Journal of Engineering Science and Technology
Vol. XX, No. Y (Year) PPP - QQQ
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THE RESILIENT MODULUS AND AGEING INDEX OF PALM KERNEL SHELL ASPHALT MIXTURE FOR MEDIUM TRAFFIC FLOW AT DIFFERENT TEMPERATURES

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Abstract

The main problem with roads is pavement failures due to cracking, fatigue, and rutting. This study uses varying percentages of 10, 20 and 30% palm kernel shell (PKS) by weight of the total aggregates as a partial replacement for coarse aggregate in asphalt mixtures mixed with 60/70 penetration grade bitumen to enhance the pavement performance. The preparation of asphalt mixture samples uses the Marshall Mix Design Method, and the asphalt mixtures were compacted at 50 blows to simulate medium traffic flow and subjected to short-term ageing (STA) and long-term ageing (LTA) conditions. The resilient modulus (M_R) test was conducted at 25 and 40°C to assess the fatigue and rutting of the mix design samples and calculates the ageing index (AI) to evaluate the effect of PKS in delaying the ageing of asphalt mixtures. Results revealed that substituting the coarse aggregate with 10 and 20% PKS increased the asphalt mixtures' resistance to fatigue by 0.6% and 1.1% respectively for STA samples and 2.0% and 2.3% respectively for LTA samples. Results at high temperature and for all ageing conditions showed that only 10% PKS asphalt mixture was more resistant against rutting failure with higher M_R value of 0.7% and 0.6% subjected to STA and LTA when compared to control sample. Replacing the coarse aggregate with 10% PKS lowered the AI value of the asphalt mixture which slower the oxidation process.

Keywords: Palm Kernel Shell, Asphalt Mixture, Resilient Modulus, Ageing index, Marshall Mix Design

1. Introduction

Pavement technologists have shown keen interest in using waste materials, such as palm kernel shell (PKS), nickel slag, nano metakaolin, rice straw, and eggshells, to modify asphalt mixtures [1, 2]. These waste products are one option for replacing the important materials used in road construction, such as aggregates. [3, 4]. Meanwhile, they have demonstrated that these waste materials can improve the qualities of asphalt mixtures by reducing pavement failures, such as fatigue, rutting, and cracking resistance, and thus produce more resilient and long-lasting pavements.

PKS is a high-energy biomass fuel typically discarded as agricultural waste [5] . Malaysia produces four million tonnes of PKS each year [1,6]. Abdullah et al. [7] estimated that about five million hectares of palm oil plant were planted in 2020. Furthermore, Malaysia is the world's second-largest palm oil producer and produces significant amounts of palm oil waste. According to Ikumapayi et al. [5], PKS has technical and environmental benefits and is widely used in various applications, including additives, energy production, reinforcement, aggregation, water purification, and composite matrix. Researchers utilise PKS as a modifier in asphalt mixtures to preserve the environment [7-10].

Among the concern with pavements in Malaysia are fatigue, rutting, cracking, and the increasing cost of construction materials [11-13]. Researchers have been experimenting with using agricultural waste as an aggregate replacement to reduce costs while ensuring its potential resources as modifier. Furthermore, the increasing demand for construction materials has a detrimental effect of depleting aggregate deposits and causing environmental deterioration and ecological imbalance. Researchers have investigated the feasibility of using aggregate replacement materials in asphalt mixes, such as rubber, sugar cane, coconut shell, and PKS. PKS is a by-product of the palm oil manufacturing process [11, 14].

Asri et al. [15] partially replaced the coarse aggregates in asphalt mixtures with PKS and determined the asphalt mixtures' optimum bitumen content (OBC) and volumetric properties. They substituted various aggregate gradations with 10, 20, and 30% PKS bound by 60/70 penetration grade bitumen. Compared to the control sample, the OBC sample with 30% aggregate substitution had the highest OBC value, and the volumetric characteristics of the PKS samples were within the specified limit. The study result indicated that PKS is a promising waste material for coarse aggregate substitutes in asphalt mixes.

Ndoke [16] used PKS as a partial coarse aggregate replacement in asphalt mixtures and assessed its performance by measuring the strength of the asphalt mixtures based on the stability and flow values. They incorporated varying weight percentages of 10, 20, 30, 50, and 70% PKS as a substitute for the total coarse aggregate, mixed it with 60/70 penetration grade bitumen and compacted the asphalt mixtures with 50 blows to simulate a medium traffic flow. The results showed that it was possible to substitute the coarse aggregates with up to 30% of PKS. The optimal substitution for heavy traffic flow is 10% PKS, and a 100% substitution was possible for roads with light traffic in rural areas.

A previous study showed that PKS substitution of the aggregates was feasible for low, medium, and heavy traffic designs. Abdulwahab et al. [17] substituted the coarse aggregates with 50 and 100% PKS for medium traffic flow design. Up to 80% PKS could be utilised as a partial substitute for the coarse aggregate in asphalt mixtures for light, medium, and high traffic flow. However, the substitution could reduce the strength of an asphalt mixture in a water-logged environment since PKS has a higher water content absorption value than granite.

Oyedepo et al. [18] researched replacing the fine and coarse aggregates in asphalt mixtures with varying percentages 20, 40, 50, 60, and 80% of crushed palm kernel shell (CPKS) and PKS by weight of the total aggregates. The results showed that PKS was a suitable substitute for coarse aggregates for roads with light, medium, and heavy traffic flow, where those with heavy traffic required replacing the fine aggregates with up to 20% CPKS and those with medium traffic with 60% CPKS. They concluded that substituting the fine and coarse aggregates in asphalt mixtures with PKS reduced construction costs.

This study investigated the fatigue and rutting performance of asphalt mixtures containing 10, 20, and 30% PKS as a substitute for the coarse aggregates subjected to two ageing conditions at different temperatures. The study also compared the ageing index (AI) of the PKS asphalt mixture designed for medium traffic flow with a Hot Mix Asphalt (HMA) mixture.

2. Materials and Method

2.1 Materials

This research used varying percentages of 10, 20, and 30% PKS by weight of total aggregates as a partial substitute for coarse aggregates in asphalt mixtures. Bio-Eneco Sdn Bhd supplied the PKS (Fig. 1), which measures about 15mm and retains on the No.4 sieve (5 to 14mm). The shell surface is either concave or convex, smooth, flaky, parabolic, and angular. The PKS was washed with hot water to eliminate dust and other contaminants that could have adverse effects on the asphalt mixture, sun-dried and then oven-dried at 400°C [19]. Table 1 presents the physical characteristics of the PKS, and Table 2 shows the physical properties of the 60/70 penetration grade bitumen used in this study.

Fig.1. The PKS used in this study

Table 1. Physical properties of the PKS

Properties	Unit	Value
Bulk density	mg/m3	0.74
Dry density	mg/m3	0.65
Void ratio	-	0.40
Porosity	%	28
Water content	%	9
Water absorption	%	13
Specific gravity	-	1.62
Impact value	%	4.50

Table 2. Physical properties of the bitumen

Properties	Unit	Specification	Value	Standard Test Method
Penetration at 25°C	0.1 mm	60-70	66	ASTM D5
Softening	°C	47-52	49	ASTM D36
Viscosity at 135°C	mPa.s	-	550	ASTM D113
Ductility at 25°C	cm	>100	100	ASTM D4402
Specific gravity	-	1.0-1.06	1.03	ASTM D70

2.1 Asphalt mixture preparation

The material used to prepare the unmodified and modified asphalt mixture are PKS, aggregates, filler, and bitumen. The OBC for the control sample was 5.40%, while the PKS asphalt mixture was based on the previous study by Asri et. al [15], as shown in Table 3. The aggregate gradation was based on the ACW14-wearing coarse selected for the mixture design in compliance with the Public Works Department of Malaysia specification (JKR/SPJ/2008-S4) shown in Fig. 2. The filler is a 2% Ordinary Portland Cement by aggregate weight. The mix aggregate gradation and bitumen content design used the Marshall Mix Design Method, which ensures the temperature remains at 160°C. After completely coating the aggregate and bitumen, the samples were poured into the mould and allowed to cool to 145°C before being compacted with 50 blows on each side using a Marshall compactor. The unmodified (HMA) and PKS asphalt mixture samples were designated 0-PKS, 10-PKS, 20-PKS, and 30-PKS.

Table 3. Percentage of the OBC [10]

PKS (%)	OBC (%)
0	5.40
10	5.30
20	5.32
30	5.53

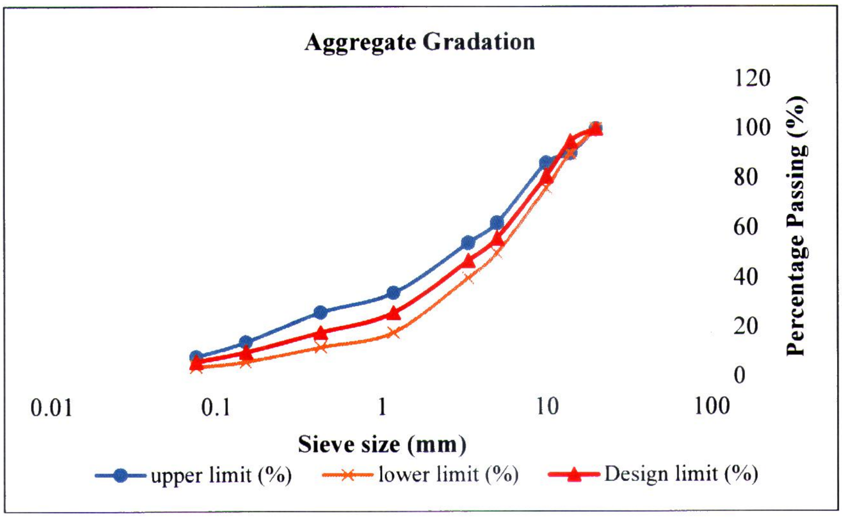

Fig. 2. Aggregate gradation limit

2.2 Ageing of the asphalt mixture

Short-term ageing (STA) describes the hardening of an asphalt mixture that occurs when mixing and compacting the asphalt mixture at high temperatures [20]. The hardness is caused by the volatilisation and degradation of the bitumen's lighter aromatics when exposed to high temperatures. After thoroughly mixing the sample at 160°C, the loose mixture was placed on the pan and put in a 135°C oven for four hours before compacting. All mixture samples were compacted with 50 blows on each side and cooled to room temperature before being extracted from the mould [21].

Long-term ageing (LTA) occurs when an asphalt mixture is exposed to the environment at a relatively low temperature for an extended period. The sample must first go through the STA condition before achieving the LTA condition. This study placed the compacted STA samples in an 85°C oven for five days to simulate the LTA condition. The samples were not tested for at least 24 hours after removal from the oven to ensure they had achieved the desired ageing [22].

2.3 Resilient modulus test

The resilient modulus (M_R) test investigates a pavement mixture's responsiveness to traffic loading by measuring the indirect tensile strength of the material under pulse repetition. The test is widely used to characterise the elastic behaviour of asphalt mixture and evaluate its performance under cyclic axial stress [23]. The criteria assessed in the lab are specified by the American Society for Testing and Materials (ASTM D4123). in This study employed the Universal Asphalt Testing Machine shown in Fig 3 to investigate the pavement performance under the M_R characteristics of the HMA and PKS asphalt mixtures. All samples were analysed at 25 and 40°C after a two-hours conditioning. The 25°C temperature was selected based on the mixture's resistance to fatigue, whereas the 40°C temperature was selected based on the mixture's resistance to rutting, also known as permanent deformation [24]. The test also computed the vertical strain at the top of the subgrade layer and the horizontal strain at the bottom of the asphalt layer. The M_R test was conducted to determine if substituting PKS as a partial replacement for the coarse aggregates changed the stiffness properties of the asphalt mixture. Table 4 presents the standard parameters of the test.

Table 4. Resilient modulus parameters

Parameters	Values
Temperature (°C)	25 and 40
Load pulse (ms)	100
Pulse repetition period (ms)	1000, 2000 and 3000
Frequency	0.1s load width and 0.9s rest period
Load repetition	5 (each specimen)

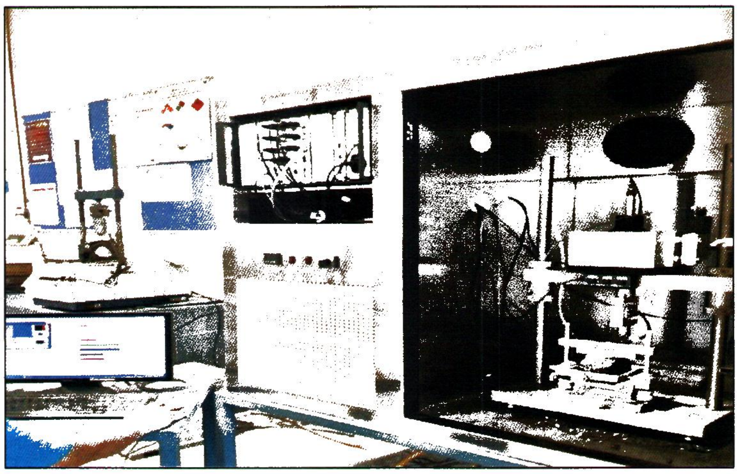

Fig. 3. Universal Asphalt Testing Machine

2.4 Resilient modulus ageing index

This study calculated the AI to evaluate the effect of PKS in delaying the ageing process of the PKS asphalt mixtures. The calculation used Eq. (1), where M_R (aged) is the M_R value after ageing, and M_R (unaged) is the M_R value in the initial state. The AI values for each ageing condition were analysed, where lower AI value indicates that the sample has a lower rate of ageing. The AI values for the PKS asphalt mixture were compared with the control sample to determine the effect of the PKS in delaying ageing process.

$$Ageing\ index\ (AI) = \frac{M_R\ (aged)}{M_R\ (unaged)} \tag{1}$$

3. Results and discussions

3.1 Resilient Modulus at 25°C

Fig. 4 shows that PKS changed the M_R values of the unaged (UA) asphalt mixture samples tested at 25°C. The M_R values of the 10-PKS and 20-PKS asphalt mixtures were higher than the 0-PKS asphalt mixture after compaction with 50 blows. However, the M_R values of the 30-PKS asphalt mixture was lower than the 0-PKS asphalt mixture, possibly because the high water content of PKS reduced the asphalt mixture's resistance to fatigue failure. The highest M_R value of 4460 MPa after compaction with 50 blows was recorded for the 20-PKS asphalt mixture, followed by 4425 MPa for the 10-PKS asphalt mixture, 4317 MPa for the 0-PKS asphalt mixture, and 2908 MPa for the 30-PKS asphalt mixture. The M_R value of the 10-PKS asphalt mixture was 2.6% higher than the 0-PKS asphalt mixture for all pulse repetitions, while the M_R value of the 20-PKS asphalt mixture was 4.0% higher. However, the M_R value for the 30-PKS asphalt mixture was 35.4% lower than the 0-PKS. In addition, increasing the pulse repetition from 1000 ms to 3000 ms resulted in a gradually smaller M_R value. Overall, the M_R value for all PKS percentages after compaction with 50 blows showed a similar trend. This result is consistent with previous study, which showed that PKS was a suitable replacement for 10% of the coarse aggregates for heavy traffic conditions, and up to 50% of the coarse aggregates in roads with light traffic could be replaced with PKS and compacted with 50 blows [19].

Fig. 5 shows that adding PKS to asphalt mixtures and compacting with 50 blows affected the M_R value of the STA asphalt mixtures. The M_R values for the 10-PKS and 20-PKS asphalt mixtures were higher than the 0-PKS asphalt mixture, but the M_R value was lower for the 30-PKS asphalt mixture. The 20-PKS asphalt mixture recorded the highest M_R value of 4553 MPa, followed by 4517 MPa for the 10-PKS mixture, 4503 MPa for the 0-PKS mixture and 3121 MPa for the 30-PKS asphalt mixture. Compared to the 0-PKS asphalt mixture, the M_R value of the 10-PKS mixture increased by 0.6 % for all pulse repetitions, while the M_R value for the 20-PKS mixture increased by 1.1% for all pulse repetitions. However, the M_R value for the 30-PKS asphalt mixture decreased by 30.7%. In addition, the M_R showed a decreasing trend when the pulse repetition was increased from 1000 ms to 3000 ms for all PKS percentages.

Subjected to LTA condition, the addition of PKS also influenced the M_R values as shown in Fig. 6. The 10-PKS and 20-PKS asphalt mixtures have higher M_R values and thus, better resistance to fatigue failure. The 20-PKS asphalt mixture has the highest M_R value of 4870 MPa, followed by the 10-PKS asphalt mixture with 4845 MPa, 0-PKS asphalt mixture with 4746 MPa and 30-PKS asphalt mixture with 3810 MPa. Compared to the 0-PKS asphalt mixture, the M_R value of the 10-PKS asphalt mixture was 2.0% higher for all pulse repetitions, while the M_R value of the 20-PKS asphalt mixture was 2.3% higher. However, the M_R value of the 30-PKS asphalt mixture was 19.7% lower. Increasing the pulse repetition from 1000 ms to 3000 ms resulted in decreasing M_R values.

The results of this study are similar to the outcome of using CPKS and PKS as a partial replacement for the coarse and fine aggregates in the asphalt mixture and compacting the asphalt mixtures with 50 blows. The results showed that PKS was a suitable substitute for the coarse aggregate of roads with light, medium, and heavy traffic; the fine aggregates for roads with heavy and medium traffic can be incorporated with 20 and 60% CPKS, respectively [25].

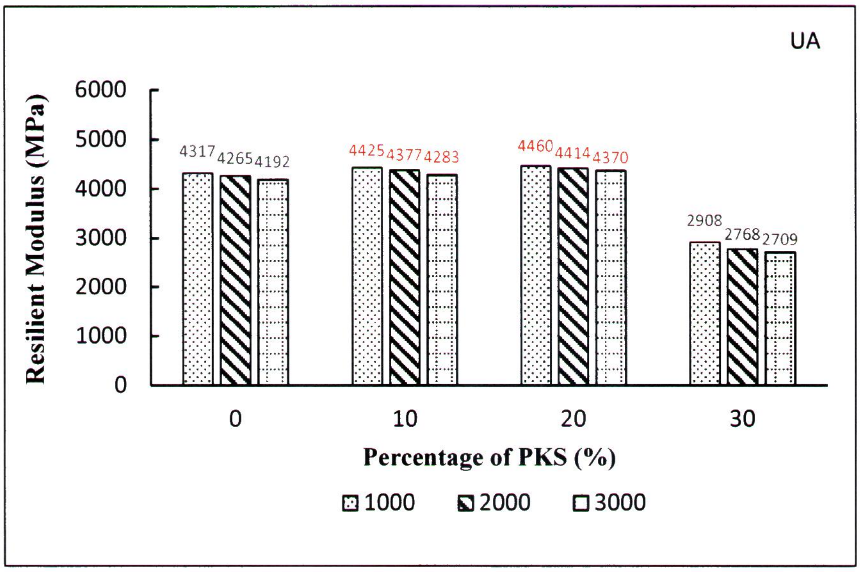

Fig. 4. M_R for the UA samples at 25°C

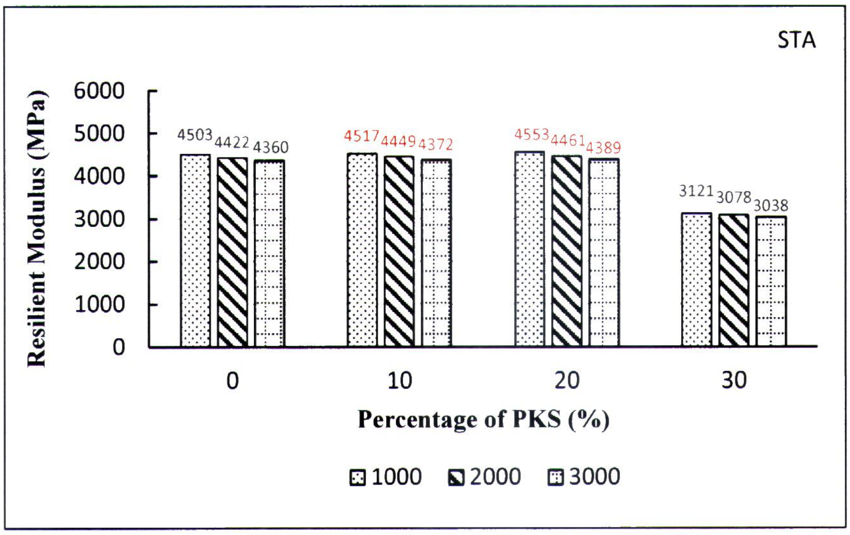

Fig. 5. M_R for the STA samples at 25°C

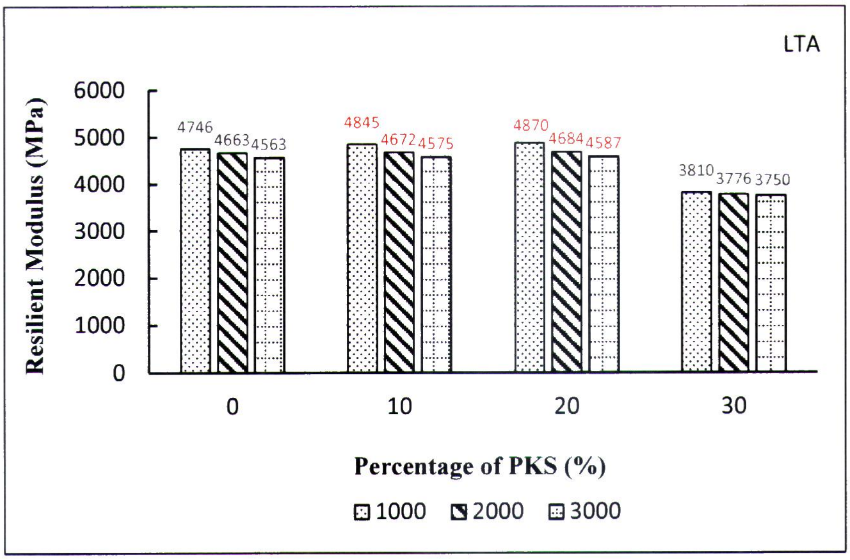

Fig. 6. M_R for the LTA samples at 25°C

3.2 Resilient Modulus at 40°C

Fig. 7 shows the changing M_R values for medium traffic flow at a high temperature. The maximum value of 1780 MPa occurred at 1000 ms pulse repetition for the 10-PKS asphalt mixture, and the lowest value of 639 MPa was at 3000 ms pulse repetition for the 30-PKS asphalt mixture in the UA condition. The graph shows that the 10-PKS asphalt mixture had the highest M_R values. The high M_R value indicates that the asphalt mixture was more resistant against rutting failure at 40°C [26].

The 10-PKS asphalt mixture had the highest M_R value of 1985 MPa for medium traffic flow under STA at 40°C and 1000 ms pulse repetition, while the lowest value of 760 MPa occurred with 30-PKS replacement at 3000 ms pulse repetition, as shown in Fig. 8. The trend is similar to the LTA condition in Fig. 9 where the 10-PKS asphalt mixture had a slightly higher M_R value, while the 20 and 30-PKS asphalt mixtures had lower M_R values. Increasing load repetition from 1000 to 3000 ms pulse resulted in gradually decreasing M_R values as the asphalt mixtures transition from UA to LTA conditions. In conclusion, the M_R values at a high temperature for all ageing conditions showed that only the 10-PKS asphalt mixture was more resistant against rutting failure for a medium traffic flow.

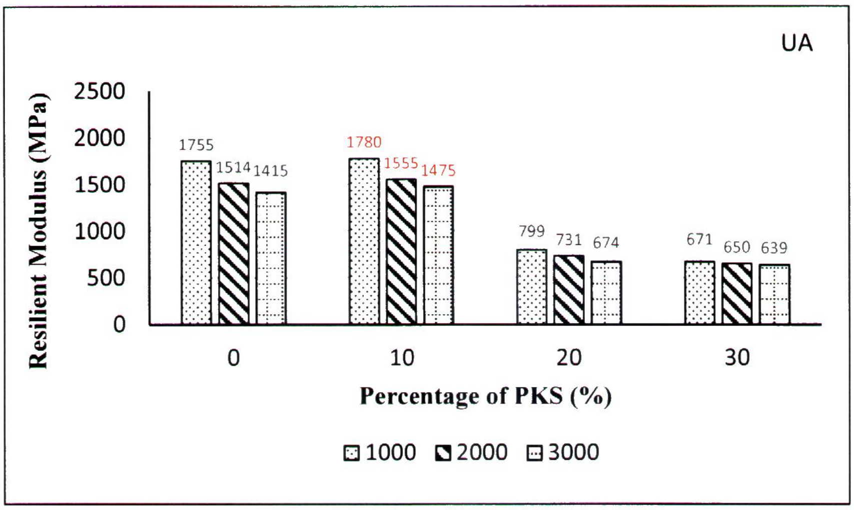

Fig. 7. M_R for the UA samples at 40°C

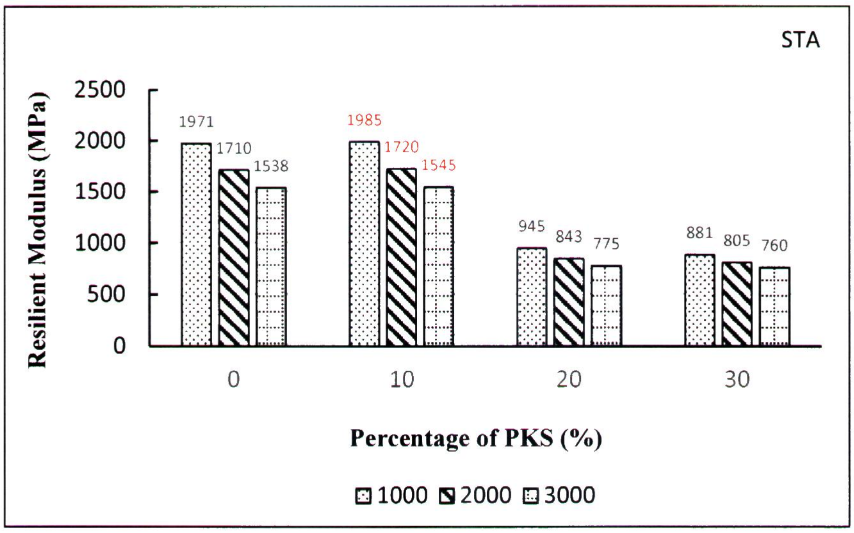

Fig. 8. M_R for the STA samples at 40°C

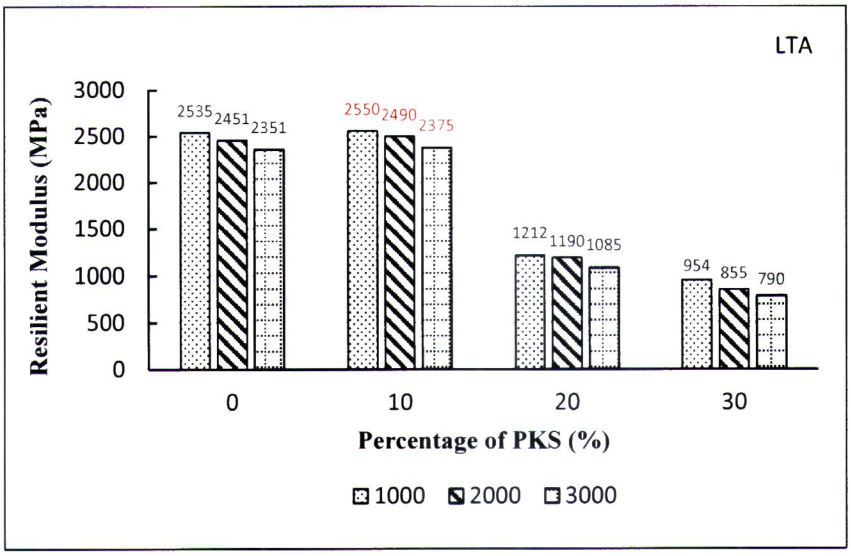

Fig. 9. M_R for the LTA samples at 40°C

3.3 Analysis of the Ageing Index

Table 5 shows that the 10 and 20-PKS asphalt mixtures had the lowest AI values under STA and LTA conditions. The control sample showed a consistent outcome. The AI value for the 30-PKS asphalt mixture was higher than the control sample under both ageing conditions. These findings demonstrate that the substitution with 10 and 20-PKS could delay the ageing process of the asphalt mixtures at 25°C.

Table 5. Ageing index at 25°C

		STA		
% PKS	**Ageing Index**			**Remark**
	1000 ms	**2000 ms**	**3000 ms**	
0	1.04	1.04	1.04	Control
10	1.02	1.02	1.02	**Lower**
20	1.02	1.01	1.00	**Lower**
30	1.07	1.11	1.12	Higher
		LTA		
% PKS	**Ageing Index**			**Remark**
	1000 ms	**2000 ms**	**3000 ms**	
0	1.10	1.09	1.09	Control
10	1.09	1.07	1.07	**Lower**
20	1.09	1.06	1.05	**Lower**
30	1.31	1.36	1.38	Higher

Table 6 shows that the AI varied at 40°C, where the 10-PKS had the lowest AI values under STA and LTA and medium traffic flow when subjected to three different load repetitions. The lower AI values achieved when substituting the 10-PKS at a high temperature made the asphalt mixture suitable for the designated traffic flow. Additionally, the AI increased when replacing the coarse aggregates with 20-PKS under STA.

Table 6. Ageing index at 40°C

	STA			
% PKS	**Ageing Index**			**Remark**
	1000 ms	**2000 ms**	**3000 ms**	
0	1.12	1.13	1.09	Control
10	1.12	1.11	1.05	**Lower**
20	1.18	1.15	1.15	Higher
30	1.31	1.24	1.19	Higher
	LTA			
% PKS	**Ageing Index**			**Remark**
	1000 ms	**2000 ms**	**3000 ms**	
0	1.44	1.62	1.66	Control
10	1.43	1.60	1.61	**Lower**
20	1.52	1.63	1.61	Higher to Lower
30	1.42	1.32	1.24	Lower

4. Conclusions

This study evaluated the pavement performance by conducting the resilient modulus test at 25 and 40°C to simulate intermediate and high temperatures, respectively. The findings of this study are as follows.

- The resilient modulus test revealed that the optimal coarse aggregate replacements for asphalt mixtures for a medium traffic flow (50 blows) are 10 and 20-PKS. These asphalt mixtures have higher M_R values under UA, STA and LTA conditions indicating higher resistance to fatigue failure. The M_R values decreased gradually from the unaged to aged condition with higher load repetitions at 25 and 40°C, indicating that the ageing reduced the M_R values.
- The AI evaluation revealed that incorporating PKS could delay the ageing process of the PKS asphalt mixtures, as indicated by the lower AI values of the 10-PKS asphalt mixtures. The analysis result was consistent at 25 and 40°C. Lower AI values indicate a slower oxidation process, which minimises brittleness and cracking in asphalt mixtures.

5. Acknowledgement

The authors wish to express their gratitude to Centre for Construction Research, Faculty of Built Environment, Tunku Abdul Rahman University of Management and Technology Malaysia for the financial support for this research (Internal Grant :UC/I/G2022-00091) and Universiti Pertahanan Nasional Malaysia for laboratory equipment's and testing used in this research.

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