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Polyethylene Terephthalate Modified Asphalt Concrete with Blended Recycled Aggregates: Analysis and Assessment

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Abstract

The research study attempts to ascertain the mechanical performance of asphalt concrete, using reclaimed asphalt concrete pavement (RAP) and recycled concrete aggregate (RCA) blends with polyethylene terephthalate (PET) as a modifier. The influence factors were evaluated, including RAP/RCA ratios and PET contents on static and cyclic performances. The static performance was assessed through the indirect tensile strength (ITS) tests, while the cyclic performance was assessed through the indirect tensile resilient modulus (IT_{MR}), indirect tensile fatigue life (ITFL), and wheel tracking tests. Compared to asphalt concrete using natural aggregate (NA), the IT_{MR} of RAP-RCA-PET asphalt concretes was higher when PET contents were between 0.2% and 0.6% for RAP/RCA = 80/20. The ITFL of RAP-RCA-PET asphalt concretes was found to be higher than that of NA asphalt concrete when PET contents ranged from 0.2% to 0.6% for RAP/RCA < 90/10. The ITFL was also higher when PET content was between 0.4% and 0.6% for RAP/RCA = 100/0. RAP-RCA-PET asphalt concretes exhibited lower rut depth than NA asphalt concrete with RAP/RCA = 90/10 and 60/40 at PET contents of 0.4% to 1.0% and with RAP/RCA = 80/20 at PET contents of 0.2% to 1.0%. The RAP/RCA = 80/20 and PET content = 0.6% were found to be the best ingredient in term of both fatigue cracking and rutting resistances. As per the systematic analysis, the fatigue distress models of RAP-RCA-PET asphalt concretes for various PET contents were developed in term of ITFL and tensile strain (ε_t) relationship and useful for mechanistic design. The results of this research will contribute to promoting RAP-RCA-PET asphalt concrete as a greener material in pavement construction.

Keywords: Reclaimed Asphalt Pavement; Recycled Concrete Aggregate; Polyethylene Terephthalate; Asphalt Concrete; Mechanical Performance; Pavement Geotechnics.

1. Introduction

Approximately 95% of the world's roads are constructed using flexible pavements, commonly known as asphalt concrete pavements [1]. These pavements consist of four layers: the subgrade layer, subbase layer, base layer, and the

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asphalt concrete surface layer [2]. Over time and under traffic loads, asphalt concrete deteriorates, leading to cracks, distortions, deformations, surface defects, and various other forms of distress [3]. The two primary types of damage caused by traffic loads are fatigue cracking and permanent deformation (rutting) [4]. Fatigue cracking occurs as cracks form due to damage accumulation from many repetitive reversible loading cycles [5]. Permanent deformation, often observed as depressions in the wheel path, is primarily caused by the repetitive passage of heavy traffic loads, especially during the summer when high temperatures reduce the viscosity of the asphalt concrete [6]. This deterioration of the road surface is typically visible in the form of cracks [7], ultimately leading to a shorter lifespan for the pavement [8]. Consequently, such issues necessitate maintenance or new pavement construction, resulting in financial losses and the depletion of natural resources. Presently, studies are focused on addressing these problems through asphalt concrete recycling to reduce the environmental impact or improving the performance of asphalt concrete mixtures to increase pavement lifespan [9-22].

Several studies have suggested using asphalt concrete and concrete wastes as sustainable recycled aggregates for the construction of pavement surfaces and structures [23-25]. According to these studies, the asphalt concrete with reclaimed asphalt concrete pavement (RAP) and recycled concrete aggregate (RCA) exhibited mechanical properties equivalent to that with natural aggregates (NA), especially for low-traffic roads. RCA has been found to provide superior mechanical properties compared to RAP [23-25]. RAP and RCA can replace NA to develop asphalt concrete with comparable performance to conventional asphalt concrete [26, 27]. Shu et al. [26] reported the significance of RAP replacement ratio (0%, 10%, 20%, and 30% by weight of NA) on the performance of asphalt concrete. Increasing the RAP replacement ratio increased the indirect tensile strength (ITS) and indirect tensile resilient modulus (IT_{MR}) but decreased the fatigue life of asphalt concrete. The improvement of ITS and IT_{MR} can be attributed to the higher stiffness of aged asphalt cement in RAP aggregate compared to new asphalt cement, which enhances the gross stiffness of asphalt concrete mixtures. However, the stiff aged asphalt cement in RAP aggregate negatively affects the fatigue resistance of the asphalt concrete due to the decreased flexibility of asphalt concrete mixtures. Abdul-Mawjoud & Ismaeel [28] also reported similar results in their study, whereby the rutting resistance and ITS increased with increasing the RAP replacement level. However, fatigue resistance decreased when increasing the RAP replacement content. Radevic et al. [29] investigated the substitution of coarse RCA (> 4.75 mm) for NA in asphalt concrete, and their findings indicated that replacing 30% of NA with RCA exhibited the highest resistance to rutting failure, resulting from interlocking and friction of rough RCA particles with sharp edges. Since RCA has higher voids and lower specific gravity, exceeding the 30% replacement of NA with RCA led to an increase in rut depth. Akkharawongwhatthana et al. [30] conducted a study on the impact of replacing RCA in coarse RAP aggregate on the performance of RAP-RCA asphalt concrete at RCA replacement ratios of 0%, 10%, and 20%. Replacing 20% of the RCA in coarse RAP aggregate resulted in the highest fatigue and rutting resistance. Hou et al. [31] reported that RCA replacement negatively impacted IT_{MR}, and fatigue resistance, attributable to RCA's high porosity and microcracks. Huang et al. [32] investigated the elastic modulus of the interfacial transition zone between asphalt cement (AC) and the surface of various aggregates, including RCA, crushed brick, aged granite, and natural limestone. The interfacial transition zone around RCA particles is thicker than the other aggregates due to their higher porosity. The interfacial transition zone of RCA asphalt concrete also exhibited the lowest elastic modulus, resulting in adverse effects on its performance [32].

The performances of RAP-asphalt concretes can be improved by adding rejuvenators, polymers, and fibers [33]. Buritatum et al. [34] and Akkharawongwhatthana et al. [30] reported that adding 0.25% hemp fiber (HF) with 24 mm of length can improve the fatigue and rutting resistance of RAP-HF asphalt concrete [34] and RAP-RCA-HF asphalt concrete [30] mixtures. However, the accessibility and ease of using hemp fiber may not match the demands of widespread implementation due to the quality of the treatment process to prevent the deterioration of hemp fiber by the environment [34]. Polymer additives are commonly utilized to heighten the fatigue and rutting resistance of asphalt concrete by enhancing the adhesion between asphalt cement and aggregate.

Polyethylene terephthalate (PET), which is used to manufacture plastic bottles, can also be used as a stabilizer in an asphalt concrete mixture [35]. Owing to its high melting point of around 250°C, achieving homogeneity when mixing PET with asphalt cement through the wet method is challenging. Hence, the dry method to incorporate PET into the asphalt concrete mixture is preferable. Laomuad et al. [36] described the presence of crushed PET with a 2.36-mm maximum size in various amounts from 0.2 to 1.0% by aggregate weight using the dry method. The results indicated that PET could enhance RAP asphalt concrete's Marshall stability, strength index, ITS, IT_{MR}, fatigue resistance, and rutting resistance. The performance improvement mechanism of asphalt concrete using PET additive involved the melted and solid PET components within the mixture. The melted PET particles can heighten the bond between aggregate and asphalt cement during the hot mixed process. On the other hand, solid PET components can absorb energy from cyclic loads. Several researchers reported that higher PET content may result in larger air voids in the asphalt concrete matrix, which leads to insufficient asphalt cement [19, 30, 36-39]. This inadequate asphalt cement ultimately results in pavement cracking due to the reduced cohesion strength. Therefore, higher asphalt cement addition is required to maintain constant air voids in the asphalt concrete mixture [34, 40]. Purohit et al. [20] reported that PET could enhance the mechanical performance of asphalt concrete by incorporating RAP and RCA blends as coarse aggregates and NA as fine aggregates. The authors also reported that the modified asphalt concrete exhibited superior ITS and IT_{MR} compared to the conventional one.

In previous studies, recycled materials such as RAP, RCA, and PET were studied separately for their application in asphalt concrete pavement. Moreover, these studies typically involved using these recycled materials alongside natural aggregates. To the authors' best knowledge, there has been no comprehensive evaluation of the performance of asphalt concrete containing only RAP/RCA blend as aggregate and modified with PET.

This study therefore evaluated the performance enhancement of RAP-RCA asphalt concrete when using PET as a modifier. The influence of RAP/RCA ratio and PET content on the performances of RAP-RCA-PET asphalt concrete was investigated through advanced laboratory cyclic tests, including ITS, IT_{MR}, indirect tensile fatigue (ITF), and wheel tracking tests. The performances of RAP-RCA-PET asphalt concrete were compared to those of NA asphalt concrete and RAP-RCA asphalt concrete reinforced with HF (RAP-RCA-HF asphalt concrete) at an optimum ingredient of 0.25% of HF with 24 mm of length, studied by Akkharawongwhatthana et al. [30]. As per the comprehensive analysis, the fatigue distress model of RAP-RCA-PET asphalt concretes was proposed for the mechanistic-empirical pavement design. The analysis of tensile fatigue life of RAP-RCA-PET asphalt concretes in terms of the distress model and IT_{MR} was performed. The outcome of the analysis is novel and fundamental knowledge for asphalt concrete technology using recycled aggregates stabilized with PET. The results of this research will contribute to promoting RAP-RCA-PET asphalt concrete as a more environmentally friendly material for pavement construction.

2. Material and Methods

This research explores using RAP and RCA as aggregates and enhancing the performance of PET. The performance of RAP-RCA-PET asphalt concrete was compared to NA asphalt concrete and RAP-RCA-HF asphalt concrete studied by Akkharawongwhatthana et al. [30]. The comparison is based on asphalt concrete performance, including indirect tensile strength, indirect tensile resilient modulus, indirect tensile fatigue, and rutting resistance. The process of materials testing and experiment testing in this study is summarized in Figure 1. The methodology is detailed as follows:

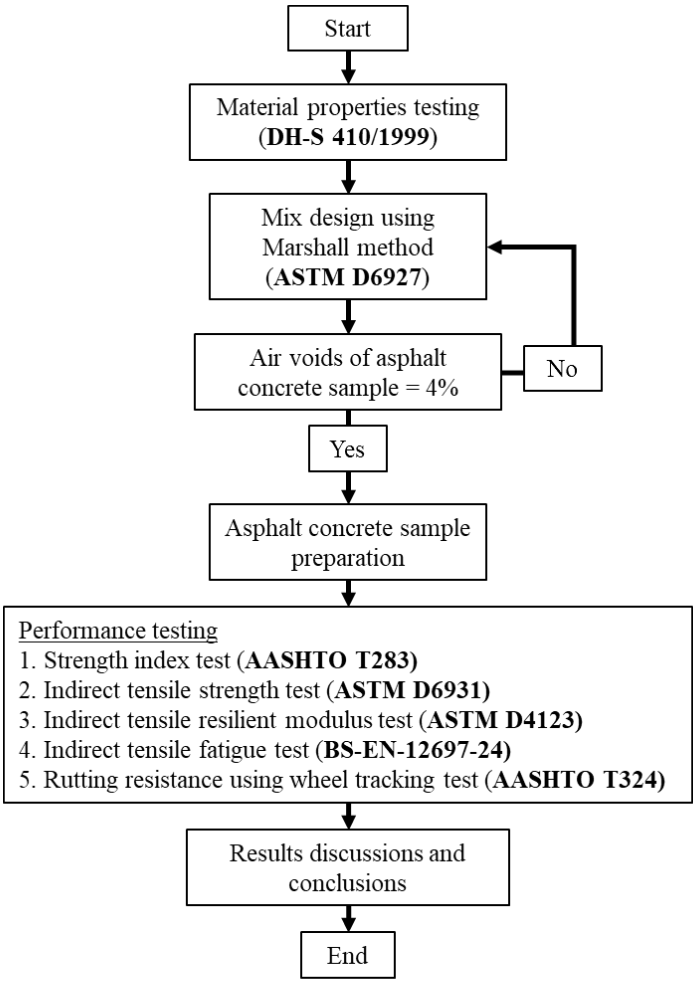


Figure 1. Process of materials testing and experiment testing

2.1. Asphalt Cement (AC)

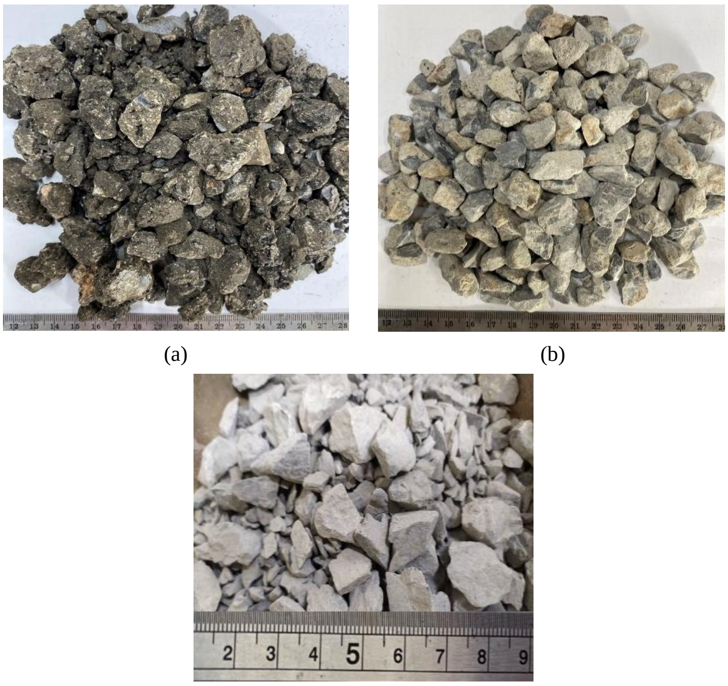
Properties of AC penetration grade of 60/70 (AC60/70) used in this research were summarized in Table 1. The studied AC60/70 was found to meet the requirements specified by the local authority [41].

Table 1. Properties of asphalt cement

Properties	Units	Test method	DOH specifications [41]	AC60/70 [34]
Penetration	-	DH-T 403	60-70	67
Flash point	ºC	DH-T 406	>232	332
Ductility 25ºC	cm	DH-T 405	>100	150
Solubility in trichloroethylene	%wt	DH-T 409	>99.0	99.97
Test on residue from thin film oven test (5 hour @ 163ºC)				
Weight loss	%	DH-T 404	<0.8	0.12
Penetration	% of original.	DH-T 406	>54	71.1
Ductility 25ºC	cm	DH-T 405	>50	150

2.2. Aggregates

The studied RAP was supplied by the Office of Nakhon Ratchasima Highways, Thailand, and the studied RCA was obtained from Thailand's Local Administration Department, as shown in Figures 2-a and 2-b, respectively. Properties of RAP and RCA were evaluated based on the national standard [42]. The studied NA was limestone, which was sourced from Sakon Nakhon province, Thailand, as shown in Figure 2-c. Summarized properties of RAP, RCA and NA are depicted in Table 2.



(a) (b)

(c)

Figure 2. Studied aggregates with (a) RAP, (b) RCA, and (c) NA

Table 2. Properties of aggregates

Properties	Unit	Test Method	DOH Specifications [42]	NA	RAP [34]	RCA [30]
Soundness	%	DH-T 213	≤ 9	3.31	10.21	3.84
Los Angeles abrasion value, LA	%	DH-T 202	≤ 40	30.4	47.03	33.13
Flakiness index	%	DH-T 210	≤ 35	15	33.00	28.00
Elongation index	%	DH-T 211	≤ 35	9	34.00	27.00
Water absorption	%	DH-T 207	-	0.47	1.49	9.10
Specific gravity	-	DH-T 207	-	2.753	2.274	2.790
Asphalt content in RAP	%	ASTM D 2172	-	-	5.67	-

2.3. Polyethylene Terephthalate (PET)

The studied PET was taken from waste drinking water bottles and obtained from a single source. However, all the PET bottles used for containing drinking water in Thailand are manufactured in compliance with TIS Standard No. 655 [43], established by the Thai Industrial Standards Institute. These standards mandate specific quality requirements, such as limits on extractable substances and the presence of metals and organic compounds in plastic. By adhering to these standards, the consistency in the quality of the recycled PET is ensured, thereby minimizing potential variations that could impact the performance of the asphalt concrete.

The PET bottles were thoroughly cleaned of dirt and contamination using plain water at room temperature. The PET bottles were then crushed into small portions using a crushing machine and were sieved to remove aggregates larger than 2.36 mm, as presented in Figure 3. Its specific gravity was 1.35. The crushed PET was used as an additive using the dry process at various ratios of 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0% by weight of aggregate.

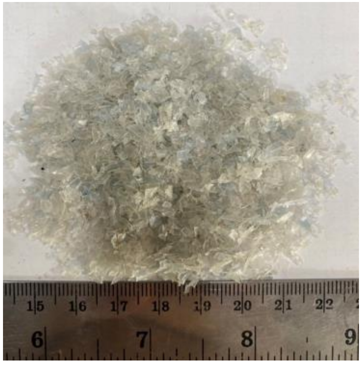


Figure 3. Studied PET

These small PET aggregates (< 2.36 mm) do not interfere with the recycling process of asphalt concrete, such as milling or crushing. Moreover, since the melting temperature of PET particles is higher than the mixing temperature, PET does not hinder the mixing process in in-plant or in-place recycling systems. In other words, PET-modified asphalt concrete does not obstruct recycling and maintains recyclability comparable to conventional asphalt concrete.

2.4. Mix Design and Sample Preparation

Before preparing RAP-RCA-PET asphalt concrete, the RAP aggregate was cleaned using trichloroethylene agents. The cleaned RAP aggregate was then sieved, and the gradation curve was altered in compliance with the pavement surface wearing course specifications outlined by the local authority [42], as illustrated in Figure 4. The gradation curves of RAP-RCA and RAP were adjusted to be within the DH-S 410/2542 [42]. Akkharawongwhatthana et al. [30] studied the effect of different RAP/RCA ratios and HF content and length on the performance of RAP asphalt concrete. Akkharawongwhatthana et al. [30] replaced the coarse RAP aggregate (4.75-19.00 mm) with RCA using RAP/RCA ratios of 100/0, 90/10, and 80/20. In addition, they varied the length of hemp fiber (20, 22, and 24 mm) and the content (0.05%, 0.10%, and 0.25% by weight of the aggregate). Their findings showed that the optimal RAP/RCA ratio is 80/20, and the HF length is 24 mm with a content of 0.25%, resulting in the highest ITS, IT_{MR}, fatigue resistance, and rutting resistance. Hence, this research considered RAP/RCA ratios of 100/0, 90/10, 80/20, and 60/40, covering the range examined by Akkharawongwhatthana et al. [30]. The gradation curve of NA is also shown in Figure 4.

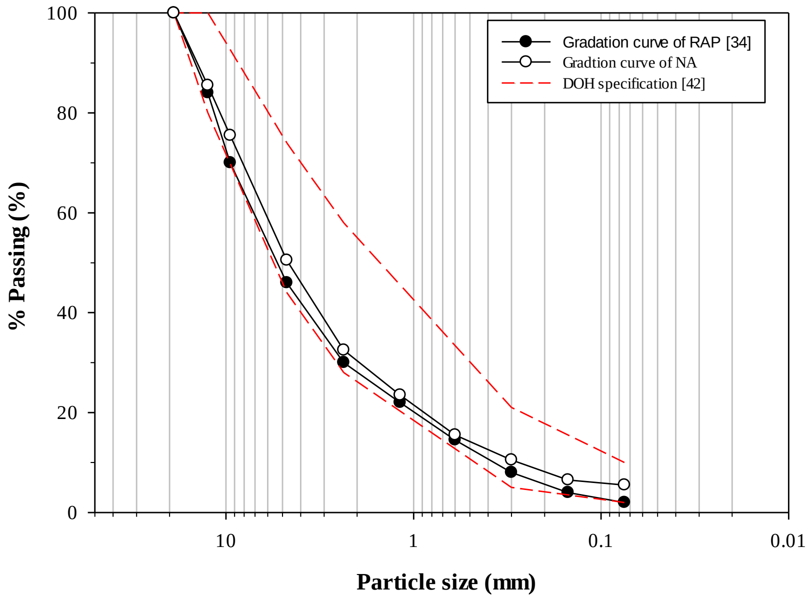


Figure 4. Gradation curve of aggregates

The appropriate mix proportions of RAP-RCA-PET asphalt concrete and NA asphalt concrete were acquired using the Marshall method in accordance with ASTM D6927 [44]. Before mixing, the aggregate and AC were warmed to 180°C and 160°C, respectively. The warmed aggregate and AC were blended at 150°C for 1 minute. The PET was then added during the mixing process for RAP-RCA-AC. The mixture was then compacted in a standard 101.6-mm mold with 75 blows to each side by a Marshall hammer. The sample was next de-molded after 24 hours at room temperature. The Marshall test was conducted to obtain the common Marshall properties of the asphalt concrete, including density, void mineral in aggregate (VMA), air void, void filled by AC (VFA), stability, and flow value.

The influence of RAP/RCA ratio and PET content on the mechanical performances of RAP-RCA-PET asphalt concretes and NA asphalt concretes was evaluated through various performance tests, including ITS, IT_{MR}, ITFL, and rutting resistance. The performance-tested samples were prepared at a constant air void of 4% based on the local authority standard [42]. For RAP-RCA-PET asphalt concretes, the optimum AC content (AC content providing 4% air void) was determined by assuming the total AC content (aged AC in RAP aggregate + added AC60/70).

3. Experimental Program

3.1. Strength Index (SI)

The strength index (SI) of the studied asphalt concretes was calculated in line with AASHTO T 283 [45]. The SI samples were prepared by compression under a constant pressure of 20.7 MPa for 2 minutes using a double plunger compactor with a 63.5-mm height and a 101.6-mm diameter. Two sample groups were made, including group 1 (unsoaked samples), which was designated as a control group, and group 2 (soaked samples), which was vacuum-saturated with the sodium chloride solution for 60 minutes and then soaked at 60°C for 1 day. The ratio between Marshall stability of soaked and unsoaked samples is the SI value. The test was run at 25°C using a compression speed of 50 mm/min. The Department of Highways, Thailand (DOH, 1999) specified that the SI value of asphalt concrete should be above 75%.

3.2. Indirect Tensile Strength (ITS)

The ITS was conducted following ASTM D6931 [46]. The ITS sample was loaded across its vertical diametrical plane at a 50 mm/min deformation speed at 25, 40, 50, and 60°C. The failure load was measured to determine the ITS value:

$$ITS = \frac{2000P}{\pi HD} \tag{1}$$

where ITS is expressed in kPa, P is the failure load (N), H is the initial height of specimen (mm), and D is the specimen's diameter (mm).

3.3. Indirect Tensile Resilient Modulus (IT_{MR})

The IT_{MR} is a prime parameter in evaluating the performance of asphalt concrete for the mechanistic-empirical design method. The IT_{MR} was determined by subjecting the Marshall sample to dynamic loading under indirect tensile condition following ASTM D4123-82 [47]. The IT_{MR} test was performed at a stress level of 15% of ITS with haversine loading (frequency of 1 Hz, with a loading period of 0.1 seconds and a rest period of 0.9 seconds) for 200 pulses at 25°C. The IT_{MR} is determined using the average of the last five elastic stiffness values after the first 150 pulses, as described in Equation 2:

$$IT_{MR} = \frac{P(0.27+\upsilon)}{HH_r} \tag{2}$$

where IT_{MR} is expressed as MPa, n is Poisson's ratio, and H_r is resilient horizontal deformation (mm).

3.4. Indirect Tensile Fatigue (ITF)

Fatigue failure is a significant distress of the flexible pavement under the accumulated damage caused by repeated loads. According to BS EN 12697-24 [48], the stress control condition was employed to evaluate the fatigue life of asphalt concrete sample. Target applied stresses of 250, 300, and 350 kPa were selected based on the BS-EN-12697-24 recommendation. The haversine loading pulse with a loading frequency of 1.0 Hz was applied on the Marshall sample until failure. Theoretically, the fatigue response is categorized into three distinct zones of the horizontal deformation versus the loading cycles plot. In the 1st zone, the initial loading cycles cause a relatively high deformation increment due to a rapid decrease in air voids. In the 2nd zone, the deformation versus number of cycles relationship is almost linear. During the loading process, plastic deformation gradually accumulated, resulting in the formation of microcracks. The microcracks from the 1st and 2nd zones propagate the macrocrack in the 3rd zone, resulting in complete failure [49]. The indirect tensile fatigue life (ITFL) is estimated from the intersection point of slopes of the 2nd and 3rd zones.

3.5. Rutting Resistance

The rutting resistance of asphalt concretes was assessed followed AASHTO_T324-14 [50] using the Hamburg wheel tracker testing machine. The wheel-tracking test samples were made by a gyratory compactor based on ASTM D6925 [51]. A testing sample comprised two cylindrical specimens, each having dimensions of 150-mm diameter and 60-mm thickness, positioned adjacent to each other to measure rut depth. The testing sample was securely mounted using plastic molds, with the cylindrical specimens precisely trimmed to fit the molds. A 47-mm wide steel wheel with the 705-N load applied to the sample at a wheel speed of 26 cycles per minute. The machine automatically terminated the test upon reaching 10,000 loading cycles or a rut depth of 20 mm, whichever occurs first. The rut depth is commonly adopted to express the resistance to rutting failure.

4. Test Results and Discussion

4.1. Static Properties

The properties of the studied RAP [34], RCA [30], and NA are depicted in Table 2 and benchmarked with the hot mix recycling standard [42]. NA has the lowest values of soundness, Los Angeles abrasion, flakiness index, and elongation index compared to RAP and RCA. This implies that NA has the highest resistance to corrosion, abrasion, and particle breaking. RCA has superior properties to RAP as shown by its lower values for soundness, Los Angeles abrasion, flakiness index, and elongation index. However, the RCA has greater water absorption than NA and RAP due to its larger porosity, indicating that the RCA has a higher ability to absorb AC. It was evident that all properties of NA and RCA meet the standard requirement.

The previous results of RAP asphalt concretes (RAP/RCA ratio of 100/0 and 0.0% PET content) by Buritatum et al. [34], RAP-RCA asphalt concrete (RAP/RCA ratio of 90/10, 80/20 and 60/40 and 0.0% PET content) by Akkharawongwhatthana et al. [30], and RAP-PET asphalt concrete modified by PET (RAP/RCA ratio of 100/0 modified by PET) by Laomuad et al. [36] were taken and diagnosed for comparison purpose in this research. The optimum AC contents of the RAP-RCA-PET asphalt concretes at different PET contents, and NA asphalt concrete are summarized in Table 3. The optimum AC content for the RAP asphalt concrete was determined to be 7.07% by weight (5.67% old AC + 1.40% new AC content) [34]. The optimum AC content of NA asphalt concrete is 5.1%. The lower RAP/RCA ratio (higher RCA replacement content) contributes to the decreased old AC content in the RAP-RCA-PET asphalt concretes at a particular PET content. As such, the lower RAP/RCA ratio (higher RCA) results in a higher optimum AC content [52-55]. At identical RAP/RCA ratio, the more PET content contributes to a greater optimum AC content due to the coating of PET particles with AC, resulting in the increased air voids of the mixture [39].

Table 3. Optimum AC content of asphalt concretes

AC Content	RAP-RCA-PET Asphalt Concrete							NA Asphalt Concrete
	RAP/RCA ratio	%PET						
		0.0	0.2	0.4	0.6	0.8	1.0	
New AC	100/0	1.40*	2.13***	2.37***	2.46***	2.58***	2.67***	5.1
	90/10	2.70**	2.95	3.00	3.10	3.13	3.43	
	80/20	3.40**	4.07	4.13	4.23	4.49	4.60	
	60/40	4.68**	5.35	5.37	5.54	5.70	5.71	
Old AC	100/0	5.67*						0.0
	90/10	5.14**						
	80/20	4.63**						
	60/40	3.61**						

* Buritatum et al. [34], ** Akkharawongwhatthana et al. [30], and *** Laomuad et al. [36].

The Marshall properties of RAP-RCA-PET asphalt concretes and NA asphalt concrete are presented in Table 4. At the same PET content, the lower RAP/RCA ratio causes a higher density of asphalt concretes due to RCA having higher specific gravity than RAP. At a given RAP/RCA ratio, the more PET content shows a lower density of the RAP-RCA-PET asphalt concrete. The VMA and VFA values of the RAP-RCA-PET asphalt concretes range from 18.7 to 21.21% and 77.55% to 82.06%, respectively. The Marshall stability and SI values of the RAP-RCA-PET asphalt concretes range from 10.5 to 20.7 kN and 81.6 to 92.8%, respectively. The lowest Marshall stability and SI values are observed in RAP asphalt concrete (no RCA and PET). The highest Marshall stability and SI values are observed in the asphalt concrete with an 80/20 RAP/RCA and 0.6% PET content. The Marshall flow values range from 8.15 to 15.1. The NA asphalt concrete has a density of 2.456 g/cm³, 15.1% VMA, 73.8 VFA, 15.2 kN stability, 12.8 flow, and 78.2% SI. The Marshall properties, including VMA, stability, flow, and SI for all mix proportions, meet the requirements of DH-S-410/1999 [42]. The exception is the SI value of RAP asphalt concrete (RAP/RCA ratio of 100/0 and PET content of 0%).

Table 4. Marshall properties of studied asphalt concrete mixtures at 4% air void

Properties	RAP-RCA-PET asphalt concrete							NA asphalt concrete	Specification [42]
	RAP/RCA ratio	%PET							
		0.0	0.2	0.4	0.6	0.8	1.0		
Density (g/cm^3)	100/0	2.262*	2.249***	2.243***	2.241***	2.237***	2.235***	2.456	-
	90/10	2.275**	2.254	2.249	2.244	2.241	2.237		
	80/20	2.281**	2.259	2.252	2.247	2.244	2.240		
	60/40	2.290**	2.267	2.261	2.256	2.252	2.248		
VMA (%)	100/0	18.70*	19.96***	20.37***	20.52***	20.72***	20.87***	15.1	min 14
	90/10	19.52**	19.99	20.06	20.24	20.29	20.79		
	80/20	19.41**	20.54	20.64	20.82	21.24	21.41		
	60/40	19.49**	20.56	20.07	20.36	20.62	20.65		
VFA (%)	100/0	78.60*	80.13***	80.38***	80.59***	80.72***	80.90***	73.8	-
	90/10	79.50**	79.99	80.05	80.22	80.27	80.81		
	80/20	79.39**	80.53	80.62	82.06	81.23	81.31		
	60/40	78.85**	77.55	80.07	80.35	80.59	80.72		
Stability (kN)	100/0	10.5*	11.3***	13.4***	13.1***	12.9***	14.0***	15.2	min 6.7
	90/10	12.4**	13.1	13.8	16.4	15.6	15.1		
	80/20	18.8**	17.5	19.1	20.7	20.6	18.4		
	60/40	16.0**	16.8	17.3	18.4	17.8	17.5		
Flow (0.25 mm)	100/0	8.7*	8.2***	8.6***	8.4***	8.2***	8.6***	12.8	8-16
	90/10	10.2**	10.8	11.3	11.8	12.3	13.1		
	80/20	11.0**	11.8	12.1	13.6	14.5	14.8		
	60/40	11.9**	12.6	13.9	14.2	15.1	15.0		
SI (%)	100/0	71.6*	84.2***	82.9***	85.5***	91.0***	90.2***	78.2	min 75
	90/10	81.6**	85.6	86.8	91.9	91.7	91.2		
	80/20	86.3**	87.4	87.8	92.8	92.5	89.7		
	60/40	83.7**	84.1	85.1	86.4	84.5	84.2		

* Buritatum et al. [34], ** Akkharawongwhatthana et al. [30], and *** Laomuad et al. [36].

The ITS of RAP-RCA-PET asphalt concretes at various temperatures, RAP/RCA ratios, and PET contents are compared with that of NA asphalt concrete and RAP-RCA-HF asphalt concrete with 0.25% HF content (HF length = 24 mm) studied by Akkharawongwhatthana et al. [30] as demonstrated in Figure 5. The raised temperature results in a decrease in ITS for all asphalt concretes due to a reduction of AC adhesion strength. The lower RAP/RCA ratio causes a more ITS until the maximal ITS value at the optimum RAP/RCA = 80/20 at a given PET content for RAP-RCA-PET asphalt concretes. Hou et al. [31] reported that RCA particles have rough surfaces and angular shapes, resulting in a higher mechanical interlocking than RAP aggregate. The improved interlocking strength at the optimum RAP/RCA ratio therefore contributes to the improved adhesion strength between aggregate and AC for all PET contents and temperatures. Although the RCA has superior basic and engineering properties than RAP, the elastic modulus of the interfacial transition zone between AC and RCA particles is lower than that of NA, as reported by Huang et al. [32]. Hence, the excessive RCA in the asphalt concretes generates weak interfacial transition zones within the asphalt concrete matrix, reducing the ITS of asphalt concretes.

For all test temperatures, at the same RAP/RCA ratios, adding PET in the RAP-RCA-PET asphalt concretes can improve ITS. The largest ITS is found at the optimum PET content of 0.6%. Adding PET enhances the ITS of RAP-RCA-PET asphalt concretes by improving bond strength between aggregate and AC through the melted components of PET during the hot mixed process [16]. However, the ITS decreases as the PET content exceeds 0.6% for all RAP/RCA ratios and temperatures. Modarres and Hamedi [56, 57] revealed that the excessive volume of un-melted PET particles, which have lower stiffness than RAP and RCA, led to a weak structure in the asphalt mixture. Compared to NA asphalt mixture, the RAP asphalt mixture (no RCA) with 0% PET content has a lower ITS at 25°C. However, ITS of RAP asphalt concretes with 0.0% PET content is higher than that of NA ones at 40, 50, and 60°C. In other words, the RAP asphalt concrete has a less significant loss of ITS than the NA asphalt concrete because of aged AC in the RAP aggregate, providing greater stiffness to the mixtures under high-temperature conditions [58]. RAP-RCA-PET asphalt concretes with the optimum RAP/RCA = 80/20 and 0.6% PET content have higher ITS values than NA asphalt concretes for all temperatures.

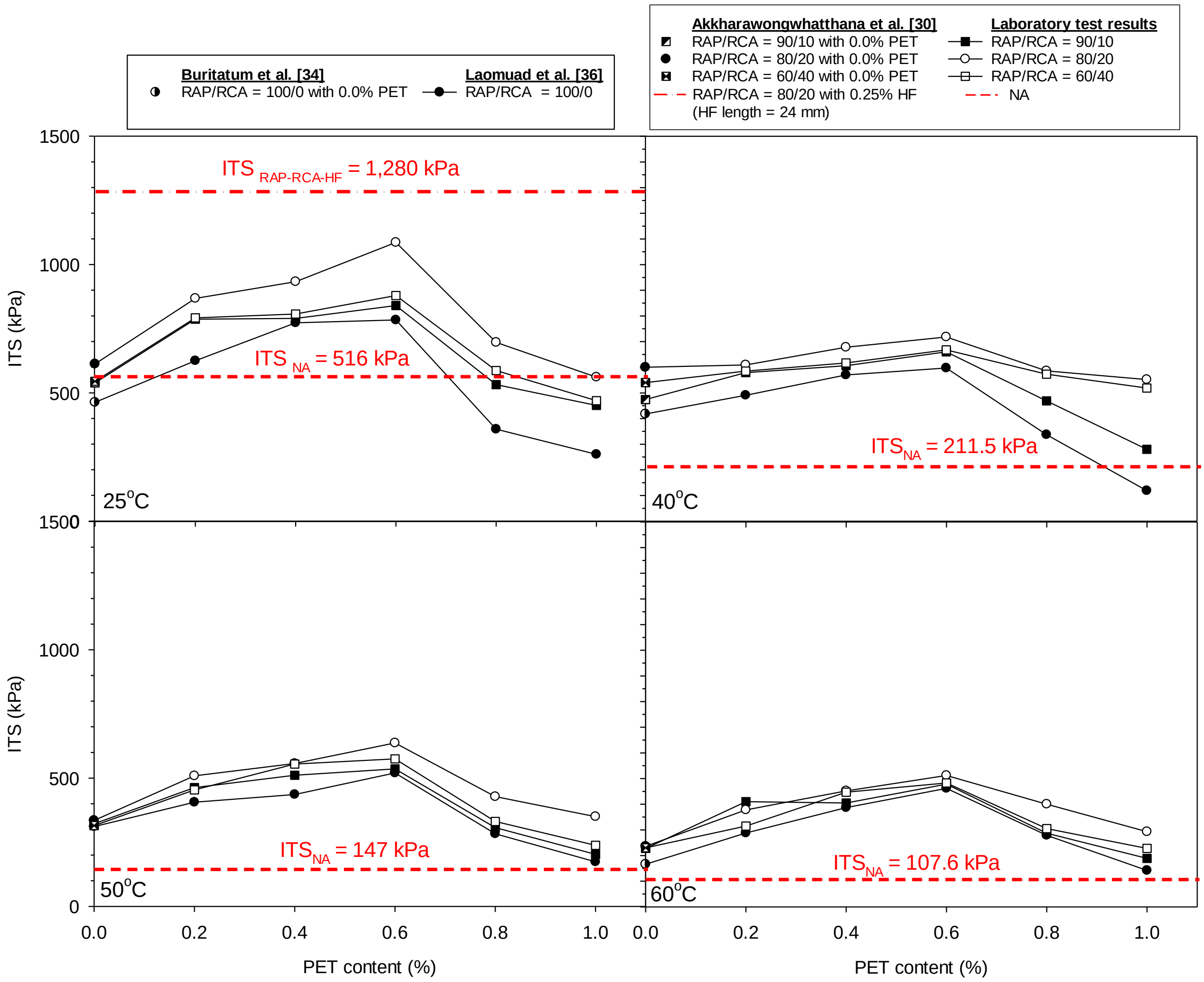


Figure 5. Relationship between ITS and PET content at 25, 40, 50, and 60°C of RAP-RCA-PET asphalt concretes and NA asphalt concrete

At 25ºC, the ITS of RAP-RCA-PET asphalt concrete with the optimum RAP/RCA ratio of 80/20 and 0.6% PET content is 1,086 kPa. Meanwhile, the ITS of RAP-RCA-HF asphalt concrete is 1,280 kPa. The result indicates that HF has more potential to enhance the tensile strength of RAP-RCA asphalt concrete than PET.

4.2. Tensile Fatigue Resistance

The IT_{MR} of RAP-RCA-PET asphalt concretes at various RAP/RCA ratios and PET contents were compared with that of NA asphalt concretes and RAP-RCA-HF asphalt concrete with 0.25% HF content (HF length = 24 mm) studied by Akkharawongwhatthana et al. [30] as illustrated in Figure 6. Similar to the ITS test results, the highest IT_{MR} of RAP-RCA-PET asphalt concretes has come across at the optimum RAP/RCA = 80/20 for all PET contents. At a given RAP/RCA ratio, the highest IT_{MR} of RAP-RCA-PET asphalt concrete is found at the PET content of 0.6%. Beyond this PET content, IT_{MR} reduces as the PET content increases. RAP-RCA-PET asphalt concretes have smaller IT_{MR} than NA asphalt concrete, except the RAP-RCA-PET asphalt concretes with RAP/RCA = 80/20 and 0.2, 0.4, and 0.6% PET contents. The RAP-RCA-PET asphalt concrete with a RAP/RCA = 80/20 and 0.6% PET content has a superior IT_{MR} of 14.1% compared to NA asphalt concrete. The IT_{MR} of RAP-RCA-PET asphalt concrete with the optimum RAP/RCA ratio of 80/20 and 0.6% PET content is 2,705 MPa. Meanwhile, the IT_{MR} of RAP-RCA-HF asphalt concrete studied by Akkharawongwhatthana et al. [30] is 2,971 MPa. The RAP-RCA-PET asphalt concrete has a lower IT_{MR} than RAP-RCA-HF asphalt concrete, similar to the ITS testing result.

Both the IT_{MR} and ITS improvement is influenced by the mixture stiffness (the addition of RCA) and the AC adhesion improvements (the addition of PET). The IT_{MR}-ITS relationship of RAP-RCA-PET asphalt concretes is therefore directly related as depicted in Figure 7. The relationship is found to be dependent upon the RAP/RCA ratio, irrespective of PET content. PET additive yields the most significant improvement in mechanical properties at the optimum RAP/RCA = 80/20, observed by the steepest gradient of the relationship.

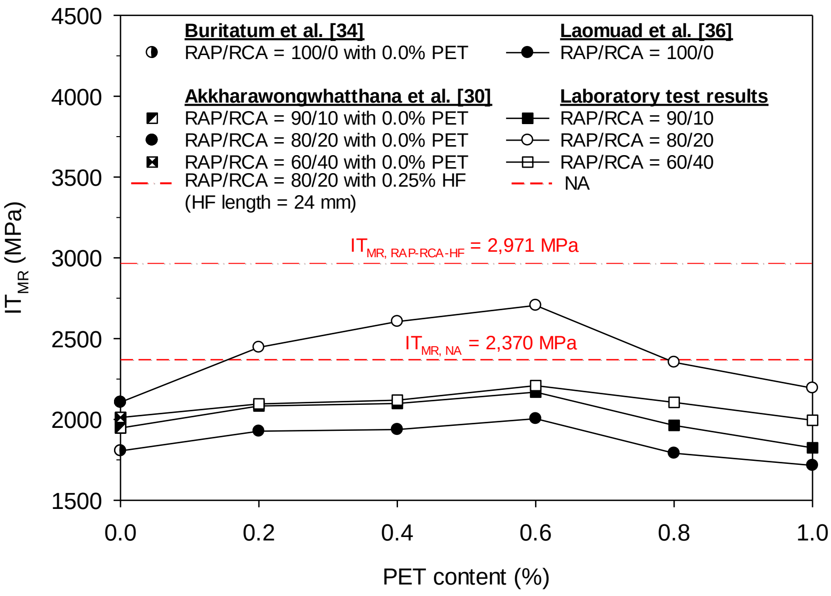


Figure 6. Relationship between ITMR and PET content of RAP-RCA-PET asphalt concretes and NA asphalt concrete

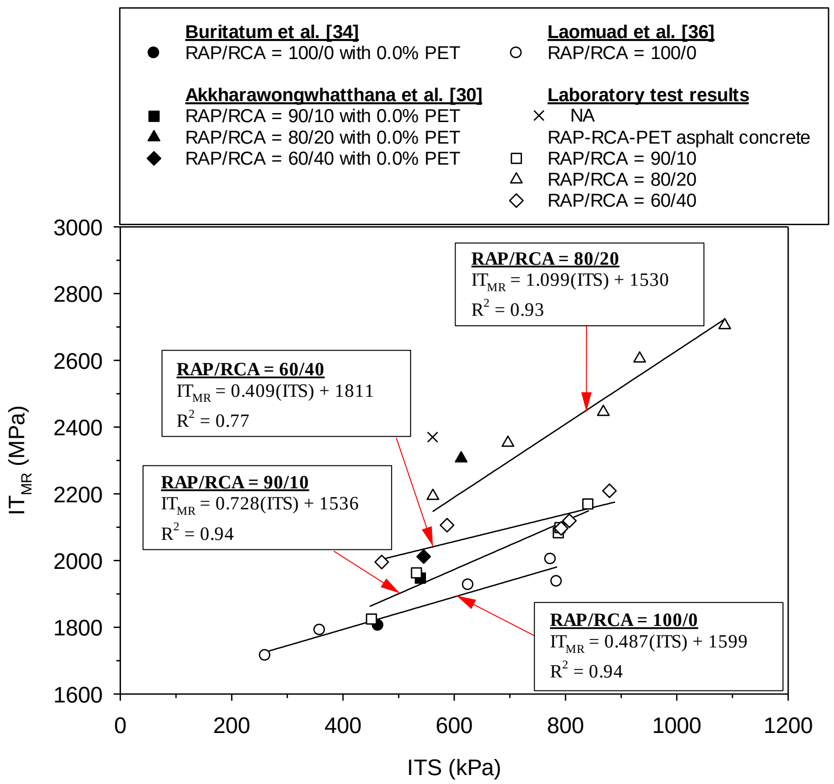


Figure 7. Relationship between ITMR and ITS of RAP-RCA-PET asphalt concretes

The ITFL values of RAP-RCA-PET asphalt concretes with RAP/RCA ratios and PET contents under different applied stresses of 250, 300, and 350 kPa were compared with those of NA asphalt concretes and RAP-RCA-HF asphalt concrete with 0.25% HF content (HF length = 24 mm) studied by Akkharawongwhatthana et al. [30], illustrated in Figure 8. The ITFL decreases with the increased applied stress for all asphalt concretes due to the higher plastic deformation. At the same applied stress, without PET, the RCA inclusion can improve the ITFL of RAP-RCA-PET asphalt concretes. Similar to the ITS and IT_{MR} results, the maximum ITFL value is observed at the optimum RAP/RCA ratio of 80/20 for all applied stresses and PET contents. At the optimal PET content of 0.6%, the ITFL of RAP-RCA-PET asphalt concretes reaches the highest value, regardless of the RAP/RCA ratio. Moghaddam et al. [16] reported that the solid components of PET (which were not melted during the hot mixed process) had the potential to absorb energy from cyclic loads, further contributing to the improvement of ITFL of asphalt concretes. Compared to NA asphalt concretes, the RAP asphalt concretes have lower ITFL values for all applied stresses. Increasing PET and RCA contents improves the ITFL of RAP-RCA-PET asphalt concretes for all applied stresses. The RAP-RCA-PET asphalt concretes with the optimum RAP/RCA ratio of 80/20 and PET content of 0.6% have superior ITFL values of 125, 243, and 379% compared to NA asphalt concretes for applied stresses of 250, 300, and 350 kPa, respectively. The ITFL of RAP-RCA-PET asphalt concrete with RAP/RCA ratio = 80/20 and 0.6% PET content at applied stress 250, 300, and 350 kPa is 3,782, 3,136, and 2,536 cycles, respectively, while the ITFL of RAP-RCA-HF asphalt concrete at applied stress 250, 300, and 350 kPa is 2,971, 891, and 477 cycles, respectively. It is evident that PET has a superior potential to improve the fatigue resistance of RAP-RCA asphalt concrete compared to HF.

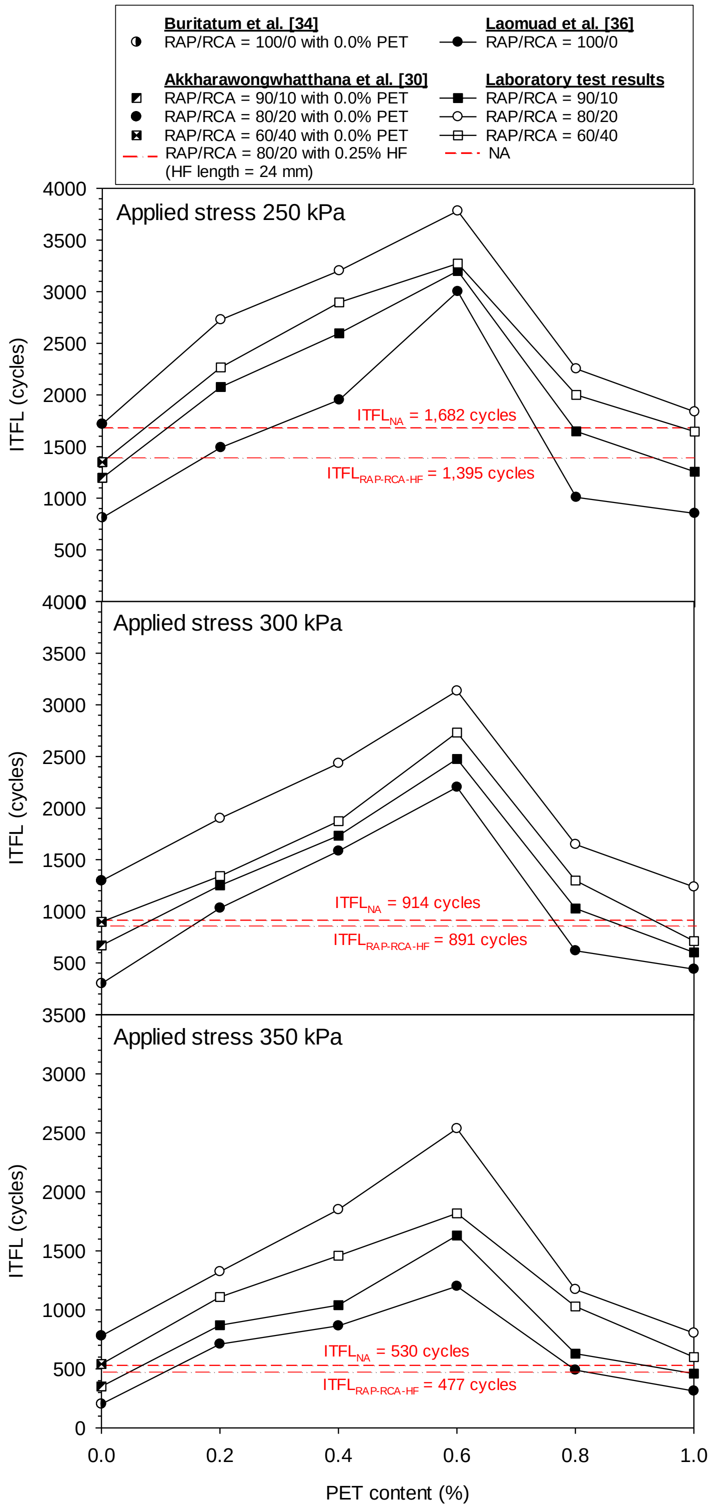


Figure 8. Relationship between ITFL and PET content at applied stress of 250, 300, and 350 kPa of RAP-RCA-PET asphalt concretes and NA asphalt concrete

As per BS EN 12697-24 [48], the initial tensile strain (ε_t) influences the ITFL (fatigue law). The asphalt concrete with a lower ε_t generally presents a higher ITFL. The ITFL of the asphalt concrete pavement can be estimated using the ε_t based on the fatigue law as follows:

$$\mathrm{ITFL} = a\left[\frac{1}{\mu\varepsilon_t}\right]^b \tag{3}$$

where a and b are the fatigue parameters, which can be determined from the regression analysis.

Kennedy [59] and Mohammad & Paul [60] revealed that the applied stress and IT_{MR} influence the ε_t in the following equation:

$$\varepsilon_t = \frac{\sigma(1+3\nu)}{IT_{MR}} \tag{4}$$

where σ is applied tensile stress (kPa), and ν is Poisson's ratio (taken as 0.35 suggested by BS EN 12697-24 [48]).

e_t of RAP-RCA-PET asphalt concretes and NA asphalt concrete, which are calculated from Eq. (4), versus PET content under different applied tensile stresses, is illustrated in Figure 9. At the same RAP/RCA ratios and PET contents, the higher applied tensile stress causes a higher e_t. Asphalt concrete with a superior IT_{MR} has a predominant resistance to plastic strain under applied tensile stress [61]. At the same applied tensile stress, the RCA replacement and PET addition contribute to a reduction in e_t, and the lowest value for a specific applied tensile stress is found at 80/20 RAP/RCA and 0.6% PET content. Compared to NA asphalt concrete, all RAP-RCA-PET asphalt concretes have higher e_t except RAP-RCA-PET asphalt concretes with RAP/RCA ratios of 80/20 and 0.2, 0.4, and 0.6% PET content for all applied tensile stresses due to higher IT_{MR} (see Figure 6).

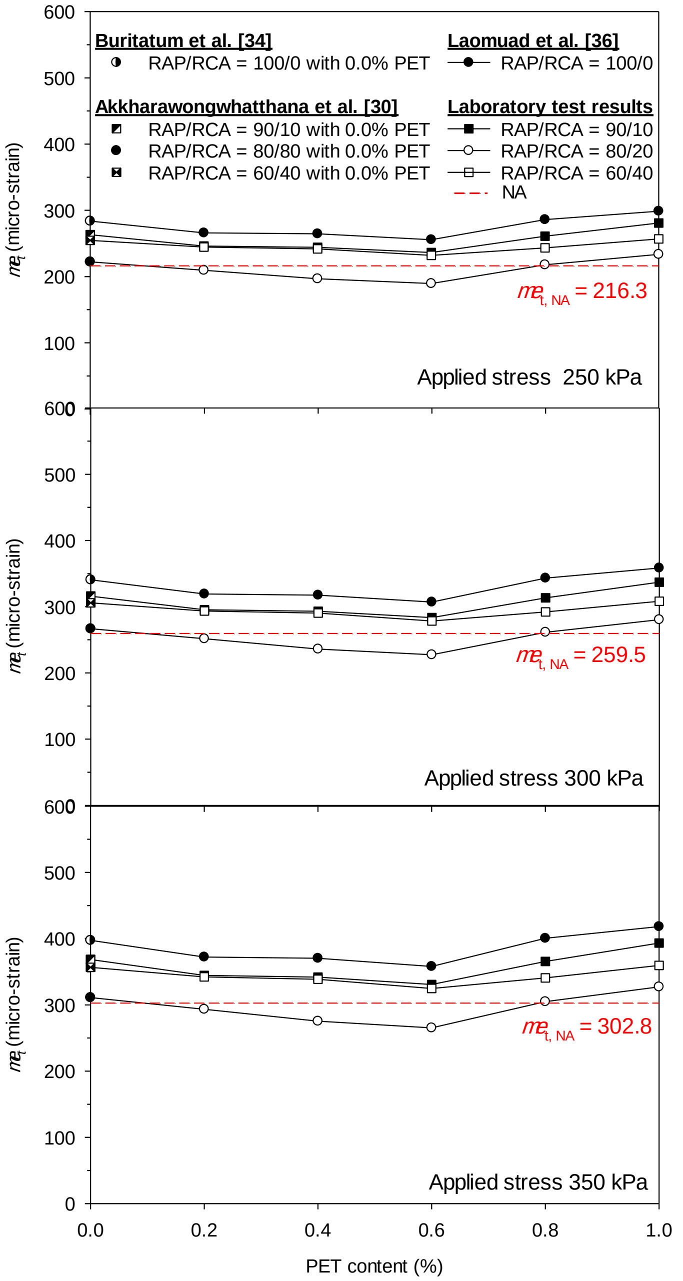


Figure 9. Relationship between ε_t and PET content of RAP-RCA-PET asphalt concretes and NA asphalt concrete

The relationship between the ITFL and the e_t in the logarithmic scale of RAP-RCA-PET asphalt concretes, and NA asphalt concrete is illustrated in Figure 10. The ITFL reduces as the e_t increases followed BE EN12697-24 [48] and finding by Modarres and Hamedi [57]. The PET content is found to significantly affect the position and the slope of ITFL- e_t relationship. It is worthwhile mentioning that the ITFL versus ε_t relationship is found to be unique for a particular PET content. Without PET, the ITFL- e_t relationship exhibits the steepest slope, whereas the gentlest slope is found at the PET content of 0.6%, regardless of the RAP/RCA ratios. Interestingly, in the range of studied strains, the ITFL- e_t relationships of RAP-RCA-PET asphalt concretes are above the ITFL- e_t relationship of NA asphalt concrete, showing the longer service life at the same induced ε_t. However, the ITFL- e_t relationships of both RAP-RCA-PET asphalt concretes and NA asphalt concrete are below the ITFL- e_t relationship of the Asphalt Institute (AI) [62]. The AI's model was developed based on the assumption that wheel loads on actual pavements are not applied at the same location and have longer rest periods, hence the higher fatigue life.

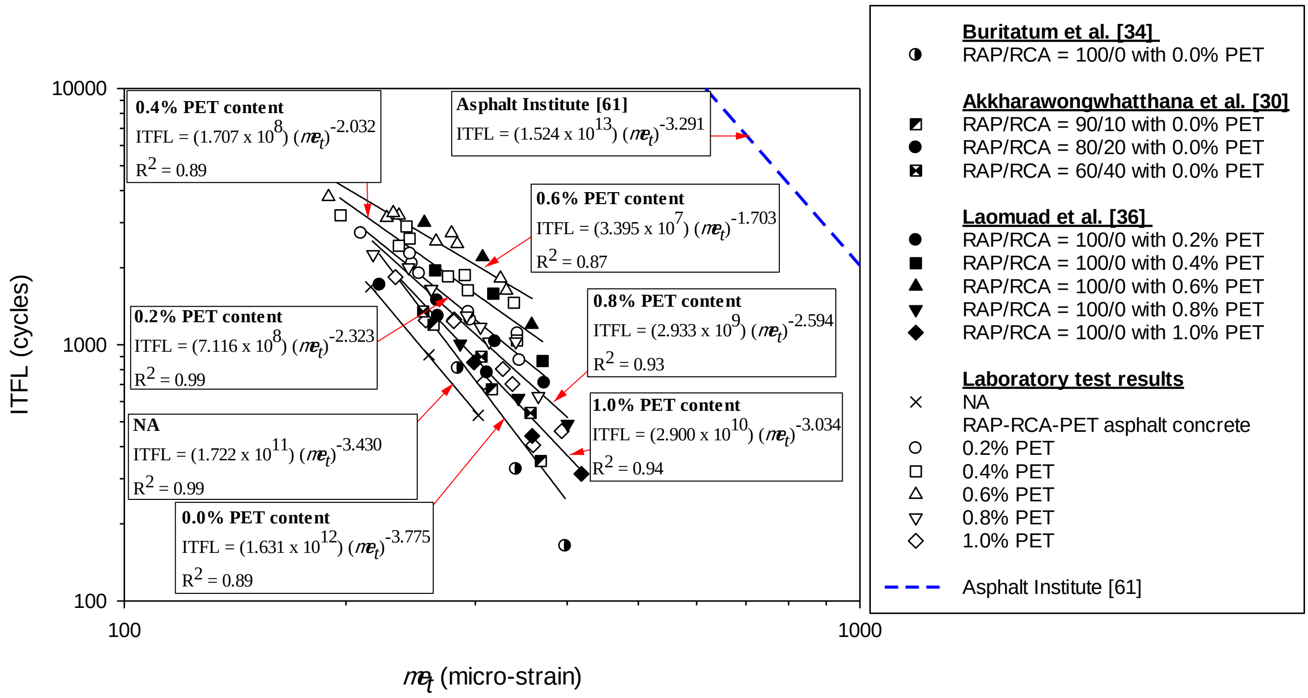


Figure 10. Relationship between the ITFL and ε_t of RAP-RCA-PET asphalt concretes and NA asphalt concrete

Different pavement material properties exhibit different tensile strain versus resistance to fatigue damage response, expressed in term of fatigue parameters *a* and *b*. The fatigue parameters of RAP-RCA-PET asphalt concretes versus PET content for various RAP/RCA ratios are given in Figure 11. Evidently, the value of parameter *a* reduces as the PET content increases and the lowest value is found at 0.6% PET content. After that, the value of parameter *a* increases with the raised PET content. On the other hand, the value of parameter *b* rises with the increased PET content, and the largest value is noted at 0.6% PET content. Then, the value of parameter *b* declines with the increased PET content. The values of parameters *a* and *b* for RAP-RCA-PET asphalt concretes can be calculated in terms of PET content using Equations 5 and 6, respectively. These equations can facilitate the ITFL estimation of RAP-RCA-PET asphalt concretes at different PET contents.

$$\log(a) = -7.333 \times (\%PET) + 11.4 \qquad \text{for } 0.0 \le \%PET \le 0.6 \tag{5-1}$$

$$\log(a) = 9.029 \times (\%PET) + 1.6 \qquad \text{for } 0.6 \le \%PET \le 1.0 \tag{5-2}$$

$$b = 3.254 \times (\%PET) - 3.4 \qquad \text{for } 0.0 \le \%PET \le 0.6 \tag{6-1}$$

$$b = -4.068 \times (\%PET) - 1.0 \qquad \text{for } 0.6 \le \%PET \le 1.0 \tag{6-2}$$

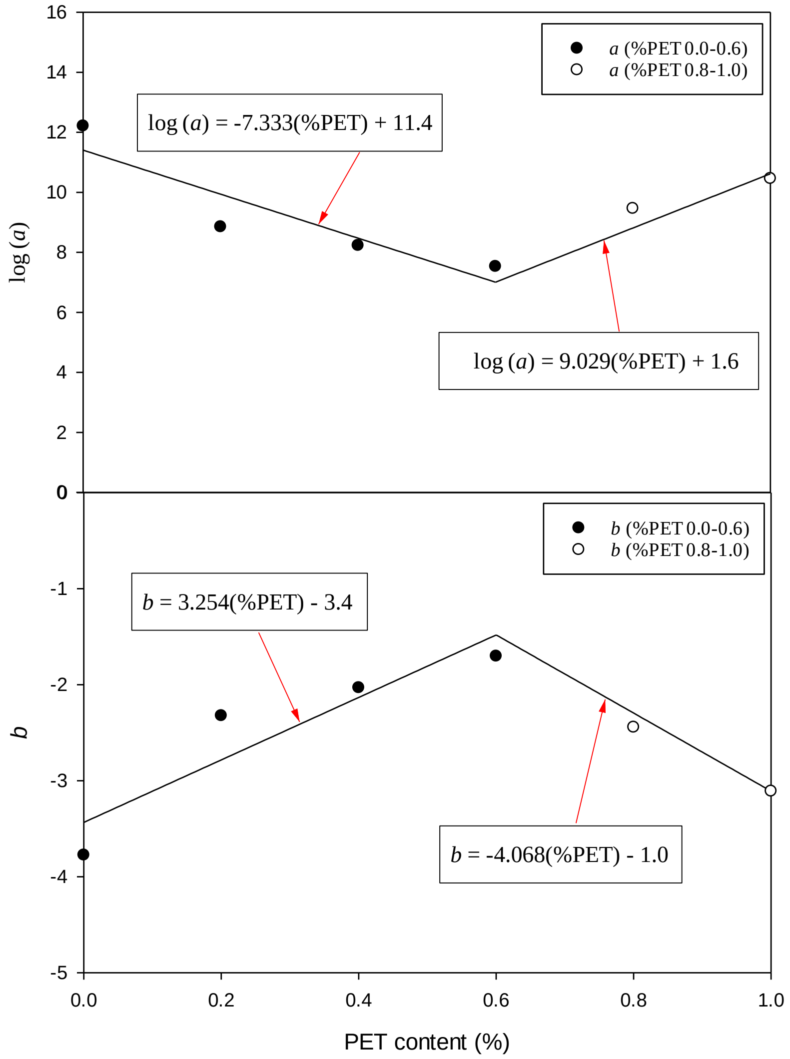


Figure 11. Relationship between fatigue parameters and PET content of RAP-RCA-PET asphalt concretes

It is logical that both the fatigue law and the IT_{MR} control the stability of asphalt concretes. The material with the location of ITFL versus e_t relationship on more right does not always exhibit a longer service life. For instance, although the position of the ITFL- e_t relationship of RAP-RCA asphalt concrete (0% PET) is above that of the NA asphalt concrete (Figure 10), the RAP-RCA asphalt concrete has lower ITFL than the NA asphalt concrete at a given applied stress of 300 kPa due to its higher e_t (lower IT_{MR}). The calculation of fatigue life of RAP-RCA asphalt concrete compared with that of NA asphalt concrete is presented in Table 5. However, when 0.6% PET content is added to RAP-RCA-PET asphalt concrete, its ITFL is greater than that of NA asphalt concrete due to its larger IT_{MR} and higher position of ITFL-e_t relationship. From Figure 6, IT_{MR} of RAP-RCA-PET asphalt concretes with PET ranging from 0.2% to 0.6% and RAP/RCA ratio of 80/20 is higher than that of NA concrete while the fatigue model is on right of the NA concrete for all PET contents and RAP/RCA ratios (Figure 10). Both distress model and IT_{MR} control the fatigue life, yielding the RAP-RCA-PET asphalt concretes with PET ranging from 0.2% to 0.6% and RAP/RCA ratio of 90/10, 80/20, and 60/40 as well as PET ranging from 0.4% to 0.6% and RAP/RCA ratio = 100/0 exhibit longer service life than NA asphalt concrete (Figure 8). This output highlights the potential of RAP-RCA-PET asphalt concrete as an alternative material that can provide a longer fatigue life than natural materials.

Table 5. Comparison of ITFL of NA asphalt concrete and RAP-RCA-PET asphalt concrete

Asphalt concrete mixtures	Applied Stress (kPa)	IT_{MR} (MPa)	Strain (micro-strain)	ITFL (cycles)
NA asphalt concrete	300	2370	259.5	903
RAP-RCA asphalt concrete with RAP/RCA ratio of 100/0 and 0.0% PET content	300	1805	340.6	450
RAP-RCA asphalt concrete with RAP/RCA ratio of 80/20 and 0.6% PET content	300	2705	227.3	3292

4.3. Rutting Resistance

The rut depth versus number of wheel cycles relationships of RAP-RCA-PET asphalt concretes at various RAP/RCA ratios and PET contents were compared with NA asphalt concrete and RAP-RCA-HF asphalt concrete with 0.25% HF content (HF length = 24 mm) studied by Akkharawongwhatthana et al. [30], illustrated in Figure 12. Figure 13 shows rut depth at target cycle of RAP-RCA-PET asphalt concretes and NA asphalt concrete. Without PET, the RAP asphalt concrete (RAP/RCA ratio of 100/0) could not withstand the repetitive wheel load and failed to reach 20 mm of rut depth at 7,203 cycles prior to reaching the target 10,000 cycles, as seen in Figure 13-a [34]. Due to the superior stiffness of RCA benchmarked with that of RAP at a given PET content, the RCA inclusion can enhance the rutting resistance at the same target cycles; the lowest rut depth value is observed at the optimum RAP/RCA = 80/20 (Figure 12 and Figure 13-c [30] and 13-d). Beyond the optimum RAP/RCA ratio, the low elastic modulus of interfacial transition zones between AC and RCA reduces the mixture stiffness [32], increasing rut depth with the decreased RAP/RCA ratio as shown in Figures 13-e [30] and 13-f.

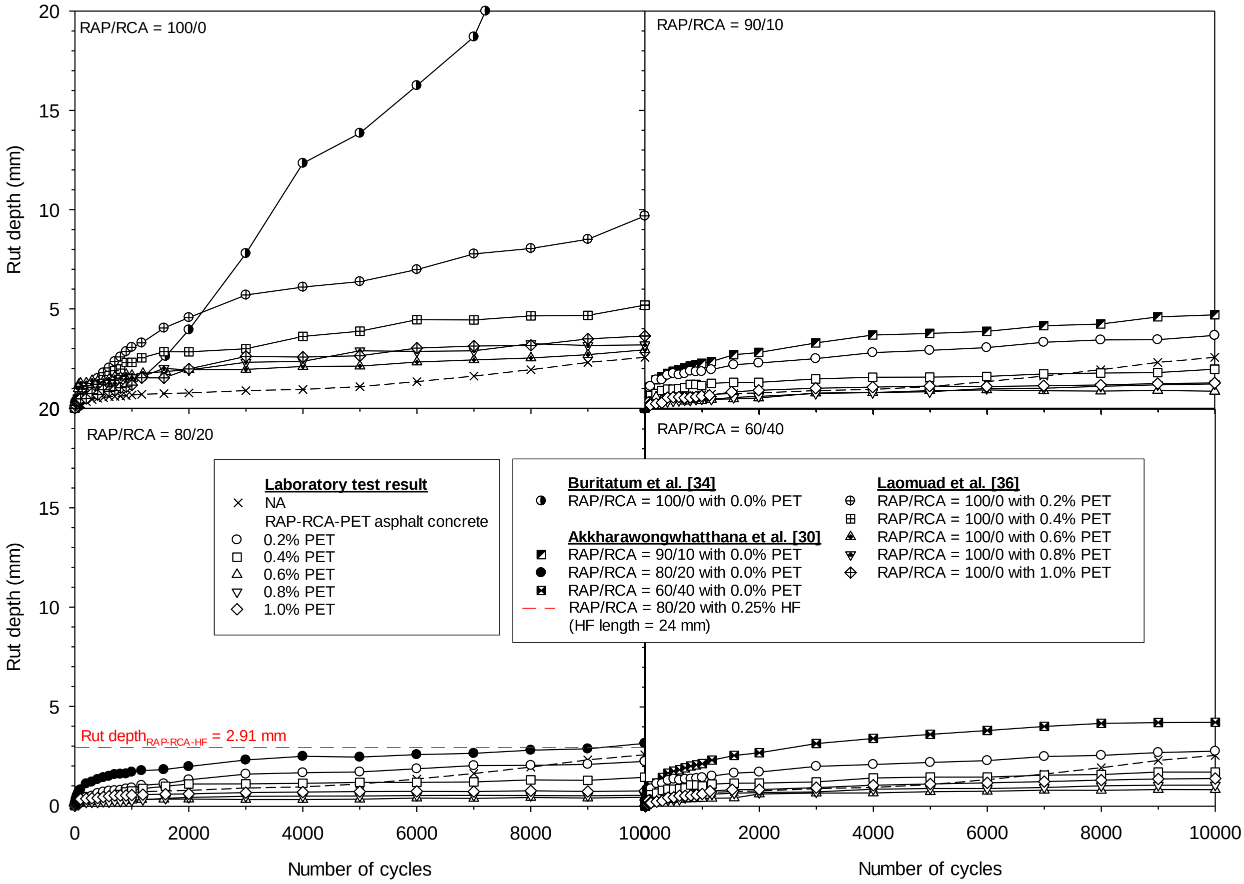


Figure 12. Relationship between rut depth and number of wheel cycles of RAP-RCA-PET asphalt concretes and NA asphalt concrete

Incorporating PET enhances RAP-RCA-PET asphalt concretes' resistance to rutting failure, as seen in Figure 12 and Figures 13-b [36], 13-d, and 13-f. At PET content of 0.6%, rut depth is the lowest for all RAP/RCA ratios. At this PET content, the rut depth of RAP-RCA-PET asphalt concretes at the target cycles is 2.94 mm, 0.85 mm, 0.42 mm, and 0.83 mm for RAP/RCA = 100/0, 90/10, 80/20, and 60/40, respectively. According to Moghadam et al. [18], adding PET into asphalt concretes can improve energy absorption against wheel loading. The improved energy absorption is caused by the higher adhesion of AC film resulting from the melted particles of PET, improving rutting resistance.

The rut depth of NA asphalt concrete at the target 10,000 cycles is 2.56 mm. Figure 12 shows that even with PET added to RAP asphalt concretes (RAP/RCA ratio of 100/0), the rut depth at the target 10,000 cycles is still larger than that of NA asphalt concrete. For the RAP/RCA ratios of 90/10 and 60/40, rut depth at the target 10,000 cycles of RAP-RCA-PET asphalt concretes is lower than that of NA asphalt concrete at 0.4 to 1.0% PET contents. Meanwhile, the rut depth of the RAP-RCA-PET asphalt concretes with RAP/RCA ratio of 80/20 is lower than that of NA asphalt concrete at 0.2 to 1.0% PET content. At the optimum PET content of 0.6% and RAP/RCA ratio of 80/20, RAP-RCA-PET asphalt concrete has a superior rutting resistance of 84% compared to NA asphalt concrete. The rut depth of RAP-RCA-PET asphalt concrete with RAP/RCA ratio = 80/20 and 0.6% PET content is 1.43 mm, while the rut depth of RAP-RCA-HF asphalt concrete is 2.91 mm [30]. The results indicated that PET has a superior potential to improve the rutting resistance of RAP-RCA asphalt concrete compared to HF.

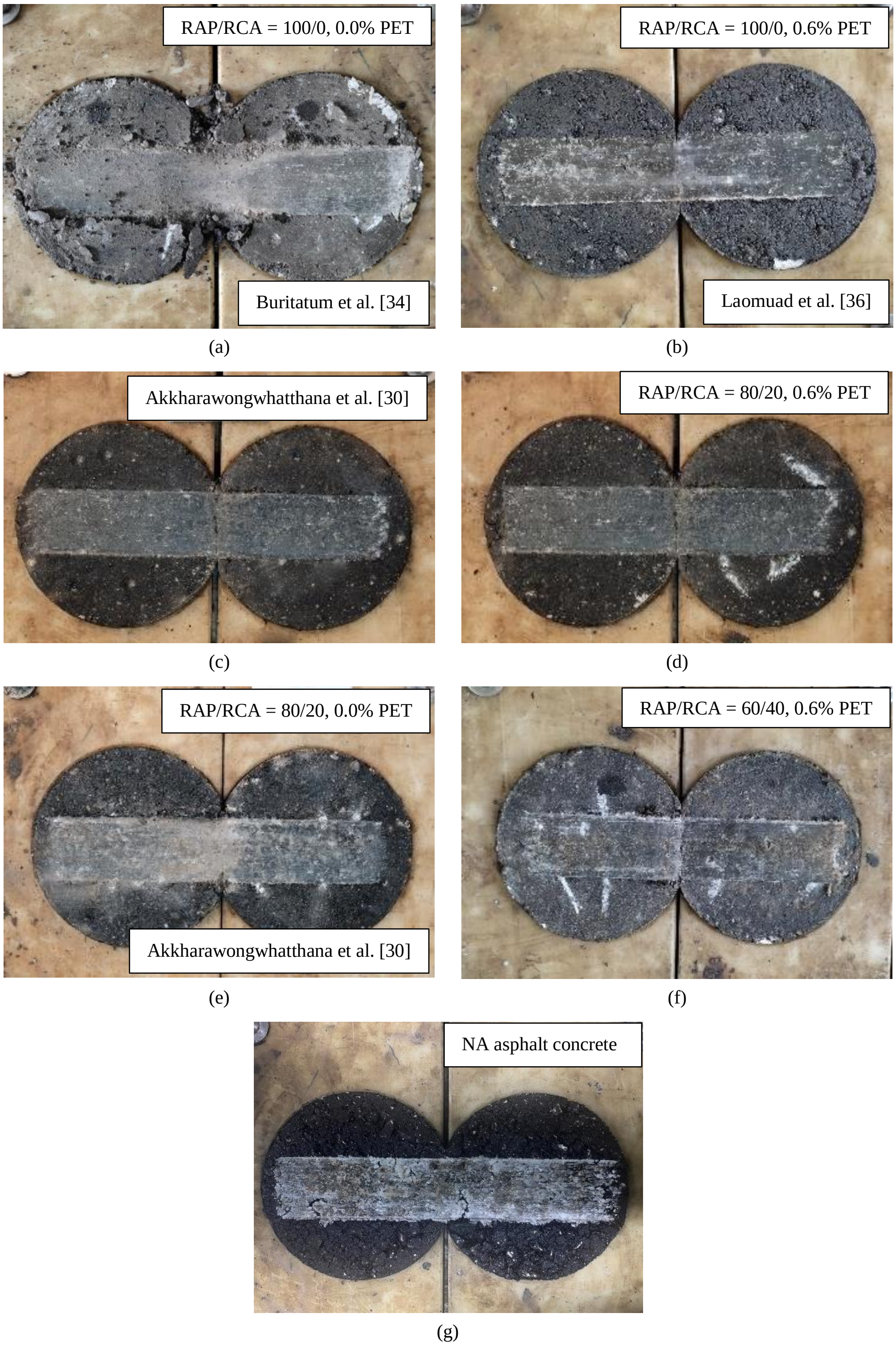


Figure 13. Rut depth at target cycle of RAP-RCA-PET asphalt concretes with (a) RAP/RCA = 100/0 with 0% PET content [34], (b) RAP/RCA = 100/0 with 0.6% PET content [36], (c) RAP/RCA = 80/20 with 0% PET content [30], (d) RAP/RCA = 80/20 with 0.6% PET content, (e) RAP/RCA = 60/40 with 0% PET content [30], (f) RAP/RCA = 60/40 with 0.6% PET content, and (g) NA asphalt concrete.

Based on the ITF and wheel tracking test results, RAP-RCA-PET asphalt concrete with RAP/RCA ratios of 90/10 and 60/40 and PET content of 0.4% and 0.6%, as well as RAP-RCA-PET asphalt concrete with RAP/RCA ratios of 80/20 and PET content of 0.2%, 0.4%, and 0.6%, exhibited better fatigue life and rutting resistance in comparison to NA asphalt concrete. Though RAP-RCA-PET asphalt concrete at the optimum RAP/RCA ratio of 80/20 and 0.6% PET content has lower ITS and IT_{MR} than RAP-RCA-HF asphalt concrete, RAP-RCA-PET asphalt concrete exhibits better long-term performance as observed by its higher fatigue and rutting resistance. The results confirm that the potential usage of PET as an additive for sustainable asphalt concrete applications. Furthermore, RAP-RCA-PET asphalt concrete with a RAP/RCA ratio of 80/20 and 0.6% PET content requires less new AC content than NA asphalt concrete as shown in Table 3. Initial processing may incur initial costs, such as milling or crushing RAP and RCA as well as cleaning and crushing PET. However, these initial costs are offset by the reduced need for new NA. Consequently, recycled PET with RAP and RCA can lower overall material expenses compared to NA asphalt concrete. Utilizing RAP-RCA-PET asphalt concrete provides a cost-effective and environmentally friendly option for pavement construction. Field studies are however suggested to validate the durability against actual traffic load and severe environmental conditions, providing reassurance about using PET as an additive in the recycling pavement industry.

5. Conclusions

This study evaluates the mechanical properties of asphalt concretes containing RAP, RCA, and PET. Based on the critical analysis of laboratory test data, the following conclusions are drawn:

- PET addition in asphalt concrete causes the higher asphalt cement required for PET particles coating, hence the higher optimum AC content of RAP-RCA-PET asphalt concretes. The RAP/RCA ratio also significantly influences the optimum AC content of asphalt concretes. Reducing the RAP/RCA ratio increases the optimum AC content due to a higher ability to absorb the AC of RCA. The Marshall properties of RAP-RCA-PET asphalt concretes meet the requirements of DH-S 410/1999 for Marshall stability, Marshall flow, VMA, and SI.
- The RAP/RCA ratio and PET content significantly affect the performance of RAP-RCA-PET asphalt concretes. The lower RAP/RCA ratio leads to a higher ITS and ITMR until the optimum RAP/RCA ratio of 80/20, where the improved interlocking strength of RCA particles and PET adhesion strength enhance mechanical properties. Beyond the optimum RAP/RCA, the excessive RCA replacement generates weak interfacial transition zones within the asphalt concrete matrix, reducing ITS, ITMR, ITFL, and rutting resistance. Addition of PET to the asphalt concrete mixture improves ITS, ITMR, and ITFL, whereby the highest values are observed at an optimum PET content of 0.6%. These improved properties are due to the melted components, enhancing the bond between the aggregate and AC as well as the high energy absorption of un-melted PET components. However, due to weak structure formation, excessive volume of PET particles (lower stiffness than RAP and RCA) reduces the performance.
- At a particular RAP/RCA ratio, the ITMR increases linearly with ITS. At the optimum RAP/RCA ratio of 80/20 and PET content ranging from 0.2% to 0.6%, RAP-RCA-PET asphalt concrete has a higher ITMR when compared to NA asphalt concrete. Based on the critical test results analysis, the fatigue distress model of RAP-RCA-PET asphalt concrete is developed in term of the ITFL- εt relationship. The relationship is dependent upon PET content and unique for all RAP/RCA ratios. The fatigue parameters are dependent on the PET content. Additionally, the ITFL-εt relationships of RAP-RCA-PET asphalt concretes are above and gentler than the relationship of NA asphalt concrete. Both ITMR and fatigue model control the service life. Consequently, even with the superior fatigue model of RAP-RCA-PET asphalt concrete, its service life is not always longer than the NA asphalt concrete for all applied stress. It is determined that the RAP-RCA-PET asphalt concretes with PET ranging from 0.2% to 0.6% and RAP/RCA ratio of < 90/10 as well as PET ranging from 0.4% to 0.6% and RAP/RCA ratio of 100/0 exhibit longer service life than NA asphalt concrete for studied applied tensile stress. The proposed fatigue distress model is helpful for the mechanistic design of RAP-RCA-PET asphalt concrete pavement, which supports a sustainable construction strategy worldwide.
- Without PET, RAP asphalt concrete failed to withstand the wheel load in the target cycles (10,000 cycles) and quickly reached the maximum rut depth of 20 mm. Replacing RCA allowed RAP-RCA asphalt concrete to be better against the wheel load cycles, reducing the rut depth due to its better properties than RAP. However, RAP-RCA asphalt concretes without PET had a higher rut depth than NA asphalt concrete. Adding PET to the RAP-RCA asphalt concrete can improve its resistance to wheel loads due to the higher adhesion of the AC film, which results from the melted PET particles. It is determined that the RAP-RCA-PET asphalt concretes with PET ranging from 0.4% to 1.0% and RAP/RCA ratios of 90/10 and 60/40, as well as PET ranging from 0.2% to 1.0% and RAP/RCA ratio of 80/20, exhibit lower rut depth than NA asphalt concrete. It is worth noting that at a RAP/RCA ratio of 100/0, the rut depth of RAP-RCA-PET asphalt concrete was higher than that of the NA asphalt concrete for all PET contents. RAP-RCA-PET asphalt concrete with a RAP/RCA ratio of 80/20 and 0.6% PET content exhibited the highest rutting resistance, similar to the ITF test result.

6. Declarations

6.1. Author Contributions

Conceptualization, A.S. and S.S.; methodology, K.A. and N.P.; software, K.A.; validation, A.B., M.H., and T.Y.; formal analysis, K.A. and N.P.; investigation, K.A. and N.P.; resources, A.S. and S.H.; data curation, A.B., M.H., and J.H.; writing—original draft preparation, A.S. and K.A.; writing—review and editing, S.H., J.H., A.C., and A.A.; visualization, J.H. and M.H.; supervision, A.S., S.H., and A.C.; project administration, A.S. and S.H.; funding acquisition, A.S., M.H., and S.H. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding and Acknowledgments

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

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