Figs. 10-12 show the SFP experienced a micro crack as observed from the drastic reduction in its stiffness and the stress–strain relationship subsequently tended to be linear again up to when the maximum stress was reached. Therefore, the modulus of elasticity after crack was calculated based on the slope of the stress–strain curve after the initial crack occurred and the magnitude is shown in Fig. 14. The figure shows the elastic modulus after the crack is almost the same for all mixtures, except for 3% and 4% WTR without zeolite which was found to have higher values.

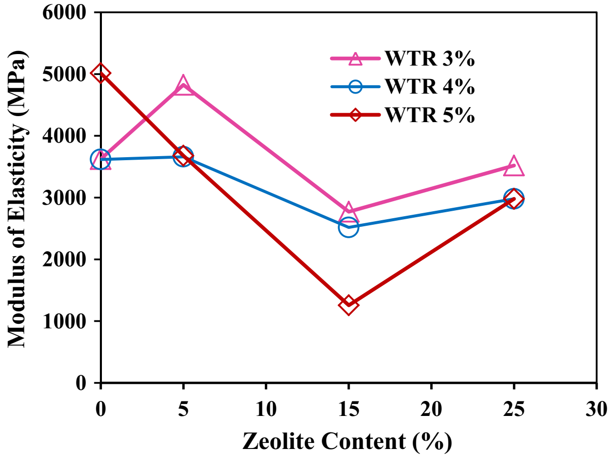

Fig. 13. Initial modulus of elasticity.

4. Durability of SFP

Due to the fact that the performance of SFP with an additional 5% WTR was better than 3% and 4%, the durability was tested on the SFP using only the 5% WTR mixture. This involved the use of a cylinder with a diameter of 102 mm and a height of 64 mm after 14 days the cement mortar was grouted. The specimens were immersed in a 5% HCl solution in order to wear out their surface and Marshall testing was conducted to obtain stability and compared the results in percent after being immersed for 30 min and 24 h. The magnitude of the durability is presented in Fig. 15 and it shows the value is increasing with the zeolite content up to 15% and later decreases at 25%. However, the best value was obtained at 15%.

According to Bina Marga Standards (2010), the pavement durability for asphalt roads is required to be greater or equal to 80% and the results showed all the fulfilled this requirement. The figure shows the SFP without the use of natural zeolite and at 25% are within the limits while 5% and 15% have better values.

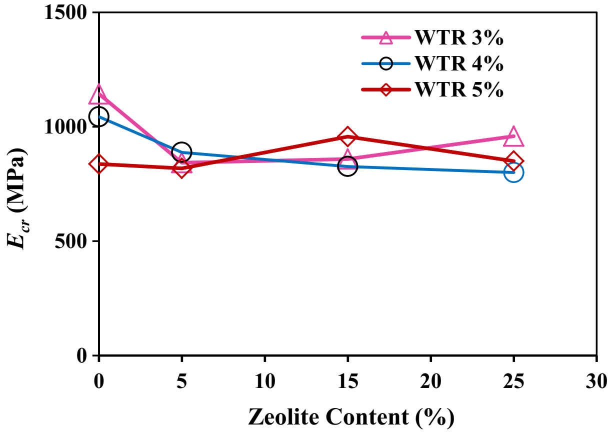

Fig. 14. Modulus of elasticity after crack (E_{cr}).

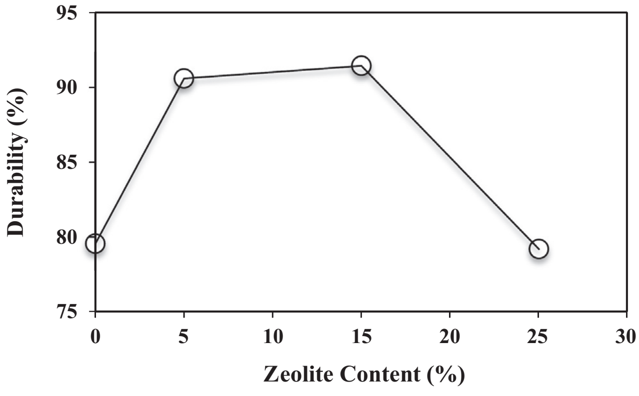

Fig. 15. Durability of SFP.

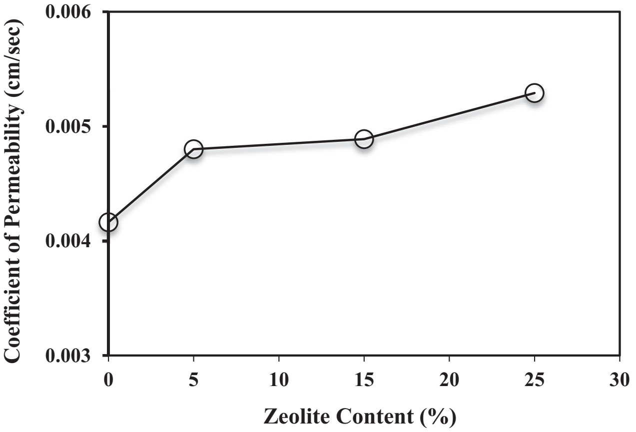

Fig. 16. Coefficient of permeability.

5. Permeability of SFP

Permeability is the rate at which the material allows the passage of water through it. In accordance with durability, this property was tested only for the mixtures with an additional 5% WTR using cylinders with a diameter of 60 mm and a height of 40 mm and by applying a falling head system. Before the test, the specimen was immersed up to the saturation point and the time required for water as high as 5 cm above the specimen to seep down was measured to obtain the magnitude of the permeability coefficient and the results are presented in Fig. 16. The value was observed to be increasing with the zeolite content. This, however, means the SFP pavement with high permeability has the ability to absorb puddles on the road after rain faster.

6. Conclusions

Based on the results in this study, the following conclusions can be drawn:

1. It is possible to replace some quantities of cement with natural zeolite in grout mortar needed in porous asphalt. The mixture with the highest compressive and flexural strengths was found to be 15% zeolite. It was also discovered to have the ability to reduce drying shrinkage and increase the semi-flexible pavement permeability and durability. Moreover, the addition of 5% waste tire rubber was also found to have the best performance.
2. The stress–strain curve of semi-flexible pavement was linearly elastic with the slope to be equal to the initial elastic modulus up to the start of the microcracks which occurred at 14% to 20% of the compressive strength. After the crack, the stiffness was observed to have decreased drastically and the curve became linear again with reduced stiffness.

CRediT authorship contribution statement

Hamzani: Methodology, Investigation, Writing - original draft. **Munirwansyah:** Supervision. **Muttaqin Hasan:** Conceptualization, Visualization, Writing - review & editing. **Sugiarto Sugiarto:** Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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