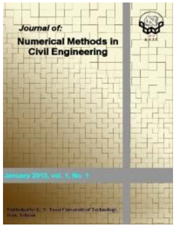

Numerical Methods in Civil Engineering

Investigating the Rutting Behavior of Modified Asphalt Mixtures with Waste Materials

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Abstract:

Recycling of waste materials has significant environmental and economic advantages. Plastic containers and steel slag waste solids were incorporated in Stone Mastic Asphalt (SMA) and the rutting performance of modified asphalt mixtures was investigated. Slab specimens with three percentage of Polyethylene Terephthalate (PET) including 3, 5 and 7 percent in two forms (PET particles and PET fibers) were prepared and wheel tracking test was performed. For various samples, rutting profiles were modeled by the Zhou model in the MATLAB environment. It was found that modified samples had better capability to resist permanent deformation. Induced rutting depth was the lowest for specimens modified with 5 percent PET followed by 7 and 3 percent, respectively. Moreover, adding PET in the form of fiber was more effective and exhibited the lowest damage ratio. Based on the obtained results, modified samples with 5 percent PET fiber caused 35 percent less rutting. According to life cycle ratio analysis, in average S-5P-F lasted 3.35 times more than the slag control sample.

1. Introduction

Poor performance of unmodified asphalt specimens has led researchers to improve the performance of bituminous mixtures [1, 2]. Permanent deformation is one of the major and common distresses on roads that many researchers have tried to address [3, 4].

In this regard application of Stone Mastic Asphalt (SMA) mixtures which exhibit high resistance to permanent deformation has been recommended [5]. SMA has a higher coarse aggregate proportion and better aggregate interlocking, which forms a stone-on-stone structure [1, 6]. Stone matrix is held tightly together through a strong mastic of filler, asphalt cement, and other additives, which enhance the stability of the sample [6, 7]. Generally, SMA mixture constitutes a large coarse proportion 70%–80%, high filler content 8%–12% and high binder percentage 6.0%–7.0% [8-11].

In recent years utilizing waste materials as secondary materials in road construction projects has become an alternative solution to enhance environmental sustainability [12]. Application of steel slag as an environmentally friendly material to produce a cleaner asphalt concrete is a wise approach from technical, economical, and environmental aspects and should be taken into consideration due to the scarcity of natural aggregate resources and escalating cost of polymers [13-16].

Slag is a co-product in the iron and steel manufacturing process and exists in forms of blast furnace (BF), basic oxygen furnace (BOF), and electric arc furnace (EAF) [17-19]. More than 50% of the steel manufactured in Iran is produced by EAF method [17]. The annual output of steel slag in Iran is more than 3 million tons, of which most of them are disposed.

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Slag exhibits better physical properties such as higher density, improved abrasion, and hardness, as well as increased bearing strength. In addition, steel slags are highly angular with improved micro and macro texture [20-22]. Slags should be merely used as a fine or coarse fraction since hot mix asphalt comprises of steel slag only, which is susceptible to air voids and bulking effects [14, 23-24].

Researches proved that replacing 75% of limestone coarse aggregates with steel slag aggregates improved the mechanical properties of asphalt mixtures [6]. A significant disadvantage that comes across with SMA mixtures is the binder drain down and high initial expense. Since SMA mixes are gap-graded mixtures with high binder content, they can be stabilized with the addition of polymer or fiber in the mixture to prevent the binder drain down [25]. In this regard, utilization of modified polymers are common in SMA mixtures [2, 26]. The positive effect of polymers in the asphalt industry to enhance pavement performance has been proved. These improvements include higher degree of stiffness, improved adhesion and degree of cohesion, as well as increased resistant to rutting [27-29].

Due to the escalating cost of common additives, researchers have focused on the mixtures containing waste materials as additives which can further enhance the environmental sustainability. Inclusion of recycled/waste materials prevents additional charges and has become an alternative to improve the asphalt mixtures and natural soil properties [1, 20, 30-31].

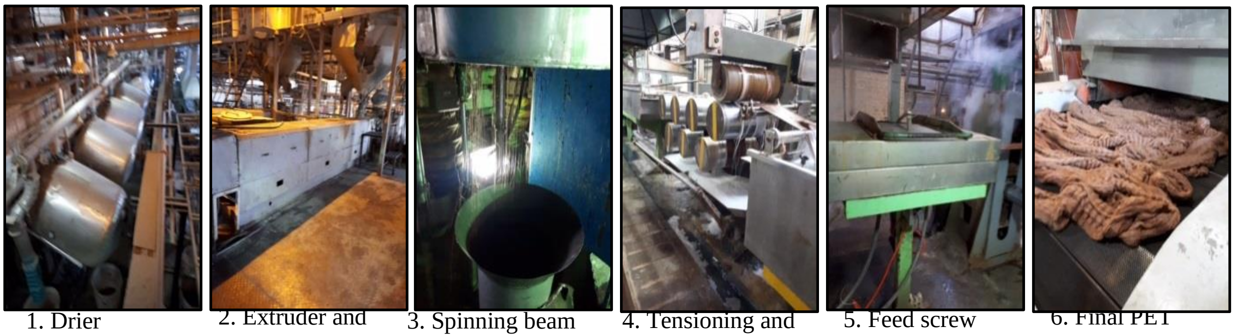
Out of various forms of waste plastics, polyethylene terephthalate (PET) is widely used in beverage bottles. Plastic containers have long biodegradation period and are highly detrimental to the environment and ecosystem balance [32-37].

Some researchers have added polymer or recycled polymer to asphalt mixtures in particle shape [2, 38]. However, other researchers have added polymer or recycled polymer to asphalt mixtures in the form of fiber [26, 39-40]. In previous researches, the PET was mostly added in the form of particles that enhanced the rutting properties of SMA mixtures. However, incorporating waste PET fiber as an additive in asphalt mixtures and its effects have not been well addressed yet.

Due to the escalating cost of polymer additives to improve asphalt mixtures rutting properties, this paper has focused on utilizing waste materials. In addition, the form of adding PET with optimum proportion and its effect on the rutting performance of SMA mixtures are investigated. Subsequently, laboratory rutting performance tests on SMA mixtures were performed. containing waste PET as the additive and steel slag as the aggregate proportion. Wheel tracking test was carried out on the mixtures that included 75% of steel slag as the coarse aggregate proportion, and various percentages of waste particle and fiber PETs (0%, 3%, 5% and 7% by weight of bitumen content) and the results were discussed. The production processes of PET particles (a) and PET fiber (b), are shown in Figure 1

1. Crusher
2. Label separator
3. Hot washer
4. Floating
5. Centrifugal dryer, storage silo
6. Final product and raw material for PET fiber production

(a)



1. Drier
2. Extruder and melt pipe
3. Spinning beam
4. Tensioning and cooling
5. Feed screw
6. Final PET fiber product

(b)

Fig. 1: PET particles (a) and PET fiber (b) Production Process

2. Materials and Mix Design Results

In order to ensure that physical properties of both the aggregate and the 60-70 penetration grade bitumen used in this research fulfills the local authority requirements [41], the following tests results were obtained and checked as in Table 1. The mean boundary of SMA specifications recommended by national asphalt pavement association is shown in Table 2 [42]. Marshall mix design method was used for determination of Optimum Asphalt Content (OAC). In order to prepare the Marshall samples, completely washed and dried aggregate was heated up to 180º C for 2 h before mixing. The weight of aggregate for each Marshall sample is approximately 1200 g. In aggregate proportion of modified samples.

Table 1. Aggregate and Bitumen Tests Results

Test	**Aggregate Tests Results**		**Requirements**
	Lime	Slag	
Los Angeles Abrasion (%) – ASTM C131	22	12	< 25
Flakiness & Elongation Index (%)- ASTM D4791	12	9	< 15
Soundness Test- ASTM C88	1	9	< 8
Fractured Particles- ASTM 5821	86	97	>75
Sand Equivalent Test- ASTM D2419	58	66	>50
Specific Gravity of Coarse Aggregate- ASTM C127	2.597	3.25	
Specific Gravity of Fine Aggregate- ASTM C128	2.567	-	
Specific Gravity of Filler-ASTM D854	2.718	-	
Test	**Bitumen Tests Results**		**Requirements**
Specific Gravity-ASTM D70	1.016		
Penetration- ASTM D5	63		60-70
Softening point- ASTM D36	49		49-56
Ductility- ASTM D113	>100		>100
Flash & Fire- ASTM D92	304		>232
Thin Film Oven- ASTM D1754	0.41		<1
Penetration after thin film oven	40		
Kinematic Viscosity at 135°C, (centistoke)- ASTM D2170	361		
Kinematic Viscosity at 165°C, (centistoke)- ASTM D2170	142		

Table 2. Proportion for each Sample

Sieve size mm (SI)		Percent passing (Mean)	Weights used for lime samples	Weights used for slag samples	
				Weight of slag (75%)	Weight of lime aggregate (25%)
19.0	(3/4 inch)	100	0	0	0
12.7	(1/2 inch)	90	120	90	30
9.5	(3/8 inch)	70	240	180	60
4.75	(No. 4)	24	552	414	138
2.36	(No. 8)	20	48	36	12
0.60	(No. 30)	14	72		72
0.30	(No. 50)	13.5	6		6
0.075	(No. 200)	9	54		54

filler	-	108	108

The EAF steel slag used (75% of the coarse proportion) that belongs to Esfahan and Mobarake Steel manufacturing companies. These artificial aggregates were used after two years of disposal as recommended by [14, 17]. Steel slags were washed to accelerate the hydration process of free lime and to eliminate the expansion problem. Proportions of each fraction (both for lime sample and modified slag specimens) are shown in table 2.

During the mix design process, the bitumen was heated up to 155º C for a period of 1 h before being blended with the aggregate. Marshall samples were prepared with 5.0, 5.5, 6.0, 6.5 and 7 percent bitumen by weight of the total mix. The Marshall compactor was then used to compact Marshall Specimens at approximately 150 ºC with 50 blows from the top and bottom side of the mixture. Since 75 compaction blows may break the aggregate without a significant increase in density compared to 50 blows, as recommended by [6], 50 blows per side of each mixture were used. In order to prepare modified samples, PET and PET fiber were added in the next stage. Based on the data provided by the local PET manufacturer, characteristics of these additives are summarized in Tables 3 and 4.

Table 3. Characteristics of the PET Particles

Image	Property	Value
	Density (gr/cm³)- ASTM D792	1.35
	PET maximum size	2.36
	Water absorption (%)- ASTM D570	0.1
	Tensile strength (MPa)- ASTM D638	79.3
	Approximate melting temperature (°C)	250

Table 4. Characteristics of the PET Fiber

Image	Property	Value
	Nominal denier tex-ASTM D 1557	8
	Length (mm)	5±1
	Tenacity (g/d)	4.5-5.5
	Elongation at break (%)	80
	Approximate melting temperature (ºC)	250

Wet or dry procedures can be used for the inclusion of the PET additives to the asphalt mixture. In the wet method, the additive is mixed with the bitumen, whereas in the dry process, the additive is blended with the aggregate first and the binder is added consequently. PET has a high melting point (approximately 250°C) while the maximum temperature for the mixing process and blending materials in the SMA mixtures is less than 180°C. Due to the high melting point, it is impractical to dissolve PET into the bitumen [3]. As recommended by [3, 43], in this research, the waste PET was added into the mixture in the last part of the mixing process, after adding and blending of the binder with aggregate. During the mixing process, aggregate, bitumen, and filler were mixed at 165±5 ºC for about 5 min; then, PET was introduced gradually into the combination and blending was continued for another 5 minutes. Different percentages of waste PET (for particles the maximum size was 2.36 mm and for PET fibers the length was 5±1 mm) were added to SMA mixtures. Six percentages of PET including 0, 3%, 5%, 6%, 7% and 9% by weight of bitumen were added in two forms (PET and PET fiber) to prepare 180 Marshall specimens (6×2×15) and to investigate the appropriateness of 2 or 3 percent increments in PET content (3,5,7 versus 3,6,9).

The bulk specific gravity of each Marshall sample was determined, and the voids analysis was carried out [44]. In order to specify the impact of artificial aggregate and waste plastic bottles PET modification on the engineering properties of Marshall-compacted samples, the volumetric and mechanical properties of asphalt mixes were calculated. Based on the obtained results in Table 5, modification has a significant effect on the properties of SMA including increased Marshall Stability and Marshall Quotient (MQ-stability/flow), as well as decreased density.

In order to determine the optimum asphalt content based on the Marshall method, asphalt content corresponding to four percent of voids in total mix (VTM) was selected. The OAC value for each mixture is illustrated in Table 5 as well. With the obtained optimum asphalt content, we should then go back to the Marshall plots and determine stability, flow, voids in mineral aggregate (VMA) and voids filled with asphalt (VFA) and compare them with SMA criteria for acceptability. Summary of Marshall samples' characteristics, at the OAC, is shown in Table 5.

Based on the obtained results, it was shown that 2 percent increment in PET content is more influential using 3%, 5%, and 7% of additive for the wheel tracking analysis. As it can be seen in Table 5, in comparison with lime samples, replacing the coarse fraction with slag caused an increase in optimum binder content. Furthermore, utilizing PET additive in both particle and fiber shapes caused a reduction in optimum binder content, while the method of adding (particle or fiber) does not have any impact on OAC value.

Table 5. Mixture Specifications and Requirements Checking

Characteristics of Samples	OAC @ 4% Air voids	Properties of samples			
		Marshall Stability (kN)	Flow (mm)	VMA (%)	VFA (%)
L	5.57	8.00	3.12	16.26	75
S	6.17	8.73	3.14	15.46	74
S-3P	5.6	9.19	2.87	15.52	75
S-5P	5.3	9.95	2.72	16.10	75
S-7P	5.4	9.26	2.76	16.20	76
S-3P-F	5.6	9.30	2.79	16.39	76
S-5P-F	5.3	10.27	2.64	15.60	72
S-7P-F	5.4	10.20	2.70	15.34	76
Requirements		Minimum 5.34	2-4 (mm)	Minimum 15	65-78

3. Wheel Tracking Test and Rutting Analysis

Finally, the above-mentioned asphalt contents were used to prepare 24 slab specimens for wheel tracking experiment (4 PET percentages, 2 PET forms and 3 replications). For wheel tracking test, the WESSEX wheel tracker apparatus and its related roller compactor were used. In addition, 96 Marshall samples were prepared for the creep test at two stress levels and two testing temperatures. However, the creep data are beyond the scope of this manuscript, and the main focus of this paper is comparison between the rutting strength of modified and unmodified samples.

All the slab specimens (305*305*50 mm) were conditioned at the testing temperature of 50 °C at least four hours prior to testing. Since the recommended testing temperature in Wessex manual was between 20 and 75°C, the temperature of 50°C was used according to the study by [45, 46]. The Wessex wheel tracking test procedure is described in [48]. Specimens were subjected to simulated trafficking containing rubber tired wheel (conform to BS 598) with a simple harmonic motion that applies 520 N load (from 18.4 kg suspended weight), and the permanent deformation values were captured at every 25 cycle intervals. The test stops after 45 minutes or at rut depth of 15 mm. In this study, 12.7 mm permanent deformation failure criterion which concurs with the Asphalt Institute failure criterion, and Hamburg wheel tracking termination point, was selected [4, 29]. The Linear Variable Differential Transducer (LVDT) monitors the rut depth at the center of the slab specimens.

Zhou model is a well-known model to conduct a comprehensive study on rutting behavior of asphalt mixtures [48-51]. In this study, rut profiles were obtained until 12.7 mm depression, and the permanent deformation profiles were modeled by the Zhou model in MATLAB environment. It has been well-established that rut profile of an asphalt mixture is divided into three zones including primary, secondary and tertiary stages, and power, linear and exponential functions, are recommended respectively for comprehensive modeling [48-51].

According to Zhou model, permanent deformation values accumulate rapidly with the initiation of densification in the primary stage. In the first stage and up to a certain number of load cycles (depending on the degree of compaction and the induced vertical stress), the asphalt materials are compressed together, and the voids in total mix are reduced. As the materials orient in a dense position and the interlocking increases, rutting depth is almost stabilized for few numbers of load cycles during the secondary stage. Finally, in the tertiary stage, the mixture flows to rupture and exhibits an increasing rutting depth.

In order to make comparisons between various tested samples, permanent deformation profiles were modeled in the MATLAB environment, and the mean values of three replications obtained are illustrated in 2D and 3D plots in Figures 2 and 3, respectively.

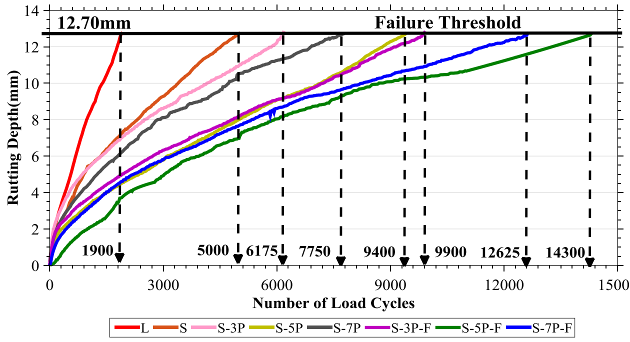


Fig. 2: Permanent Deformation Profiles for Various Samples

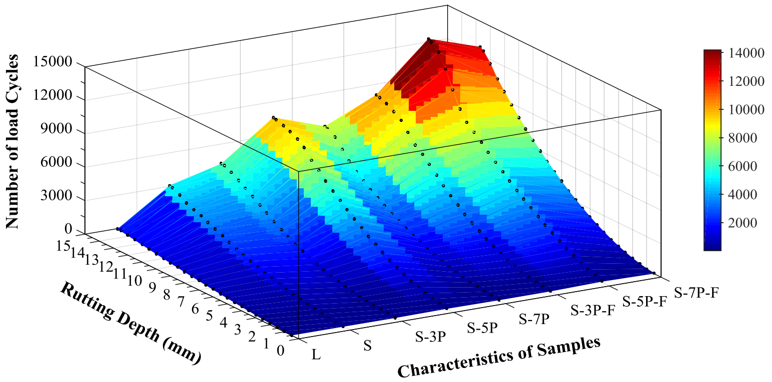


Fig. 3: 3D Plot for Permanent Deformation Profiles of Various Samples

As it can be seen, lime samples reached the failure threshold earlier, while slag sample with 5 percent PET fiber (S-5P-F) exhibited the best performance with largest rutting life. As it can be seen in Figures 2 and 3, 12.7 mm permanent deformation caused by the lime and slag unmodified samples occurs at low number of load cycles, which implied that modified samples had a better capability to resist permanent deformation. Therefore, adding PET to asphalt mixtures remarkably decreases its susceptibility to rutting. Furthermore, it can be seen that the optimum PET content to be added is 5 percent by the weight of bitumen. Therefore, for both PET particles and PET fibers, five percent additive exhibited the best rut performance. Table 6 shows the 3-stage permanent deformation models in the MATLAB environment. During the wheel tracking test, all samples underwent the three stages and the inflection points were tabulated. 3-stage model outweighs the previously established conventional methods; that ascertains the transition points and separates the distinct behavior during the life cycle.

Table 6. 3-Stage Zhou Model for Permanent Deformation

	Primary stage	Secondary stage			Tertiary stage
Samples	Model	Initial point	End point	Model	Model
L	$RD=0.05083N^{0.73195}$	1225	1825	$RD=9.2566+0.00496(N-1225)$	$RD=12.2336+0.05339\left(e^{0.036581(N-1825)}-1\right)$
S	$RD=0.10825N^{0.5566}$	3225	4350	$RD=9.712+0.00185(N-3225)$	$RD=11.7918+0.202\left(e^{0.00267(N-4350)}-1\right)$
S-3P	$RD=0.2477N^{0.44326}$	4000	4950	$RD=9.7875+0.00114(N-4000)$	$RD=10.8722+0.2426\left(e^{0.001688(N-4950)}-1\right)$
S-5P	$RD=0.05918N^{0.5756}$	6100	7350	$RD=8.9353+0.00085(N-6100)$	$RD=9.9928+0.4065\left(e^{0.00094(N-7350)}-1\right)$
S-7P	$RD=0.12923N^{0.51414}$	5025	6875	$RD=10.334+0.00074(N-5025)$	$RD=11.6994+0.14577\left(e^{0.00197(N-6875)}-1\right)$
S-3P-F	$RD=0.11552N^{0.50021}$	6425	7500	$RD=9.2765+0.00095(N-6425)$	$RD=10.298+0.42736\left(e^{0.000763(N-7500)}-1\right)$
S-5P-F	$RD=0.01963N^{0.68938}$	8900	11925	$RD=10.3692+0.000347(N-8900)$	$RD=11.4211+0.24052\left(e^{0.000812(N-11925)}-1\right)$
S-7P-F	$RD=0.07159N^{0.54908}$	8175	11250	$RD=10.0729+0.00059(N-8175)$	$RD=11.8984+0.135\left(e^{0.0013627(N-11250)}-1\right)$

With a coded m-file in MATLAB, initiation of secondary stages and flow numbers were calculated and were shown in Table 6. For modified samples, number of load cycles to failure was significantly larger compared to the reference slag sample. The slag sample was considered as the control sample since it includes the artificial slag aggregates but not the PET additives. Furthermore, number of load cycles to failure for specimens modified with 5 percent PET fiber was the highest followed by 7 and 3 percent, respectively. Based on the obtained results, significant enhancement occurred in the behavior of mixtures modified by 5 percent PET fiber. With reference to the established functions, constant component of the power functions decreases considerably for the modified samples. Furthermore, for modified samples with 5 percent PET fiber, the reduction in the slope of the secondary stage model is clear. In addition, the exponent of exponential function decreases considerably for modified samples.

Since flow number is considered as the initiation of rupture, the difference between the operational life of slag samples (4350) and S-5P-F sample (11925) was 93%.

4. Factorial Analysis for Vertical Deformation

Factorial analysis for rutting depth until 12.7 mm permanent deformation was done in order to study the effect of additive modification on the induced rutting depth at various load cycles. A two-way ANOVA analysis was performed to test the null hypotheses for the main and interaction effects. Null hypotheses in the factorial analysis of variance assume no significant difference between various load cycles and PET modifications. Full factorial assumptions were checked and since there were no interaction effects; the main effects, and the associated test results of F, and Sig., values are listed in Table 7.

Based on the statistical analysis results in Table 7, null hypotheses were rejected and significant differences were found between different load cycles, and various samples (Sig. <0.05). For instance, the mean rutting depths across all load cycles were 13.9 mm, 12.1 mm and 8 mm for lime, slag and S-5P-F samples, respectively. Therefore, in terms of induced rutting 41% difference exists between S-5P-F and slag samples. In total, the R squared value indexed the adequacy of the analysis model and 97% of data variability was explained (R^2=0.97) by the exploited predictors in the established model.

5. Rutting Rate

Varying patterns of permanent deformation rate may be seen in rutting profiles depending on the strength of materials at various stages. As it can be seen in Figure 2, in the first stage and up to certain number of load cycles permanent deformation values accumulated rapidly, while the rutting per cycle (rutting rate) in Figure 4 tended to decrease, reaching the minimum value (almost completion of the densification process and onset of the secondary stage). As the materials orient in a dense position and the interlocking increases, asphalt materials exhibit the lowest rutting rate after which deformation rate is almost stabilized for few numbers of load cycles during the secondary stage.

Table 7. Factorial Analysis of the Effects of N and Additives on Permanent Deformation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	24558.387	579	42.415	123.815	0.00
Intercept	111774.611	1	111774.611	326283.986	0.00
N	24367.866	572	42.601	124.358	0.00
Sample (additive)	5060.186	7	722.884	2110.188	0.00
Error	678.628	1981	.343		
Total	194995.132	2561			
Corrected Total	25237.015	2560			
R Squared = 0.973 (Adjusted R Squared = 0.965)					

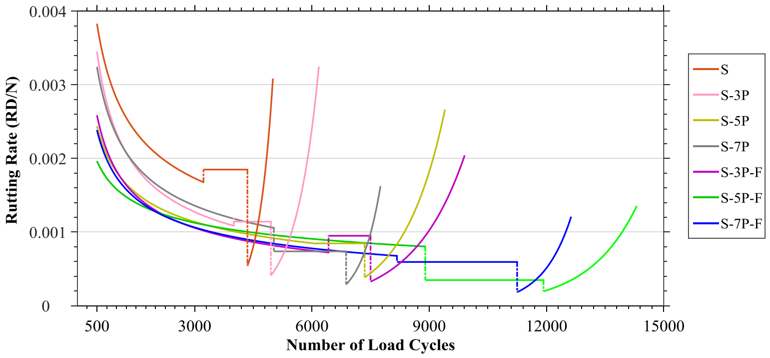


Fig. 4: Rutting Rate Profiles for Various Samples

Finally, in the tertiary stage, asphalt mixture flows to rupture and shows an increasing rate of rutting since the material resilient response is reduced due to the large application of wheel loading. In the third stage, the rutting rate increased at a much faster rate towards the end of the life cycle time and the asphalt mixture flows to rupture. As it can be seen in Figure 4; in the first stage, due to densification of asphalt mixtures, rutting per cycle ($\frac{\mathrm{RD}}{\mathrm{N}}$) is the highest and decreases as the number of load cycles increases. Based on the obtained results, rutting per cycle is the highest for lime sample with ever-increasing rate followed by slag sample. In modified specimens, samples with 5 percent PET fiber (S-5P-F) exhibited significantly improved performance. For the whole life cycle, in average, rutting rate was 0.002 $\frac{\mathrm{mm}}{\mathrm{N}}$ for the slag sample and 0.001 $\frac{\mathrm{mm}}{\mathrm{N}}$ for the S-5P-F (58% difference).

The amount of permanent deformation in slag mixtures, as well as its rate of accumulation outran that of modified mixtures. This behavior is attributed to the formation of a stiffer mixture, which improves the rutting resistance of the modified mixtures [28, 42-53]. When PET is heated, its properties begin to alter and eventually changes to a semi-crystal substance, which causes a stiffer mixture [3].

In order to compare the performance of PET and PET fiber, both rutting and rutting rate profiles were shown in a single plot in Figure 5 for modified samples with 5 percent PET. As it can be seen in Figure 5, adding PET in the form of fiber is more influential and it could produce more resistant asphalt mixtures with lower rutting rate.

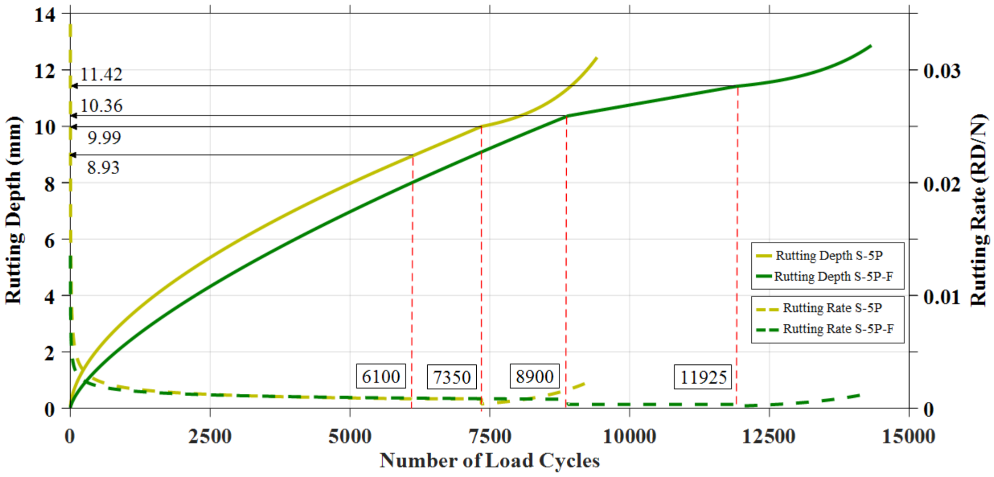


Fig. 5: Rutting and Rutting Rate Profiles for samples with 5 Percent PET Modifications

6. Relative Damage

In relative damage analysis (Equation 1), number of load cycles to cause 12.7 mm rut depth for slag control sample is divided to the corresponding number of load cycles for modified specimens. As it can be seen in Table 8, damage ratio is considered one for the slag control sample, while it is greater than one for the lime sample, and smaller than unit for the modified samples.

$$\text{linear damage ratio} = \frac{\text{Number of load cycles to cause 12.7 mm rutting depth for control samples}}{\text{Number of load cycles to cause 12.7 mm rutting depth for modified sample}} \tag{1}$$

Table 8. Linear Relative Damage for Various Samples

Characteristics of Samples	Number of Load Cycles to Failure	Linear Relative Damage
L	1900	2.632
S	5000	1.000
S-3P	6175	0.810
S-5P	9400	0.532
S-7P	7750	0.645
S-3P-F	9900	0.505
S-5P-F	14300	0.350
S-7P-F	12625	0.396

In damage analysis, rutting relative ratios were calculated. Considering artificial slag specimens as the control sample, it was found that the natural lime sample was 2.6 times more damaging.

As it can be seen in Table 8, adding 5 percent PET in the form of fiber is more effective and exhibits the lowest damage ratio. Based on the obtained results, S-5P-F caused 35 percent less rutting.

7. Life Cycle Ratio Analysis

In order to investigate the impact of sample modification not only at the 12.7 mm rutting failure point but also through the entire life cycle, numbers of load cycles were calculated. Number of load cycles which causes from 0.5 mm to 12.7 mm permanent deformation, were tabulated in Table 9.

Number of load cycles in Table 8 is obtained from permanent deformation established models in Table 6. The minor difference between the numbers of load cycles to cause 12.7 mm, is the difference between actual experiment and the established models. In order to obtain the life cycle ratios, number of load cycles for the tested samples were divided by that of the slag control sample and the values were tabulated in Table 10 and illustrated in Figure 6 both in counter and 3-D plots.

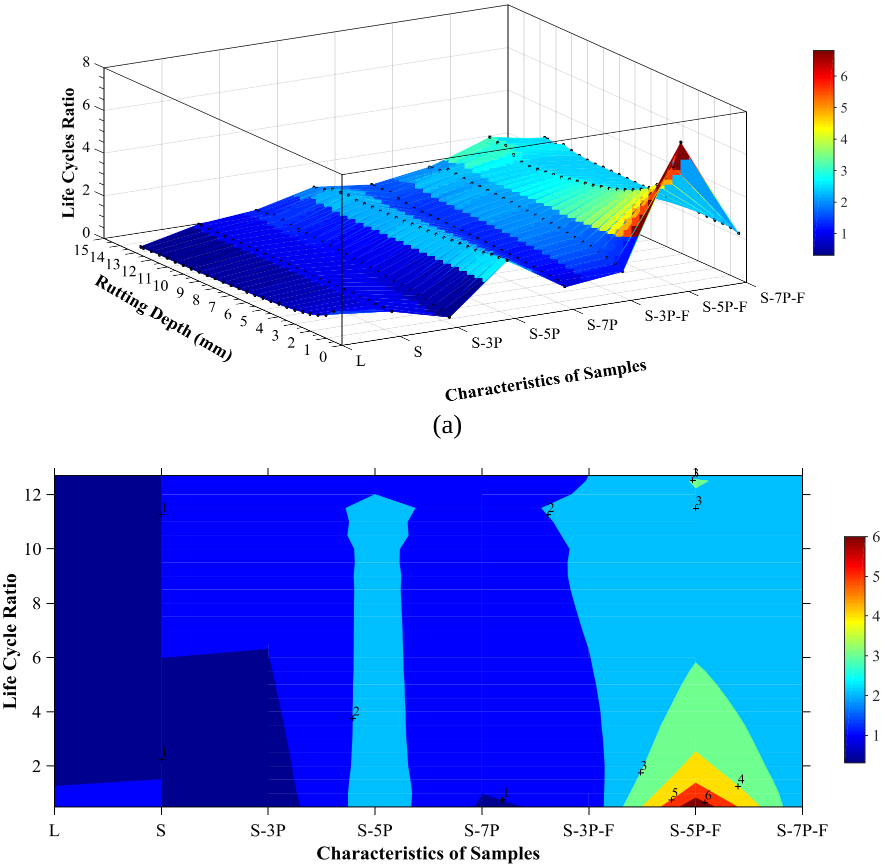
As it can be seen, in average S-5P-F can last 3.35 times more than the slag control sample. Furthermore, the operational life in lime samples is almost half compared to the samples produced with artificial slag aggregates. Therefore, assuming traffic loading, environmental conditions and other factors to be the same, highway facilities which are constructed with modified asphalt mixtures (S-5P-F) can last 3.35 times longer.

Table 9. Number of Load Cycles for various Rutting Depths

Rutting Depth (mm)	**L**	**S**	**S-3P**	**S-5P**	**S-7P**	**S-3P-F**	**S-5P-F**	**S-7P-F**
0.5	23	16	5	41	14	19	109	34
1.0	59	54	23	136	54	75	299	122
1.5	102	112	58	275	118	168	539	255
2.0	151	189	111	453	206	299	818	430
2.5	205	282	184	667	318	467	1130	646
3.0	263	391	278	916	453	673	1473	900
3.5	324	515	393	1197	612	915	1842	1192
4.0	389	655	531	1510	793	1195	2235	1520
4.5	457	810	693	1853	997	1513	2652	1884
5.0	528	978	879	2225	1224	1867	3090	2283
5.5	602	1161	1090	2625	1474	2259	3548	2716
6.0	677	1358	1326	3054	1745	2689	4025	3182
6.5	756	1568	1589	3509	2039	3155	4521	3681
7.0	836	1791	1878	3992	2356	3659	5034	4213
7.5	919	2027	2194	4500	2694	4200	5563	4777
8.0	1004	2276	2538	5034	3054	4779	6109	5373
8.5	1090	2538	2910	5593	3436	5395	6671	6000
9.0	1179	2813	3310	6176	3841	6048	7248	6659
9.5	1274	3100	3740	6767	4266	6660	7839	7348
10.0	1375	3381	4186	7369	4714	7187	8445	8067
10.5	1476	3651	4624	8208	5250	8009	9276	8894
11.0	1576	3922	5201	8671	5927	8775	10714	9737
11.5	1677	4047	5707	8992	6605	9256	12152	10579
12.0	1778	4615	5976	9238	7282	9607	13590	11421
12.5	1874	4913	6160	9437	7824	9883	15028	12495
12.7	1887	4987	6220	9508	7921	9979	14194	12671

Table 10. Life Cycle Ratios

Rutting Depth (mm)	L/S	S/S	S-3P/S	S-5P/S	S-7P/S	S-3P-F/S	S-5P-F/S	S-7P-F/S
0.5	1.44	1	0.31	2.56	0.88	1.19	6.81	2.13
1.0	1.09	1	0.43	2.52	1.00	1.39	5.54	2.26
1.5	0.91	1	0.52	2.46	1.05	1.50	4.81	2.28
2.0	0.80	1	0.59	2.40	1.09	1.58	4.33	2.28
2.5	0.73	1	0.65	2.37	1.13	1.66	4.01	2.29
3.0	0.67	1	0.71	2.34	1.16	1.72	3.77	2.30
3.5	0.63	1	0.76	2.32	1.19	1.78	3.58	2.31
4.0	0.59	1	0.81	2.31	1.21	1.82	3.41	2.32
4.5	0.56	1	0.86	2.29	1.23	1.87	3.27	2.33
5.0	0.54	1	0.90	2.28	1.25	1.91	3.16	2.33
5.5	0.52	1	0.94	2.26	1.27	1.95	3.06	2.34
6.0	0.50	1	0.98	2.25	1.29	1.98	2.96	2.34
6.5	0.48	1	1.01	2.24	1.30	2.01	2.88	2.35
7.0	0.47	1	1.05	2.23	1.32	2.04	2.81	2.35
7.5	0.45	1	1.08	2.22	1.33	2.07	2.74	2.36
8.0	0.44	1	1.12	2.21	1.34	2.10	2.68	2.36
8.5	0.43	1	1.15	2.20	1.35	2.13	2.63	2.36
9.0	0.42	1	1.18	2.20	1.37	2.15	2.58	2.37
9.5	0.41	1	1.21	2.18	1.38	2.15	2.53	2.37
10.0	0.41	1	1.24	2.18	1.39	2.13	2.50	2.39
10.5	0.40	1	1.27	2.25	1.44	2.19	2.54	2.44
11.0	0.40	1	1.33	2.21	1.51	2.24	2.73	2.48
11.5	0.41	1	1.41	2.22	1.63	2.29	3.00	2.61
12.0	0.39	1	1.29	2.00	1.58	2.08	2.94	2.47
12.5	0.38	1	1.25	1.92	1.59	2.01	3.06	2.54
12.7	0.38	1	1.25	1.91	1.59	2.00	2.85	2.54
Average	0.57	1	0.97	2.25	1.30	1.92	3.35	2.37



(a)

(b)

Fig. 6: Life Cycle Ratios for Modified and Unmodified Samples

8. Conclusion

Feasibility and the effect of two waste materials including steel slag and plastic containers were investigated.

Slab specimens with three percentages of PET including 3, 5, and 7 percent in two forms (PET particles and PET fibers) were prepared and wheel tracking test was performed.

In comparison with lime samples, replacing the coarse fraction with slag caused an increase in optimum binder content. Furthermore, utilizing PET additive in both particle and fiber shapes caused a reduction in optimum binder content.

In order to show the efficiency of modification, permanent deformation profiles were obtained until 12.7 mm rutting depth and the rut profiles were modeled by the Zhou model in the MATLAB environment. Generally rutting profiles of lime and slag control specimens developed faster than the modified specimens, which implied that modified samples had a better capability to resist permanent deformation. It was found that induced rutting depth was the lowest for specimens modified with 5 percent PET followed by 7 and 3 percent, respectively.

Based on the obtained results in damage analysis, natural lime sample was 2.6 times more damaging compared to the slag control sample. Furthermore, the operational life in lime samples is almost half of that for artificial slag samples. Moreover, adding PET in the form of fiber is more effective and exhibits the lowest damage ratio. Based on the obtained results, modified samples with 5 percent PET fiber caused 35 percent less rutting. According to life cycle ratio analysis, in average S-5P-F can last 3.35 times more than the slag control sample

The suggested modified asphalt samples were greatly cost effective and environment friendly. These samples caused significant reduction in the induced permanent deformation and considerably increased life span. Finally, implementation of the introduced long –lasting modified asphalt mixtures is highly recommended for highway and pavement agencies.

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