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Investigating the Creep Properties of PET-Modified Asphalt Concrete

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ABSTRACT: This study has investigated the creep properties of asphaltic concrete modified with different dosages of waste polyethylene terephthalate (PET) in two different ranges of size. Uniaxial dynamic creep test at 40°C was conducted on the cylindrical specimens of the mixtures. The load was applied in two different frequencies of 0.5 and 5Hz. Creep test results showed that the accumulated strain under dynamic loading increased with increasing PET content, with lower values for the mixtures containing finer PET particles. Moreover, it was found that the accumulated strain under the loading with higher frequency was more than that under lower frequency, with higher sensitivity to frequency for the mixtures containing finer PET. The results of dynamic creep tests were used for determination of the constants of a three stage model. The linear creep slope in the second region of the creep curve and the flow number showed that the increase of PET content and size results in decrease of permanent deformation resistance. However, the mixtures modified with 4% of fine and coarse PET particles had the highest loading cycles at the end of primary creep region, where most of the strain was recoverable.

Keywords: Asphalt Concrete, Creep Strain Rate, Dynamic Creep Test, Flow Number, PET.

INTRODUCTION

Ever increasing generation of solid waste materials by municipalities as well as service and manufacturing industries has become a major environmental problem in societies. In addition to occupying valuable lands for landfilling of such waste materials, they adversely affect the environment. Thus, waste management has become a main concern of authorities. Plastics comprise a major fraction of total solid wastes. The global production of plastics in 2015 was reported to be 407 million tons (Geyer et al., 2017). Plastics have many applications in our life. One type of plastic which is wasted more than other types is polyethylene terephthalate (PET). PET is a semi-crystalline thermoplastic polymer (Shukla and Harard, 2006), which has many applications including packaging of beverages, water, household cleaners, food products and oil (Modarres and Hamedi, 2014). PET is produced by the polymerization of ethylene glycol which is a colorless liquid obtained from ethylene, and terephthalic acid which is a crystalline solid obtained from xylene (Sinha et al., 2010). When heated together under the influence of chemical catalysts, they produce PET in the form of a viscous mass that can be solidified and used for later processing as a plastic or spun directly to

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fibers. These applications of PET is due to its high mechanical and chemical resistance, impermeability to gas, thermal stability and electrical insulation, and also its lower density than the traditional packages of glass and aluminum. PET wastes are mainly produced by households, as the bottles of consumed drinks or foods, and are usually thrown away after a single use. The disposed bottles are landfilled, buried or burnt, all of which impact the environment. In US alone, 2675 tons of PET was wasted in 2010, from which only 29.1% was recycled and the rest was disposed (Container Recycling Institute, 2017). PET is not a degradable material, and it takes centuries to decompose. Its disposal in environment causes pollution of rivers and oceans and endangers creatures' lives. Therefore, managing waste PET is very important for conserving the environment. One way to reduce the environmental pollution of waste PET is its recycling. To this end, chemical and physical recycling can be chosen. In chemical recycling, PET is mixed with catalysts at elevated temperatures and pressures, which make it costly. In the cheaper method of physical recycling, the problem is that, due to external contaminations, a high quality uniform recycled material cannot be obtained (Baghaee Moghadam et al., 2014a). Therefore, only 25% of waste PET is recycled in US. Finding applications, in which high quality material is not required, is a way to effectively reuse waste PET (Hassani et al., 2005). One of these applications is construction industry. Construction industry consumes a large amount of natural resources such as aggregates, which can degrade the environment. In recent years, sustainable development has been considered in the construction industry, by measures such as using recycled materials instead of virgin materials and lowering energy consumption. Asphaltic mixtures, unbound aggregates and Portland cement concrete are the main materials with the potential to receive recycled waste materials in their production. Different types of waste materials such as reclaimed asphalt pavement, recycled concrete aggregate, waste tires, plastics, etc., have shown to be applicable as a replacement for virgin materials.

One of the potential applications of PET is in asphaltic mixtures (Baghaee Moghaddam et al., 2014a; Ahmadinia et al., 2011; Ahmadinia et al., 2012; Baghaee Moghaddam et al., 2014b; Modarres and Hamedi, 2014b; Earnest, 2015). Like other polymers, PET can be added into asphaltic mixtures in three different forms of binder modifier, mixture reinforcement and aggregate replacement (Ahmad et al., 2017). Some studies have investigated the effects of using PET in gap graded asphaltic mixture of atone matrix asphalt (SMA). Stiffness and fatigue properties of SMA containing different percentages of PET with the maximum particle size of 2.36 mm were investigated by Baghaee Moghaddam et al. (2012). They found that the maximum stiffness was obtained at a PET content of 1% (by the weight of aggregate), after which it decreased with increasing PET content. They also found that the fatigue performance of the mixture was considerably improved by PET inclusion. Yet in another study, Baghaee Moghadam et al. (2014a) investigated Marshall stability, indirect tensile strength, and static and dynamic creep properties of SMA mixtures containing different percentages of PET. They indicated that PET inclusion decreased the Marshall stability and indirect tensile strength of the mixture. It was also revealed that the creep behavior was different under static and dynamic loading. While the increase of PET content resulted in the increase of permanent deformation under static loading, the behavior was the opposite under dynamic loading. Using dynamic creep test over a range stress levels and temperatures, the deformation behavior of

SMA mixtures incorporated by different concentrations of PET was investigated by Ahmadinia et al. (2012). It was concluded that under any test condition, the PET-modified mixtures are more resistant against rutting than the unmodified mixtures. Conducting another study, Ahmadinia et al., (2011) found that the highest Marshall stability and Marshall Quotient (MQ) were obtained by using 6% (by the weight of binder) of PET in SMA mixture. They also studied the drain down, resilient modulus and deformation behavior of SMA mixtures incorporating different concentrations of PET, and found that the resilient modulus of the mixture containing 6% of PET was 16% higher than that of the unmodified mixture (Ahmadinia et al., 2012). The wheel track tests revealed that among the mixtures modified with 0, 2, 4, 6, 8 and 10%, the mixture containing 4% of PET was the most resistant against plastic deformation, with a rut depth of 29% less than that of the mixture containing 0% of PET. It was also found that the drain down of the mixtures decreased with increasing PET content.

Some properties of asphalt concrete containing ground PET were studied by Modarres and Hamedi (2014a,b). They found that the stiffness and tensile strength of the mixture can be improved by inclusion of 2% (by the weight of binder) of PET. They also realized that PET had a comparable effect with SBS on the stiffness at low temperatures and fatigue at intermediate temperatures. The properties of asphaltic binder and asphalt concrete modified by inclusion of different percentages of PET were investigated by Earnest (2015). The binder was modified by adding the PET in wet process, and the mixture was modified using both wet and dry processes. It was found that PET modification increased the performance of the binder and mixture at high temperatures, without affecting the viscosity and workability. It was also found that PET modified mixtures had higher maximum specific gravity and lower bulk specific gravity than the control mixture. It was revealed that more improvement in rutting and moisture damage resistance can be achieved by wet process than dry process. Both Hamburg and indirect tensile strength (ITS) tests showed that the mixtures modified using the dry process had better performance against moisture damage. The phase angle and dynamic modulus of the mixtures modified by PET were found to be, respectively, higher and lower than those of the control mixture without PET. Almeida et al. (2017) added micronized PET in amounts of 0, 4, 5 and 6% of binder weight into a Superpave asphaltic concrete and investigated the indirect tensile strength, moisture damage resistance, resilient modulus and rutting resistance of the mixtures. It was revealed that the mixture modified by 5% of micronized PET had higher indirect tensile strength, resistance against moisture damage and fatigue cracking and resilient modulus than the base mixture containing 0% of PET. However, the base mixture showed a higher flow number than the modified mixture, indicating that PET-modification decreases the resistance of the mixture against plastic deformation. They also found that the improvement in resilient modulus at higher temperatures was less than that at intermediate temperature. Taherkhani and Arshadi (2017) investigated the effects of the content and size of PET particles on some engineering properties of asphaltic mixtures. They found that the highest MQ quotient was achieved by adding 4% of PET into asphalt concrete. This is while the mixtures modified by 2% of PET particles had the highest tensile strength and moisture damage resistance. Further, by conducting dynamic creep tests, they found that PET-modification results in the increase of permanent deformation, with a lower resistance for the mixtures containing coarser PET particles.

Exploring literature shows that the findings of the limited studies on resistance against permanent deformation of asphalt mixtures are not consistent. Some studies on SMA mixtures have demonstrated that the PET inclusion improves the deformation resistance, while the research on asphalt concrete shows that the PET modification causes increase of permanent deformation with increase of PET content; thus, more investigation is required in this regard. Furthermore, the effect of loading frequency has not been investigated yet. Therefore, this research aimed to study the permanent deformation resistance of a typical asphaltic concrete modified by different dosages of fine and coarse graded PET particles and under different loading frequencies. Moreover, the creep property of the mixtures was investigated using a three stage model.

MATERIALS

Three types of materials including waste ground PET, a performance grade asphalt cement and limestone aggregates have been used in this research for fabricating the specimens. The binder used for making the mixtures was a performance grade asphalt cement of PG58-16. The properties of the binder are presented in Table 1. Dolomite limestone aggregates were provided by an asphalt plant in Zanjan City, the northwest of Iran. Following standard methods the aggregates properties were checked to satisfy the requirements of national specifications. The moisture absorption of the coarse and fine fraction was 0.1 and 1.2%, respectively, and the bulk density of the coarse, fine and filler fraction was 2.65, 2.66 and 2.65, respectively. A dense gradation was selected from the gradations proposed for asphalt concrete in Iranian Asphalt Pavements Code (Management and Planning Organization, 2012). The maximum aggregate size of the selected gradation was 19 mm. Figure 1 shows the mixtures gradation and the upper and lower limit of the specified band. The PET was obtained from grounding waste water bottles, collected from a solid waste depot. Before grinding, first, the caps and labels were removed. Then, they were washed, cut into small parts, and ultimately grounded to finer particles using a special crusher. The crushed PET was sieved and those passing sieve No. 30 and remaining on sieve No. 50 were used as fine PET particles, denoted by P50 in this paper. For coarse PET particles, denoted by P16 in this paper, those passing sieve No. 8 and remaining on sieve No. 16 were used. A sample of the coarse and fine PET particles is shown in Figure 2. Tables 3 and 4 show, respectively, the size distribution and some physical and mechanical properties of PET particles used in the mixtures.

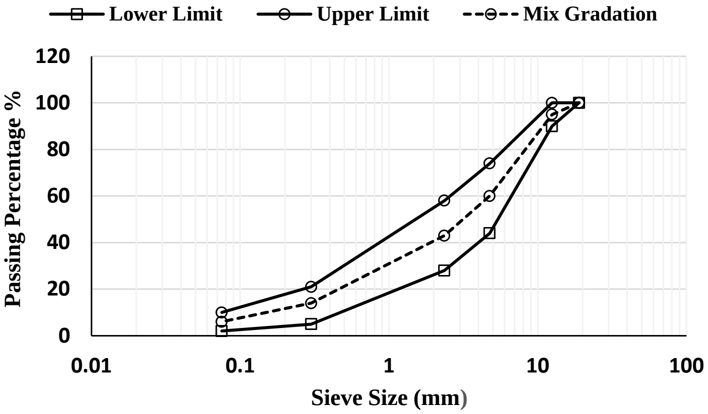

Fig. 1. Specification limits and the grading curve of the mixtures

Table 1. The list of available cross-sectional areas from the AISC code

Properties	Standard	Results	Specifications Limits
The average seven-day maximum pavement temperature (°C)		-	≤58
The minimum pavement design temperature		-	≥-16
Virgin binder			
Flash point °C		> 300	≥230
Viscosity at 135 °C (Pa.s)	AASHTO T316	0.2945	≤3Pa.s
$G^*/\sin\delta$	AASHTO T315	1.45	≥1kPa
RTFOT Residue (AASHTO T240)			
$G^*/\sin\delta$	AASHTO T315	3.33	≤2.2kPa
PAV Residue (AASHTO R28)			
$G^*\sin$ (Test temperature 25 °C)	AASHTO T313	5410	≤5000kPa
Creep stiffness (Test temperature -6 °C)		70.374	≤300MPa
m-value (Test temperature -6 °C)		0.3933	≥0.3

Table 2. Size distribution of the PET particles

Sieve Size (mm)	Percentage of Passing (%)
Coarse graded PET	
2.36	100
1.18	5
Fine graded PET	
0.6	100
0.3	5

Table 3. Some properties of waste PET used in this research

Properties	Standard Method	Value
Density (gr/cm3)	ASTM D792	1.35
Moisture absorption (%)	ASTM D570	0.1
Melting point (°C)	-	250
Tensile strength (kPa)	ASTM D638	850
Glass Transition Temperature (°C)	-	75

Fig. 2. Coarse and fine PET particles

MIX DESIGN AND PREPARATION OF SPECIMENS

The mixtures were designed using Marshall mix design, following ASTM D1559 standard method. The optimum asphalt cement content of the mixture without PET (control mix) was determined to be 4.5%. According to previous studies, the optimum binder content of PET-modified mixtures is similar to that of the control mixture (Baghaee Moghaddam et al., 2014a,b). Therefore, the mixtures containing PET were made with 4.5% of binder content. The volumetric properties of asphaltic concrete are highly effective on their performance in pavement (Taherkhani, 2016). The volumetric terms of the mixtures (Table 5) were checked to satisfy the requirements of specification. With the same binder content, it was found that the volume of air voids and the voids in mineral aggregate (VMA) of the compacted mixtures grows with increasing PET content. However, the requirements of the specification (IAPC, 2012) were satisfied. The grow of air voids and VMA with increasing PET content was attributed to the excess binder consumed for coating the PET particles, leaving more voids in the mixture. The resiliency of the PET particles was also responsible for the growing of air voids and VMA content. As seen in Table 5, the fine PET particles resulted in more air voids content and VMA in the mixtures than the coarse PET particles.

After determination of the optimum asphalt cement content for making the mixtures, the specimens for creep testing were fabricated following ASTM D1559 standard method. According to previous studies (Ahmadinia et al., 2011, 2102), the required weight of PET particles was added after mixing the heated asphalt cement and aggregate for 5 minutes, and thoroughly mixed for 2 minutes until the aggregate and PET particles were fully coated with the binder. By this method of mixing, semi-crystalline state of PET was maintained and minimum changes occurred in its properties and shape. The glass transition of PET was around 70 °C. Therefore, at the mixing temperature, the amorphous part of PET was melted, resulting in the increase of binder cohesion, while the crystalline part remained intact. The crystalline part of PET filled part of voids between the aggregates, thereby enhancing the stiffness of the mixture. The samples were allowed to be cooled for 24 hours, after which were extruded from the molds and stored until use in experiments. Forty-four specimens were made in this study.

DYNAMIC CREEP TESTS

The permanent deformation behavior of mixtures was examined by uniaxial dynamic creep test. The tests were performed following EN 12697-25 standard method by using a UTM-10 machine (Figure 3). The creep tests were performed at 40 °C and by applying a constant vertical stress of 300 kPa. The temperature was selected as the representative of the conditions at which the major permanent deformation of the mixtures occurs. Also, the stress has been used as an average value of stress levels experienced by the asphaltic mixtures in the surface layer under heavy vehicles wheel load.

Table 4. Volumetric properties of the mixtures

Mixture	**Additive Content (%) (By the Weight of Asphalt)**		**Air Voids Content**	**Voids in Mineral Aggregate (VMA) %**	**Voids Filled with Asphalt (VFA) (%)**
	Coarse Graded PET	**Fine Graded PET**			
Control	0	0	4.15	13.296	68.787
P16-2	2	-	4.256	13.526	68.55
P16-4	4	-	4.362	13.756	68.312
P16-6	6	-	4.468	13.985	68.075
P16-8	8	-	4.574	14.215	67.837
P16-10	10	-	4.68	14.445	67.599
P50-2		2	4.28	13.547	68.431
P50-4		4	4.41	13.798	68.077
P50-6		6	4.54	14.049	67.72
P50-8		8	4.67	14.299	67.366
P50-10		10	4.8	14.55	67.01

The loads were applied at two different frequencies of 0.5 and 5 Hz, in which the loading and rest time of each test were the same. These frequencies were selected as representatives of low and medium loading speed with the objective of examining the loading time effects on creep property of asphaltic mixtures. For the loading frequency of 0.5 Hz, both the loading and rest time was 1 second, whereas for the loading frequency of 5 Hz, the loading and rest time were 0.1 second. In each test, the specimen was left in the temperature-controlled cabinet, set at the test temperature, for two hours, to make sure that specimen is homogenously at the test temperature. Each test was set to be finished after 10000 loading cycles or reaching an accumulated strain level of 4%. During the test period, the vertical deformation and load values were collected by the computer connected to the UTM test set up. Before applying the main stress level of 300 kPa in each test, a vertical stress of about 30 kPa was applied for a duration of 10 min to remove any possible gap between the platens and the specimen and make sure the platens are in full contact with the surfaces of the sample.

MODELING CREEP BEHAVIOR

Asphaltic mixtures behave as a viscoelastic material in most of the conditions they experience in pavements, for which creep is a characteristic behavior. The creep curve of a viscoelastic material can be divided into three regions, as shown in Figure 3. The trend of strain accumulation in these regions is different. While the strain accumulates at a decreasing rate in primary region, it increases almost linearly in the secondary region and the rate of strain accumulation in tertiary region increases with increasing the number of loading repetition. The creep behavior in the regions have been characterized by a three-stage model, developed by Zhou et al. (2004), as shown in Eqs. (1-3). The model for primary region is a power function and those for the secondary and tertiary region are linear and exponential functions, respectively.

$$\varepsilon_p = aN^b\,,\quad N \le N_{ps} \tag{1}$$

primary region

$$\varepsilon_p = \varepsilon_{PS} + c(N - N_{PS}), N_{PS} \le N \le N_{ST} \;\text{و}\; \varepsilon_{PS} = aN_{PS}^b \tag{2}$$

secondary region

$$\varepsilon_p = \varepsilon_{ST} + d\left(e^{f(N-N_{ST})} - 1\right), N \ge N_{ST} \;\text{و}\; \varepsilon_{ST} = \varepsilon_{PS} + c(N_{ST} - N_{PS}) \tag{3}$$

tertiary region

in which, ε_p: is the plastic strain, N: is the number of load repetitions, a, b, c, d and f: are the constants of material, N_{PS} and N_{ST}: are load repetitions to reach the beginning of the secondary and tertiary creep region, respectively, ε_{PS} and ε_{ST}: are the plastic strains accumulated at the end of primary and secondary region, respectively. By programming in MATLAB, the models were fitted to the primary, secondary and tertiary creep regions of the mixtures for finding the model parameters.

RESULTS AND DISCUSSIONS

Creep Tests Results

The creep curves of the mixtures were plotted using the results of creep tests conducted at both the loading frequencies of 0.5 and 5 Hz. Creep curves of the mixtures modified with different dosages of fine and coarse graded PET particles under 0.5 and 5 Hz of loading frequency, are shown in Figures 4 to 7, in which the vertical strain versus load repetitions are plotted. As can be seen, in all the figures, the accumulated strain increased with increasing PET content, indicating that addition of PET into asphalt concrete decreased its resistance against permanent deformation. For instance, after applying 10000 loading cycles with a frequency of 0.5 Hz, the accumulated vertical strain in control mix was about 17000 µs. However, the mixtures containing 10% of P16 and 10% of P50 reached 40000 µs after about 2200 and 4100 loading cycles, respectively. Previous studies (Baghaee Moghaddam et al., 2014a,b) on gap graded mixture of SMA revealed that addition of PET improved the permanent deformation resistance of the mixtures, which contradicts the finding in this study. This contradiction is related to the difference between the gap graded SMA mixture and the dense gradation of asphalt concrete used in this research. However, Almeida et al. (2017) and Earnest (2015) also found that the permanent deformation resistance of asphalt concrete decreases with PET modification. In a gap graded asphalt mixture, the aggregate interaction and stiffness of the asphalt mortar are responsible for the resistance against deformation. Addition of PET results in the increase of mortar stiffness and the resistance against plastic deformation. The deformation resistance of a dense graded mixture is mainly provided by the aggregates interlock. Addition of PET forms a layer on the aggregate surface and decreases the interlock and deformation resistance, which cannot be compensated by the improvement of the binder stiffness.

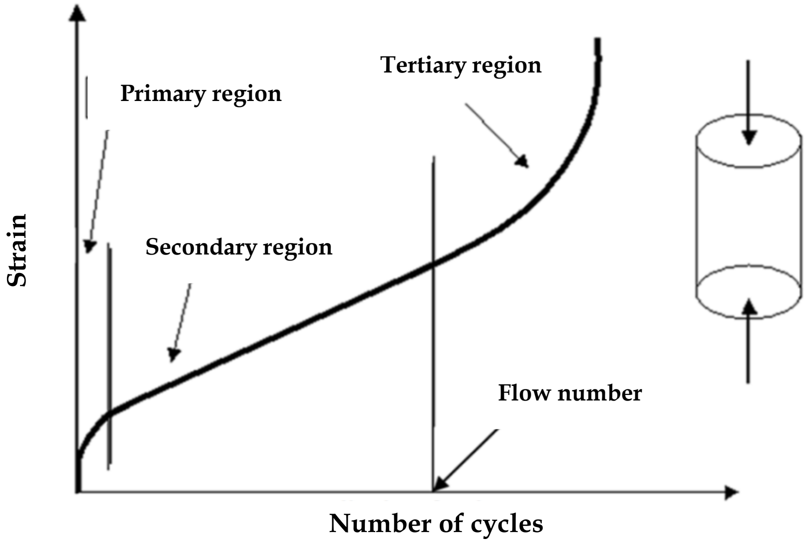

Fig. 3. Creep curve of asphaltic mixtures

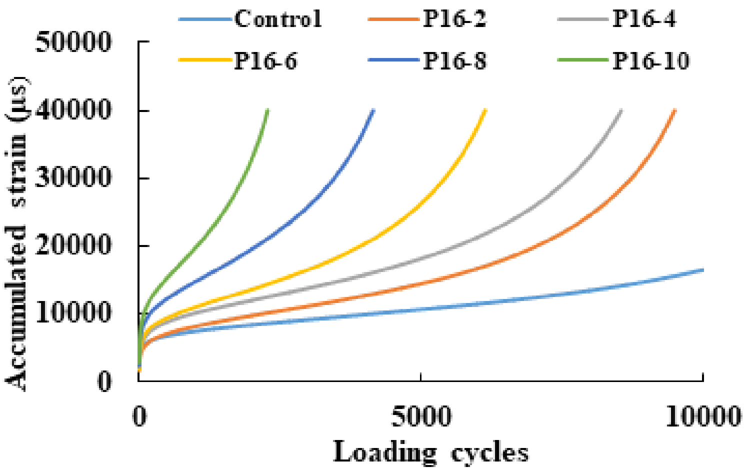

Fig. 4. Creep curve of the mixtures containing coarse PET particles under loading frequency of 0.5 Hz

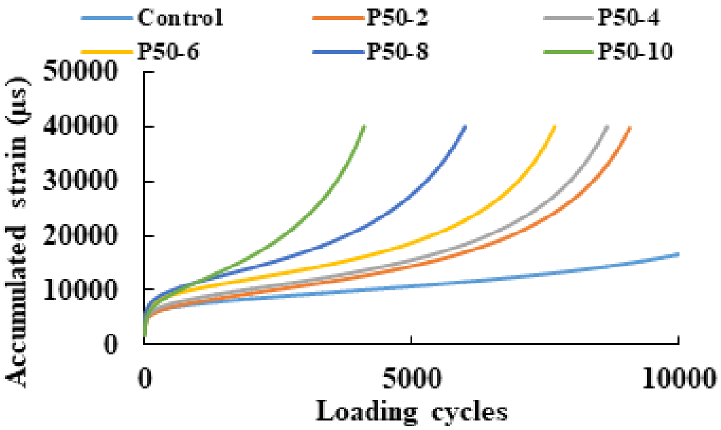

Fig. 5. Creep curve of the mixtures containing fine PET particles under loading frequency of 0.5 Hz

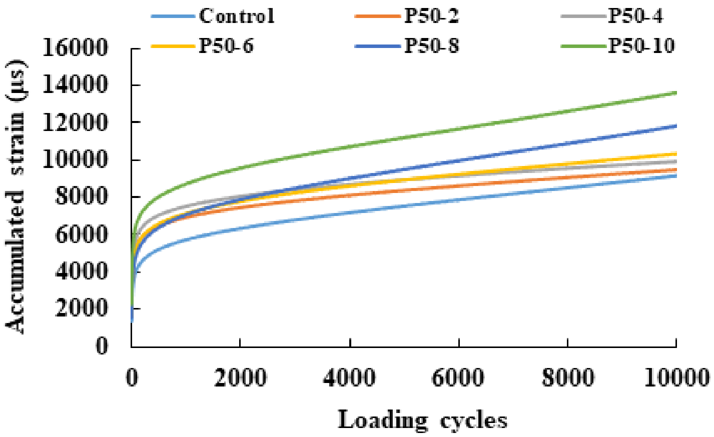

Fig. 6. Creep curve of the mixtures containing coarse PET particles under loading frequency of 5 Hz

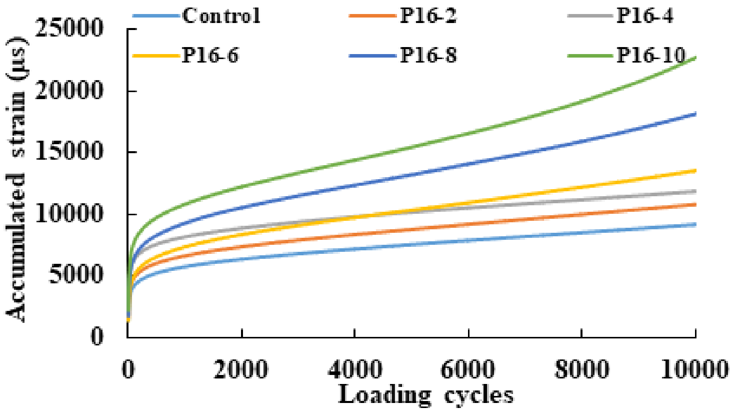

Fig. 7. Creep curve of the mixtures containing fine PET particles under loading frequency of 0.5 Hz

Comparing the creep test results of the mixtures modified with coarse and fine graded PET in Figures 4-7 revealed that the deformation resistance of the mixtures containing fine graded PET particles was more than that of the mixtures containing coarse PET particles. The accumulated strain after 2000 loading cycles was plotted against PET content under loading frequencies of 0.5 and 5 Hz are shown in Figure 8. Moreover, for both the 0.5 and 5 Hz loading frequencies, the accumulated vertical strain increased with increasing PET content, with higher strains for the mixtures modified with coarse graded PET particles of P16. Furthermore, results in Figure 8 reveal that the difference between the strain of the mixtures modified with fine and coarse graded PET particles increased with increasing PET content. Also, the results revealed that the strain for the loading frequency of 5 Hz was less than that under 5 Hz, which is because of lower loading time experienced by the mixtures at the higher frequency.

In order to compare the effect of loading frequency on creep behavior, the accumulated strain of the mixtures after 600 seconds of loading and rest time was obtained from the creep test results. In the tests conducted under the loading frequency of 0.5 Hz, 600 seconds of loading and rest time was associated with 600 loading cycles, while under 5 Hz, it was associated with 6000 loading cycles, as shown in Figures 9 and 10. As can be seen, after the same loading and rest time, the accumulated strain under higher frequency was more than that under lower frequency, indicating that the asphaltic mixtures containing PET had a better performance in pavements subjected to a lower traffic speed, such as city streets and parking lots, than those under higher traffic speed, such as interstate highways. It is also shown in the figures that the mixtures containing PET were less sensitive to loading frequency than the control mixture, with lower sensitivity of the mixtures containing fine PET particles than those containing coarse PET particles.

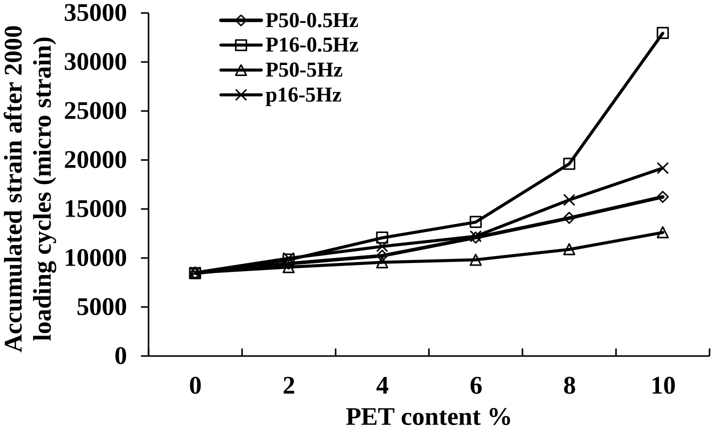

Fig. 8. Accumulated strain after 2000 loading cycles with frequency of 0.5 Hz

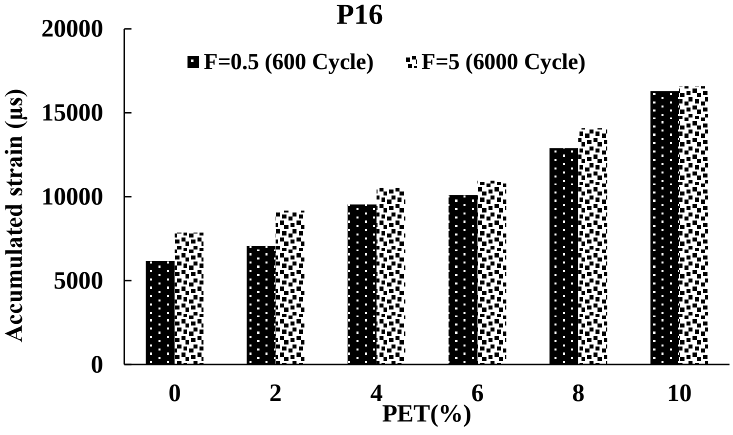

Fig. 9. Accumulated strain of the mixtures containing coarse PET particles after 600 (sec) of loading and rest time

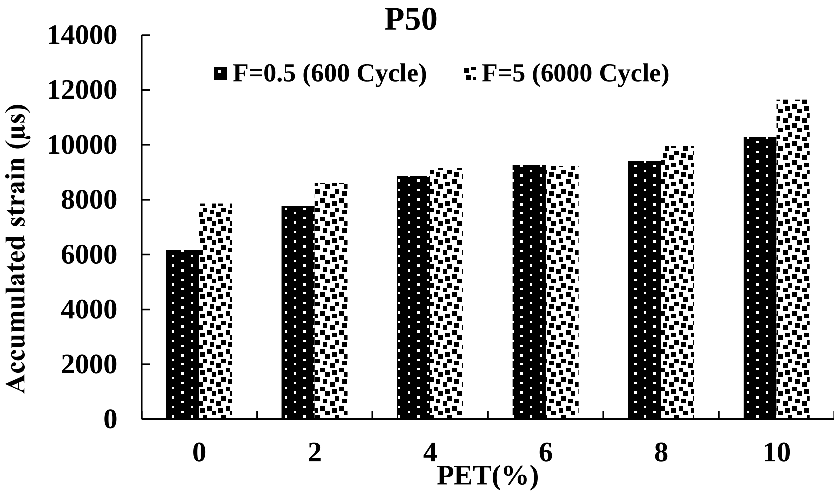

Fig. 10. Accumulated strain of the mixtures containing fine PET after 600 (sec) of loading and rest time

Three-Stage Model

As mentioned earlier, using MATLAB software, the parameters of the models for primary, secondary and tertiary regions of creep curve (Eqs. (1-3)), were determined by fitting the models to the test results. The fitting showed that the models can well predict the strains in three regions. The values of model parameters for the PET modified mixtures under loading frequency of 0.5 and 5 Hz are shown in Table 6. Among the parameters, N_{PS}, N_{ST} and c are more commonly used as indicators of permanent deformation resistance of asphaltic materials. The strains occurring in the primary creep region are mostly recoverable (Katman et al., 2015). Therefore, a higher value for N_{PS}, which is the number of loading repetitions up to the start of secondary creep region, is beneficial to rutting resistance of asphaltic mixture. The creep occurring in the secondary creep region is mostly plastic, and a lower rate of strain accumulation (parameter c) is beneficial to resistance against permanent deformation. N_{ST} is the loading repetitions at the end of the secondary region, which is also known as the flow number. Figures 11 and 12 show, respectively, N_{PS} of the mixtures in the tests utilizing the 0.5 and 5 Hz loading frequencies. As can be seen, at both the frequencies, there was a peak value for the mixture containing 4% of PET content, beyond which it decreased with increasing PET content. Therefore, the mixtures containing 4% of PET remained longer in their primary region. The results also showed that the mixtures containing finer PET particles of P50 had a longer primary region than those containing coarse PET particles of P16. The difference between the length of the primary region of the mixtures containing fine and coarse PET was more at higher loading frequency. This indicates that in applications where the loading time is low, use of finer PET particles is more effective for having a mixture resistant against permanent deformation. The results also revealed that the primary creep region for the frequency of 5 Hz was longer than that for 0.5 Hz.

Figures 13 and 14, respectively, showed the values of c, which is the rate of strain accumulation in the secondary creep region, for the mixtures containing different percentages of PET particles in the creep tests conducted under the loading frequencies of 0.5 and 5 Hz. As can be seen, c increased with increasing PET content, with higher values for the mixtures containing the coarse PET particles. For instance, in the tests conducted under the loading frequency of 0.5 Hz, the value of c for the mixtures containing 10% of coarse and fine PET particles was about 9 and 4 times higher than that of the control mixture, respectively. Moreover, the results indicated that the strain rate in the secondary creep region decreased with increasing loading frequency.

The parameter N_{ST} in the models is the flow number, which is the number of loading cycles at the end of the secondary creep region. Flow number is commonly used as a criterion for resistance of asphaltic mixtures against permanent deformation. A mixture with a higher flow number is more resistant against permanent deformation (Taherkhani and Afroozi, 2017). As seen in Table 6, under the loading frequency of 5 Hz, none of the mixtures reached the tertiary creep region. Therefore, flow number was only determined for the mixtures under the loading frequency of 0.5 Hz. Figure 15 shows the flow number of the mixtures containing different percentages of fine and coarse PET. As can be seen, the flow number decreased with increasing PET content, which is consistent with the results of previous studies (Zhou et al., 2004). It can also be observed that the flow number of the mixtures containing finer PET of P50 was generally higher than that of the mixtures containing coarse PET particles of P16, indicating that using finer PET particles results in a higher resistance against permanent deformation.

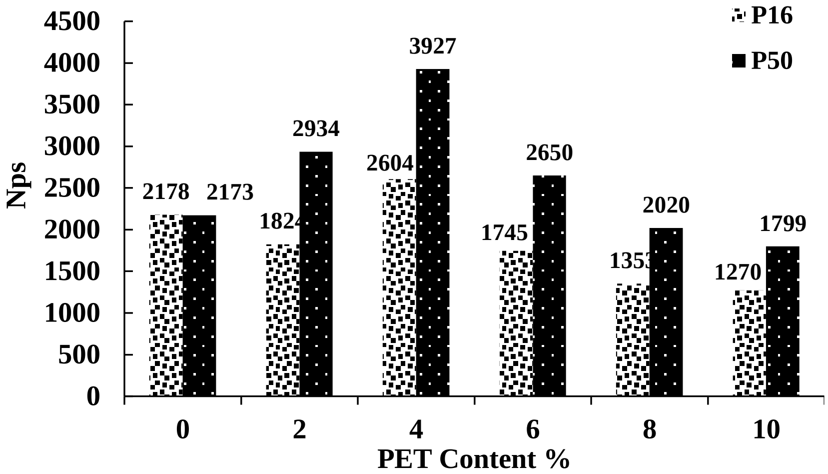

Fig. 11. The number of cycles at the beginning of secondary region for the loading frequency of 0.5 Hz

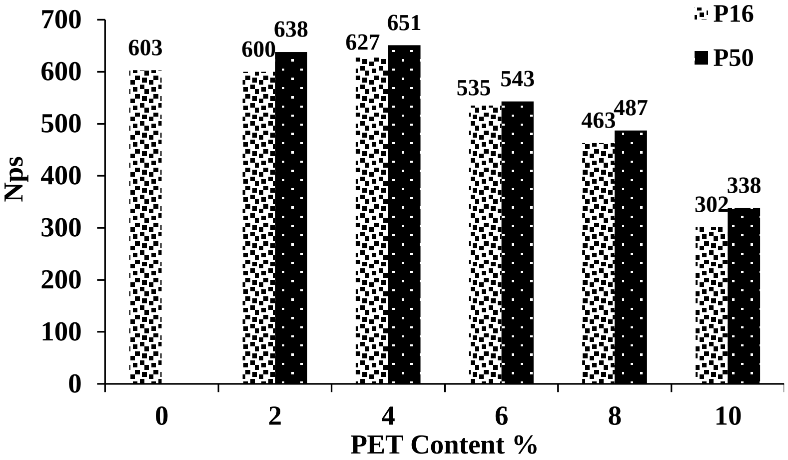

Fig. 12. The number of cycles at the beginning of secondary region for the loading frequency of 5 Hz

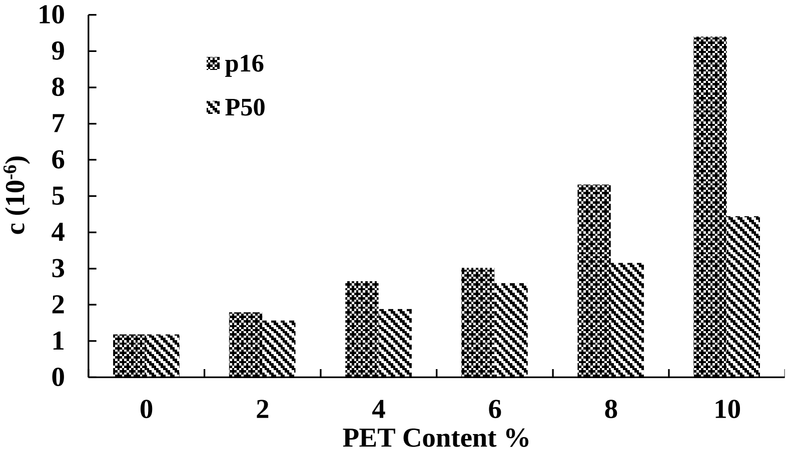

Fig. 13. The slope of strain rate in the secondary creep region for the loading frequency of 0.5 Hz

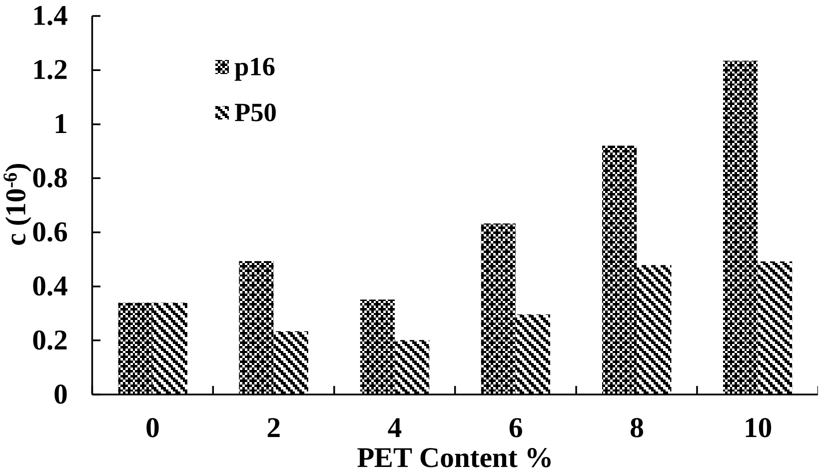

Fig. 14. The slope of strain rate in the secondary creep region for the loading frequency of 5 Hz

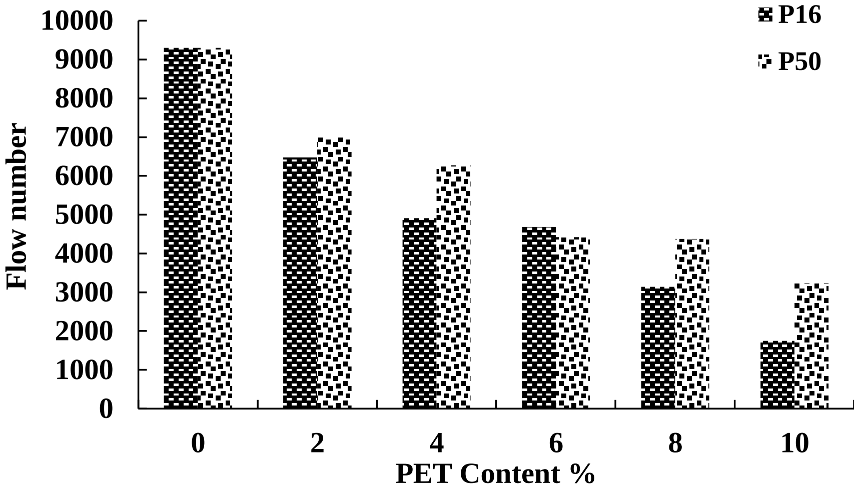

Fig. 15. Flow number of the mixtures for the loading frequency of 0.5 Hz

Table 5. Constants of the three-stage model for the mixtures

Frequency	**Mixture**	a	b	ε_{PS}	N_{ps}	N_{ST}	f	ε_{ST}	c
0.5 Hz	Control	2149	0.1646	6160	603	9297	0.001207	16300	1.179
	P16-2	2410	0.1679	7060	600	6472	0.0008816	17300	1.793
	P16-4	2793	0.1919	9610	627	4909	0.001345	20700	2.649
	P16-6	3181	0.18	9850	535	4687	0.001164	22100	3.017
	P16-8	3485	0.2027	12100	463	3136	0.001906	26000	5.318
	P16-10	3871	0.2178	13400	302	1750	0.002715	24700	9.398
	P50-2	3667	0.138	8940	638	6988	0.001073	18700	1.562
	P50-4	2579	0.1728	7900	651	6273	0.0009429	18200	1.881
	P50-6	3114	0.1699	9080	543	4416	0.001497	18900	2.596
	P50-8	3414	0.1716	9870	487	4371	0.001241	21800	3.152
	P50-10	2355	0.2129	8140	338	3241	0.002039	20800	4.44
5 Hz	control	2177	0.1404	6390	2173	-	-	-	0.3399
	P16-2	2507	0.1409	7220	1824	-	-	-	0.4193
	P16-4	3613	0.1182	9150	2604	-	-	-	0.3509
	P16-6	2265	0.1707	8100	1745	-	-	-	0.6329
	P16-8	3001	0.1636	9760	1353	-	-	-	0.9207
	P16-10	3789	0.152	1120	1270	-	-	-	1.235
	P50-2	3317	0.1067	7780	2934	-	-	-	0.2341
	P50-4	3678	0.1034	8660	3927	-	-	-	0.2013
	P50-6	3033	0.1241	8070	2650	-	-	-	0.2961
	P50-8	2512	0.1501	7870	2020	-	-	-	0.4781
	P50-10	3777	0.1215	9370	1779	-	-	-	0.4918

CONCLUSIONS

In this study, different percentages of ground waste PET were added into a typical asphalt concrete. Of interest was to investigate the permanent deformation of the mixtures by conducting uniaxial dynamic creep tests at 40 °C and applying a stress level of 300 kPa at the loading frequencies of 0.5 and 5 Hz. The following are the highlighted results in brief.

- Resistance against permanent deformation decreased with increasing PET content.
- Fine PET particles resulted in more resistance against permanent deformation compared with coarse PET particles.
- The effect of PET particle size on permanent deformation was more noticeable at higher PET contents. For example, after applying 2000 loading cycles at the frequency of 0.5 Hz, *f* the accumulated strain of the mixtures containing 2 and 10% of coarse PET particles is 4.1% and 102%, respectively, higher than that of the mixtures containing coarse PET particles.
- Under the same loading and rest time, the accumulated strain in the mixtures increased with increasing loading frequency. The control mixture was more sensitive to loading frequency than the mixtures containing PET. Moreover, the sensitivity to frequency decreased with decreasing the size of PET particles.
- Based on the three-stage model, the length of the primary creep region increased with increasing PET content up to 4%, after which it decreased with increasing PET content. In addition, the length of the primary creep region was longer for the mixtures with finer PET particles. Under the loading frequency of 0.5 Hz, the length of the primary creep region of the mixtures containing 4% of fine and coarse PET particles was 7.9 and 4%, respectively, higher than that of the control mixture.
- The slope of the strain rate in the secondary creep region increased with increasing PET content, with a lower value

for the mixtures containing finer PET particles.

- The strain rate in the secondary creep region decreased with increasing loading frequency.
- The flow number of the mixtures decreased with increasing PET content with a lower values for the mixtures containing coarse PET particles.
- As future research, sensitivity to temperature and stress level of mixtures containing PET particles is recommended to be investigated. It is also suggested to investigate the permanent deformation of mixtures using wheel tracking test.

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