Investigating the Effect of Using Cross-Linked Polyethylene Waste as Fine Aggregate on Mechanical Properties of Hot Mix Asphalt

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Received: 08.04.2019 *Accepted: 03.09.2019*

Abstract

Cross-linked polyethylene (XLPE) is an appropriate insulating material for high-voltage cables which has been widely used as electrical cable coating. In this study, Crushed XLPE wastes with different volume percentages (25, 50, and 75%) were used in hot mix asphalt (HMA) as a substitute for fine aggregates remained on sieve no. 8 whose size varies from 1.18 to 2.36 mm. The dynamic stiffness (indirect tensile test) and fatigue test (indirect tensile fatigue test) were used to evaluate the dynamic behavior of the asphalt mixtures at temperatures of 5 and 25°C. The moisture susceptibility of the asphalt mixtures was also evaluated by Marshall stability ratio (MSR). The results showed that using crushed XLPE wastes as aggregates enhanced the fatigue life and resilient modulus of asphalt mixtures at 5°C. Also, increasing the XLPE content resulted in further enhancement in the resilient modulus and fatigue life at this temperature. However, as XLPE content increased at temperature of 25°C, the resilient modulus and fatigue life were reduced. Moreover, the MSR values showed that XLPE specimens exhibits an appropriate reaction against moisture resistance.

Keywords: Hot mix asphalt, cross-linked polyethylene, recycling, fine aggregates, mechanical properties

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1. Introduction

Hot Mix Asphalt (HMA) consists of binder and aggregates. Aggregate gradation is considered as an important parameter in asphalt mixtures affecting the properties such as stiffness, stability, durability, workability, permeability, fatigue resistance, and moisture resistance.

Recently, natural resources have been severely depleted due to a remarkable increase in construction activities. Moreover, the high amounts of the industrial wastes have inflicted negative impacts on the environment. Meanwhile, almost 350 million tons of polymer are produced annually [PlasticsEurope, 2018]. Plastic waste, rubber, and polyethylene products are produced by packaging industry, car industry, and electrical cables, respectively. These wastes are one of the main reasons of environmental pollutions. In addition, the isolation and reconstruction processes of them impose high costs. Hence, the recycling process of these materials is highly considered and encouraged [Struik and Schõen, 2000].

Increase in waste production has resulted in research interests about the recycling process. Polyethylene terephthalate (PET) -a thermoplastic polymer resin of the polyester family- has been widely used in producing beverage bottles. In a study, PET was used to replace fine aggregates with different percentages (5, 10, 15, 20, and 25%) by weight of asphalt mixture. The results obtained from the indirect tensile stiffness modulus test showed that at 25°C, the resilient modulus decreased as PET content increased. Moreover, the least permanent deformation was obtained by replacing 20% of aggregate with PET. Overall, PET enhanced the resistance of the asphalt against rutting [Rahman and Wahab, 2013].

The fatigue and stiffness properties of PET modified mixes were evaluated at 5 and 20°C. The results were also compared with a conventional polymer modifier (styrene butadiene styrene). According to the results, the resilient modulus decreased at both temperatures by using more than 2% PET. In addition, the fatigue behavior at both temperatures was improved in asphalt mixes containing PET. Overall, both additives enhanced the fatigue response of the mixes [Modarres and Hamedi, 2014a]. In another study, fatigue and resilient modulus models were also developed for asphalt mixes containing waste plastic bottles [Modarres and Hamedi 2014b].

The addition of PET waste to bitumen, increases ductility, penetration, softening point and viscosity values. It has also been indicated that addition of 12% PET waste conducts zero percent stripping even after 48 hours [Shoeb Ahmad and Mahdi, 2015].

Impact of high-density polyethylene (HDPE) -another member of the polymers category- on fatigue life and rutting of asphalt mixtures was investigated. The results showed that applying HDPE as a bitumen modifier in asphalt mixtures increased theirs fatigue life, the resistance against rutting, and the resilient modulus. Furthermore, increasing the HDPE content enhanced the fatigue life, resilient modulus, and the adhesion between bitumen and aggregates [Moghadas Nejad et al. 2014]. Impact of recycled plastic wastes (RPW) including polypropylene (PP), high- and low-density polyethylene (HDPE and LDPE) as bitumen modifier on the performance of asphalt mixtures were also evaluated. Results revealed that applying these materials enhanced rutting resistance and increased resilient modulus of asphalt mixtures [Dalhat and Al-Abdul Wahhab, 2017]. In addition, Use of waste plastic and waste tire ash led to the improvement in the temperature susceptibility resistant characteristics, elastic recovery properties, and viscous properties by satisfying the essential criterion of polymer modified bitumen [Karmakar and Kumar Roy, 2016].

Recently, several studies have been conducted on recycling and reusing wastes because of large volume of environmental pollutants. In addition, some studies have investigated the application of wastes (e.g., construction and demolition debris) that have less threat to the environment than industrial wastes in asphalt mixtures [Perez et al., 2012; Rafi et al., 2011]. The glass is a non-metallic inorganic material made by sintering selected raw materials including silicate and other minor oxide. Through dynamic indirect tensile testing on typical asphalt mixtures and those containing glass fragments, it was found that the dynamic behavior of asphalt mixtures was enhanced when glass fragments were added to the asphalt mixture. The larger angle of internal friction resulting from the sharper glass fragments had a significant role in improving the stiffness modulus of asphalt mixtures containing glass fragments. It should be mentioned that the glass fragments cannot absorb bitumen due to their smooth surface. In addition, the stiffness modulus decreased when the number of glass fragments in the mix increased above a certain level. Based on the Marshall test and indirect tensile test on specimens having aggregates graded for surface course and binder, the optimum glass content was assumed to be 15% [Arabani, 2011]. Other values were suggested by other researchers [Alhassan et al., 2018; Jony et al., 2011; Wu et al., 2004].

Cross-linked polyethylene (XLPE) which is an insulating material for high-voltage cables, due to its high electrical insulation and heat resistance has been extensively used in electrical cable coating for more than 50 years. A large amount of high-voltage electrical cables is annually produced across the world, all of which contains wastes. XLPE wastes are rarely recycled because of their non-biodegradable components, low fluidity and poor moldability. Then, most XLPE wastes are burned as a fuel or buried. Burning XLPE causes environmental pollution and requires huge initial investments. A large amount of unused land is also required for burying XLPE. These materials contaminate the natural environment because it takes a lot of time to return to nature cycle [Shamsaei et al., 2017]. Based on the research conducted in Japan, it was estimated that 10000 tons of XLPE wastes were buried in 2003 [Tokuda et al., 2003]. It was also estimated that 40000 tons of XLPE was buried in Sweden in 2007 [Christéen, 2007].

Application of recycled pyrolytic cross-linked polyethylene wax (RPPW) made from recycled XLPE as warm mix asphalt (WMA) additive in styrene-butadiene-styrene (SBS) modified asphalt was investigated. Also, the effects of RPPW on asphalt mixtures were studied. The results indicated that the use of RPPW increased softening point and reduced penetration of SBS modified asphalt. Overall, the addition of RPPW had remarkable construction performance at lower temperature for WMA [Shang et al., 2011].

In another research, a kind of XLPE waste was used simultaneously as aggregate and binder modifier. Fatigue, rutting, moisture susceptibility and stiffness modulus test results were compared between control specimens and those which 5% of their aggregates replaced by XLPE wastes. Used XLPE waste particles had a nominal diameter between 0.5 to 4 mm, melting point around 130°C and density equal to 0.9386 g/cm^3 at 25°C. It was observed that XLPE melting point below the asphalt mixture production temperature (180°C) caused bitumen to be modified. Moreover, the results showed that this kind of XLPE waste can reduce permanent deformation of asphalt mixtures, but may have adverse effects on fatigue life at 20°C and moisture susceptibility [Costa et al., 2017].

Although XLPE is rarely recycled, its recycling process is crucially important for researchers. Using these wastes as aggregate replacements can facilitate to alleviate the environmental problems and save the energy [Shamsaei et al., 2017]. Moreover, the construction costs are reduced because XLPE wastes are inexpensive or even free. So, in this study, it is attempted to investigate the feasibility of using XLPE waste in the asphalt mixture without side effect on its bitumen.

An overview of previous studies reveals that the mechanical behavior of HMA mixture containing XLPE waste as an aggregate (not as a bitumen modifier) has not been conducted yet. Thus, this study aims to investigate the effect of using XLPE waste on mechanical properties of the asphalt mixture. So, natural fine aggregate was replaced with XLPE waste in different volume percentages. Moreover, the behavior of asphalt mixture specimens containing XLPE was compared to control specimens. The tests conducted on the asphalt mixture include dynamic stiffness (indirect tensile test) and fatigue test (indirect tensile fatigue test). In addition, Marshall stability test was used to assess the moisture susceptibility of the asphalt mixtures.

2. Materials

2.1 Aggregate and Bitumen

The aggregates used for this study were a combination of dune sand and natural crushed limestone aggregate. Moreover, the limestone filler was determined to be 4% by aggregate weight. The limestone aggregates were extracted from the Sidoon mine, 20 Km far from Shahrood, Iran, while the dune sand was provided from Rahsazan Kavir Asphalt Co. in Miami, Semnan Province, Iran (Table 1). The physical properties of natural aggregates were reported by the factory. Pure binder with penetration grade 60/70 was used in the mix received from Pasargad Oil refinery, Tehran (Table 2). The gradation curve of the natural aggregates is shown in Figure 1 (ASTM-3515 [ASTM, 2001]).

2.2 Cross-linked Polyethylene (XLPE)

The XLPE wastes used in this study were provided from the Moghan Wire & Cable Co. in Iran, having a specific gravity of 0.8 g/cm3. After they were crushed by crushing machine (Figure 2), the XLPE particles were added to the asphalt mixture, as substitutes for the aggregates of the same size on the sieve no. 8 (1.18 to 2.36 mm).

Table 1. Physical properties of natural aggregates

Test	Standard	Unit	Result	Specification limit
L.A. Abrasion	ASTM-C 131	%	25	Max 25
Specific gravity (coarse agg.)	ASTM-C 127	g/cm^3	2.68	-
Absorption (coarse agg.)	ASTM-C 127	%	0.58	Max 2.5
Sodium sulfate soundness (coarse agg.)	ASTM-C 88	%	1.5	Max 8
Flat and elongated particles	ASTM-D 4791	%	6.5	Max 10
Aggregate angularity	ASTM-5821	%	61	Min 50
Sand equivalent	ASTM-D 2419	%	78	Min 50
Specific gravity (fine agg.)	ASTM-C 128	g/cm^3	2.71	-
Absorption (fine agg.)	ASTM-C 128	%	2.2	Max 2.5
Sodium sulfate soundness (fine agg.)	ASTM-C 88	%	1.8	Max 12

Table 2. Specification of binder

Test	Standard	Result
Penetration (0.1mm, 25 □C)	ASTM-D5	65
Softening point (□C)	ASTM-D36	55
Ductility (cm, 25 □C)	ASTM-D113	100
Flash point (□C)	ASTM-D92	288
Specific gravity (g/cm^3)	ASTM-D70	1.03

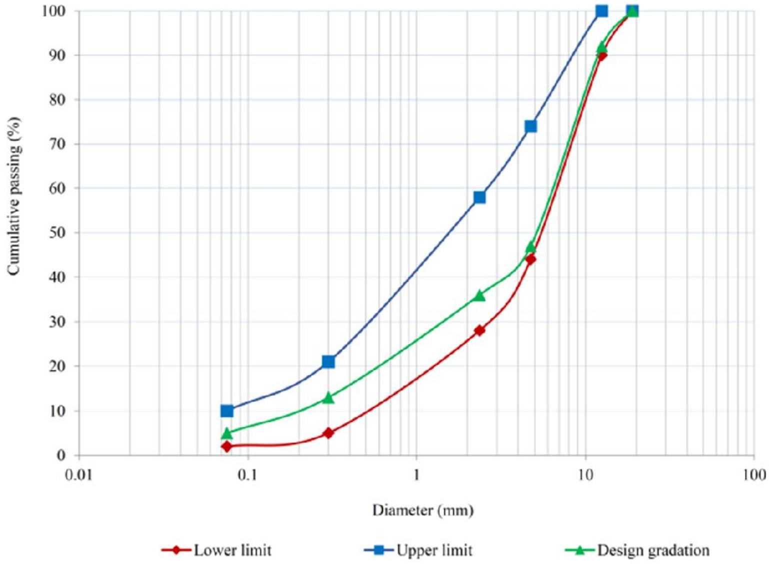

Figure 1. Recommended aggregate grading limits for mixture and gradation curve of used natural aggregates

Figure 2. Crushed XLPE wastes

3. Methodology

3.1 Specimen Preparation

The standard Marshall test method was used to prepare the specimens (ASTM D1559 [ASTM, 1992]). Standard diameter and height of the specimens are 101.6 mm and 63.5 mm, respectively. The specimens were compacted by 50 blows per side of each specimen. The XLPE was used as a substitute for fine aggregates in the asphalt mixture in different volume percentages of 0, 25, 50, and 75%. The specimens were prepared at binder contents ranging from 4.0% to 6.0% by weight in 0.5% increment. The optimum binder content (OBC) was determined for the control specimens and those containing 25, 50, and 75% XLPE based on achieving the appropriate values for Marshall stability, Marshall flow and air void content, simultaneously. The OBC values of XLPE mixtures were obtained close to the control mixture (Table 3). Then, Fatigue, resilient modulus, and Marshall stability tests were conducted on specimens prepared at OBC. Three specimens were evaluated for each test.

3.2 X-ray computed tomography (CT) scanning

The X-ray CT scanning was used to show the internal structure of the asphalt mixture, including the arrangement of the aggregates and the distribution of empty spaces [Zhang et al., 2015; Zhang et al., 2016]. In fact, the X-ray CT images are generated because of the different densities of the materials. Therefore, it is difficult to identify and differentiate between materials having similar densities through this method [Hassan et al., 2015]. The X-ray CT images of the control asphalt mixture and the mixture containing XLPE waste are shown in Figure 3. As it is shown in Figure 3(b), the aggregates of the XLPE specimen are darker due to their higher density, while the XLPE is lighter because of its lower density compared to the aggregates. Moreover, the empty spaces in the specimen are the darkest. Some of the empty spaces in specimen (blue areas) and some of XLPE particles used as aggregates (green areas) in the asphalt mixture are shown in Figure 4(a). Overall, the distribution of the air voids, XLPE particles, and aggregates are depicted in the asphalt specimen (Figure 4).

Table 3. Results obtained by the Marshall test

Mixtures	OBC (%)	Stability (kg)	Flow (mm)	Unit weight (kg/m^3)	Air void (%)	VMA (%)	MQ (kN/mm)
Mix 1 (Control)	4.25	1020	3.82	2.37	4.06	12.74	2.67
Mix 2 (25% XLPE)	4	990	3.5	2.34	4.5	13.48	2.83
Mix 3 (50% XLPE)	4	980	3.83	2.3	4.77	15.07	2.56
Mix 4 (75% XLPE)	4.25	875	5.77	2.25	5.84	17.01	1.52

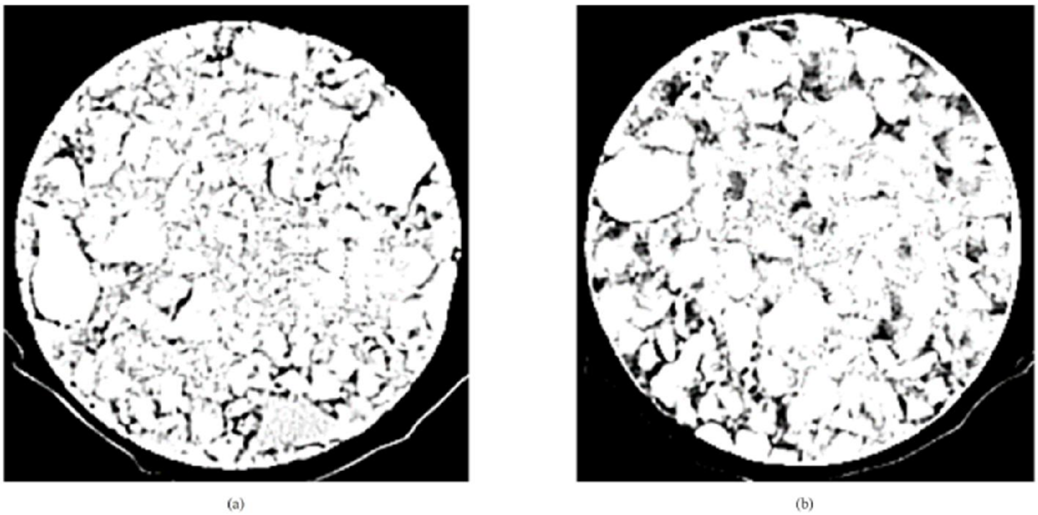

Figure 3. The CT scan images of (a) the cylindrical specimen containing natural aggregate specimen, (b) the cylindrical specimen containing XLPE

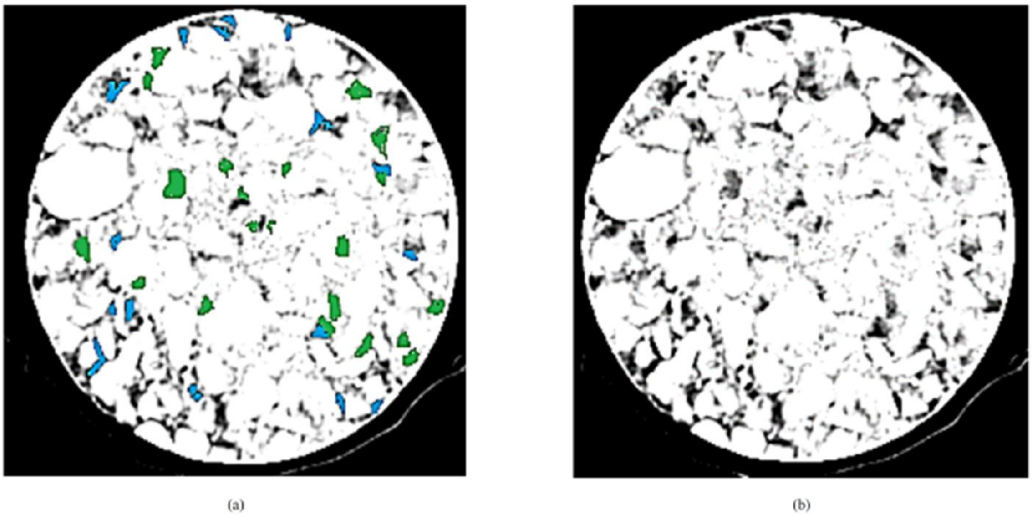

Figure 4. The cylindrical specimen containing XLPE, (a) distinction between some of XLPE particles and the empty spaces, (b) original image of cylindrical specimen containing XLPE

3.3 Mechanical Tests

Testing methods used in this study are indirect tension test for resilient modulus (ASTM D4123 [ASTM, 2000]) and indirect tensile fatigue (ITF) test. These tests were conducted on all specimens at 5 and 25°C by the Nottingham asphalt tester (NAT). The Marshall stability ratio (MSR) was also used to evaluate the moisture susceptibility of the asphalt mixtures.

3.3.1 Marshall Tests

The Marshall properties of mixtures were assessed based on ASTM D1559 [ASTM, 1992]. The Marshall quotient (MQ) is an indicator of the resistance against deformation of the bituminous mixture. MQ, which is the ratio of stability over flow value, was calculated for all the mixture designs given in Table 3. The MQ can used as a measure of the material's resistance to shear stresses, permanent deformation and hence rutting. High MQ values indicate a mixture with high stiffness and with a greater ability to spread the applied load.

3.3.2 Resilient Modulus Test

The resilient modulus of the specimens was determined by the indirect tension test, using the NAT machine. This test was designed in 1980 for determining the mechanical behavior of asphalt mixtures under dynamic loading (ASTM D4123 [ASTM, 2000]). The resilient modulus test is performed by applying linear force along the diametrical axis of the specimen. The loading conditions and the location of sensors in this test are shown in Figure 5.

Each loading cycle of the test takes 1 s. Total duration of loading and unloading take 0.1 s, and the rest time period of each cycle is 0.9 s (ASTM D4123 [ASTM, 2000]). All of the specimens were tested for their resilient modulus at 5 and 25°C with constant stress equal to 100 kPa. The resilient modulus is calculated by Eq. 1.

$$SM = \frac{P(\nu+0.27)}{t \times \Delta h} \tag{1}$$

where SM is the resilient modulus (MPa), P is the maximum dynamic load (N), ν is Poisson's ratio (which is assumed to be 0.35 for the specimens at 25°C and 0.2 for the specimens at 5°C [NCHRP 1-37, 2004]) , t is the thickness of the specimen (mm), and Δh is the recoverable horizontal deformation (mm).

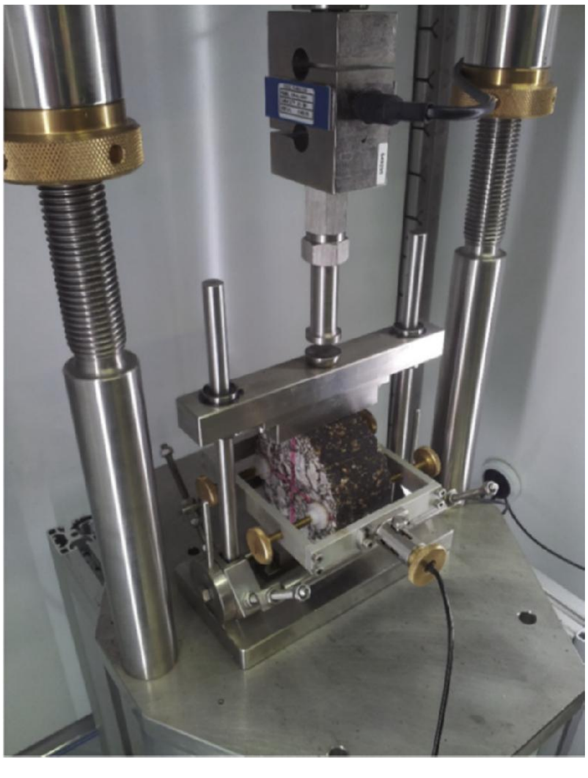

Figure 5. Loading and location of sensors in resilient modulus test

3.3.3 ITF Test

The ITF test was used to evaluate the fatigue behavior of the asphalt mixture. The test was conducted using NAT machine. The test can be either stress-controlled or strain-controlled. In this study, a stress-controlled fatigue test (the constant stress was considered equal to 100 kPa) with a load frequency of 1 Hz (0.1 s loading and 0.9 s unloading) was used. The strain increased with the number of loading pulses because the fixed cyclic stress was applied along the diametrical axis of the specimen. By considering the tensile strains associated with each stress, the relationship between tensile strains and the number of cycles before failure can be plotted.

3.3.4 Moisture Susceptibility Test

The Marshall test is used to determine the moisture susceptibility of asphalt mixtures. This method was applied by some other researchers [Aksoy et al., 2005; Kok and Yilmaz, 2009; Niazi and Jalili, 2009]. For this test, the specimens were divided into two groups. The first group consisted of conditioned specimens soaked in water bath at 60°C for 24 h, while the second group included unconditioned specimens kept in 60°C water bath for 40 min. Then, both groups were put under a Marshall jack immediately after passing the predetermined time period. The MSR is obtained by Eq. 2.

$$MSR = \frac{M_1}{M_2} \times 100 \qquad (2)$$

where M_1 and M_2 are the average Marshall stability for conditioned and unconditioned specimens, respectively.

4. Results and Discussion

4.1 Marshall Test Results

As can be seen in Table 3, the air void content and the voids in mineral aggregate (VMA) increased by increasing the XLPE content. The elastic deformation of XLPE particles under compaction effort may be considered as the reason for the increased air void content. Further, it can be seen that the stability decreased with an increase in XLPE waste content. For all percentages of XLPE waste, stability values were lower than the control mixture. The decrease in stability with increasing XLPE content may be attributed to low internal friction between the XLPE particles and aggregates. According to Table 3, Marshall flow was increased with increasing XLPE wastes. The lowest flow was obtained for a mixture with 25% XLPE content that it may be due to good adhesion between bitumen and XLPE in comparison with the aggregates in control mixture. On the other hand, with increasing XLPE wastes, the lower internal friction between XLPE particles and aggregates has more impact on the flow values than the adhesion between XLPE and bitumen.

Based on the obtained results, some Marshall parameters of XLPE mixtures have not followed criteria mentioned in Asphalt Institute Marshall mix design (e.g. air void content for Mix 4) [Asphalt Institute, (2014)]. This is due to changes in the aggregate skeleton for specimens containing XLPE (compared to control specimens). Failure to comply with the Asphalt Institute recommendations related to XLPE mixtures may be susceptible them to some kind of distresses. And, this should be considered for further researches.

The MQ values are given in Table 3. In mixes containing XLPE, small changes in the values were obtained in comparison to the control mix. Thus, mixture containing lower percentage of XLPE showed a great potential for resisting failure in rutting. In the same conclusion, Costa et al. [2017] represented that with 5% aggregate replacement by XLPE wastes in asphalt mixtures, less deformation occurred in the wheel tracking test compared to the control specimens at 50°C.

4.2 Determining the Resilient Modulus by Indirect Tension Test

The results of the resilient modulus test for different XLPE contents at 5 and 25°C were shown in Figure 6. As shown in Figure 6a, at 5°C, the resilient modulus increased with increasing XLPE content in the specimens. But it was shown in Figure 6b that at 25°C, the resilient modulus decreased as XLPE content increased in the specimens. The effects of asphalt binder on the changes of asphalt mixtures' stiffness values were not significant, because all specimens were fabricated at the almost same OBC. In addition, higher air void makes mixture less stiffer, so the decrease in stiffness values for asphalt mixtures containing XLPE waste cannot be attributed to the percentage of air voids, since the addition of XLPE content leading to increasing air voids had adverse effect on mixture stiffness at temperature 5°C. Thus, it can be concluded that the behavior of asphalt mixtures containing XLPE particle is sensitive to the temperature changes.

As the temperature increased, the resilient modulus of the asphalt mixture decreased due to the reduction in viscosity and the stiffness modulus of the bitumen. Given that, XLPE particles had a considerable impact on resilient modulus. At temperature of 25°C, the stiffness of the asphalt mixture decreased because of lower stiffness of XLPE compared to aggregates. Moreover, transition from 25°C to 5°C increased the stiffness of XLPE particles; thus, increasing XLPE particles had a noticeable effect on resilient modulus.

The variation rate of the resilient modulus (M_r) versus temperature is an indicator for temperature susceptibility of the asphalt mixture. The relation between Log (M_r) and temperature is used to evaluate the asphalt temperature susceptibility. The general equation between the resilient modulus and temperature (T) is shown in Eq. 3. A larger value of the slope (B) suggests higher temperature susceptibility.

$$Log(M_r) = A - BT \quad (3)$$

As can be seen in Figure 7, the relationship was obtained for specimens containing different XLPE contents. The slope increased as the XLPE content increased, indicating that the temperature susceptibility of the asphalt mixture enhanced with an increase in the XLPE content

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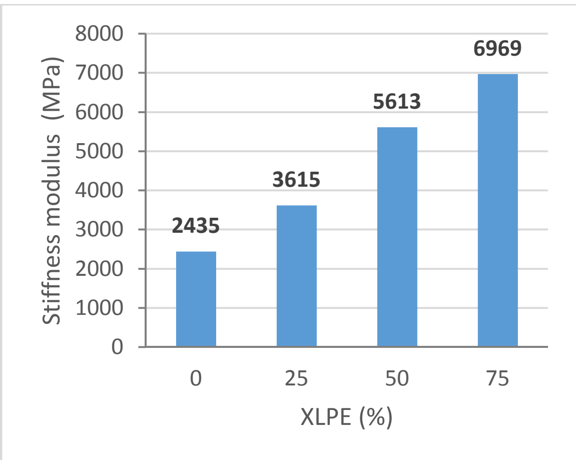
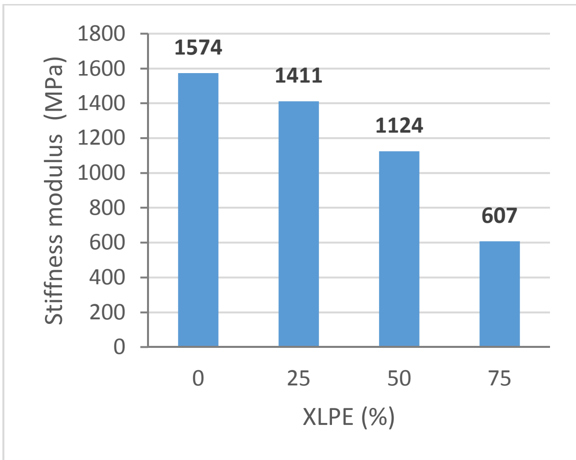


(a)



(b)

Figure 6. Resilient modulus of the specimens (a) at 5°C, (b) at 25°C

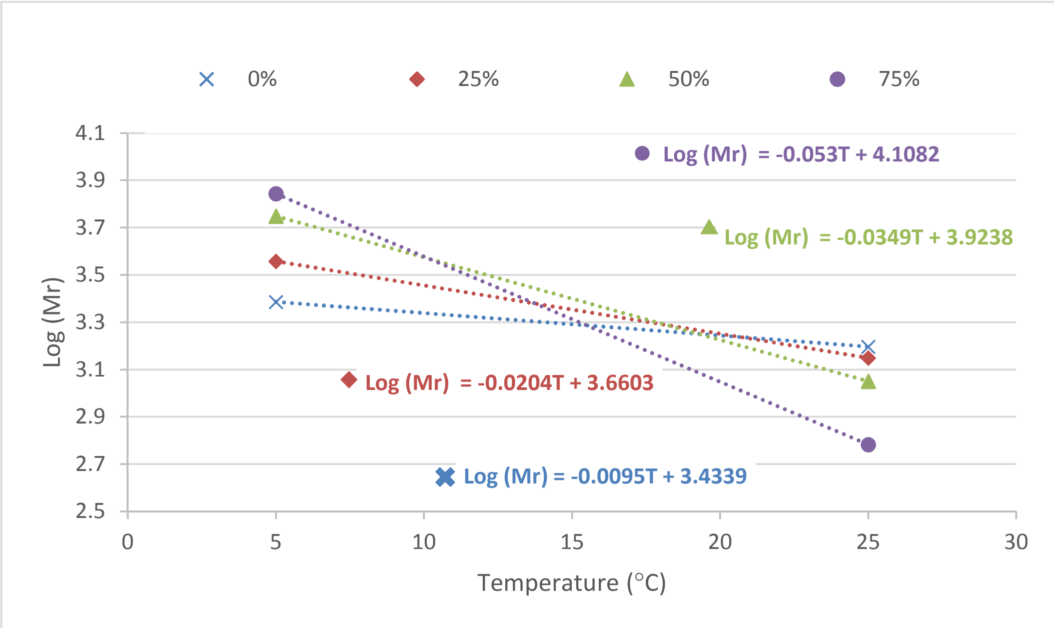
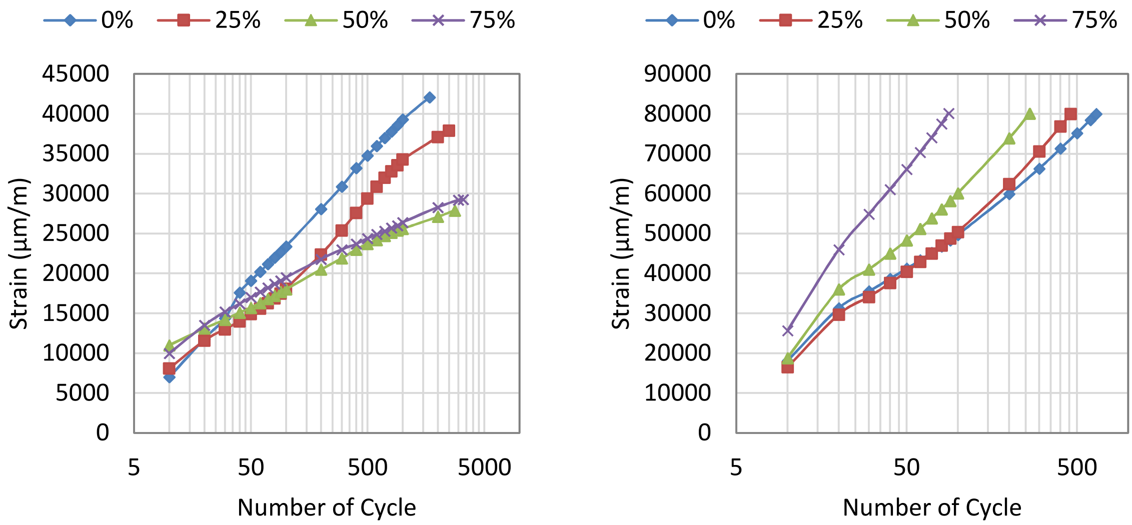


Figure 7. Temperature susceptibility of the asphalt mixtures in different specimens

4.3 ITF Test Results

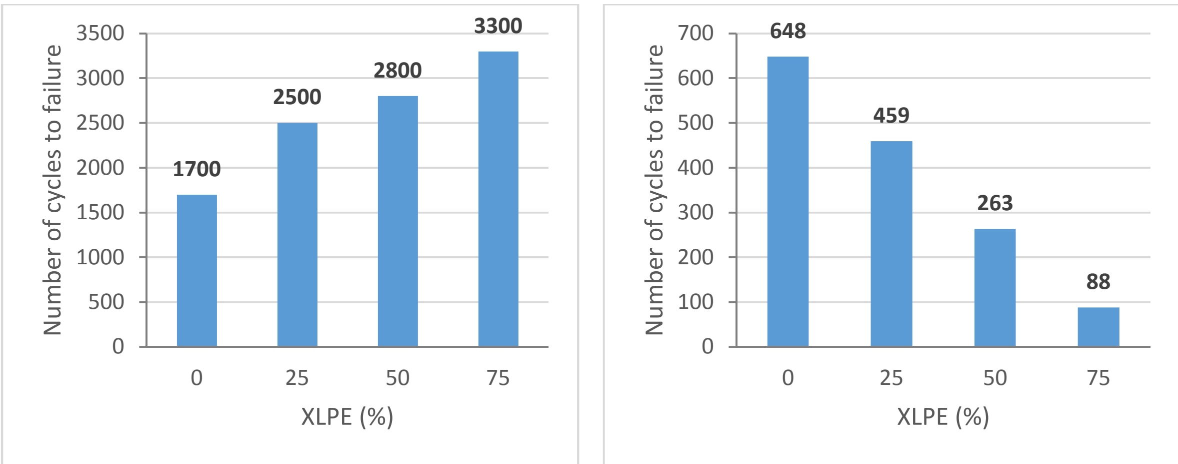
In order to compare the fatigue behavior of the asphalt mixture specimens, the strain was plotted versus the number of loading cycles for specimens having various XLPE contents at 5 and 25°C (Figure 8). As revealed in Figure 8a, at 5°C, strain in the specimens decreased as XLPE content increased. On the other hand, the number of cycles to failure increased. As can be seen, increasing XLPE content caused strain to be reduced. Overall, it can be concluded that the cracks induced by fatigue led to a shorter fatigue life in specimens with low XLPE content. While in specimens with higher XLPE content, crack propagation was hindered, resulting in a longer fatigue life. This can be attributed to the interaction between bitumen and XLPE particles. Since XLPE wastes have elastic deformation, crack initiation in the interface between XLPE particles and bitumen is less than the interface between aggregates and bitumen. So, mixtures which have more replacement ratio of aggregates by XLPE particles have less micro crack initiation leading to macro fatigue cracks.

As seen in Figure 8b, at 25°C, specimen failure occurred at almost the same strain level as XLPE content increased. However, by increasing XLPE content, the number of cycles to failure decreased. It happened due to decreasing mixture stability caused by replacing aggregates with low rigidity particles (XLPE wastes). This can be confirmed by the results of resilient modulus test conducted in this study and research findings of Costa et al. [2017]. They realized that fatigue life of asphalt mixtures was not improved by substituting 5% of their aggregates with XLPE wastes at 20°C. Figure 9 shows the number of loading cycles to failure at 5 and 25°C.



(a) **(b)**

Figure 8. Fatigue behavior of the specimens (a) at 5°C, (b) at 25°C



(a) **(b)**

Figure 9. The number of cycles to failure (a) at 5°C, (b) at 25°C

4.4. Results of Moisture Susceptibility Evaluation

MSR values are presented in Table 4 to evaluate the moisture susceptibility of the specimens. As can be seen in Table 4, the MSR values of XLPE mixtures were higher than the control mixture. Thus, the specimens containing XLPE performed well in terms of moisture susceptibility which can be due to low water absorption by XLPE and proper adhesion between bitumen and XLPE particles

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Table 4. MSR values for the specimens

Mixtures	M_1 (kN)	M_2 (kN)	MSR
Mix 1 (Control)	8950	9900	0.9
Mix 2 (25% XLPE)	9550	9650	0.99
Mix 3 (50% XLPE)	9750	9800	0.99
Mix 4 (75% XLPE)	7830	8100	0.97

5. Conclusions

This study aimed to investigate the effect of using XLPE wastes as fine aggregates on mechanical properties of HMA mixtures. To this end, the resilient modulus and fatigue tests were performed at 5 and 25°C, and the Marshall stability test was used for evaluating moisture susceptibility. The prominent results of this study are as follows:

1- Reducing the temperature increased the stiffness modulus of asphalt mixture. This trend can be because of increasing the stiffness of bitumen and XLPE particles.

2- Considering the variation rate of resilient modulus (M_r) versus the temperature, the temperature susceptibility of the asphalt mixtures increased as XLPE content increased. It means that adding higher amount of XLPE resulted in less stiffer mixture at 25°C. Therefore, increasing replacement ratio of aggregates by XLPE particles had a noticeable effect on resilient modulus.

3- At 5°C, the number of cycles leading to failure increased with increasing the XLPE content. Thus, it could hinder the fatigue crack propagation and extend the fatigue life of specimens, resulting in the favorable performance of the asphalt mixture. At 25°C, the number of cycles leading to failure decreased with an increase in the XLPE content. According to the stiffness modulus results, reducing the temperature increased the stiffness modulus of XLPE mixtures and subsequently their stability under repetitive loads; thus, it is reasonable that the fatigue life of XLPE mixture increased at 5°C.

4- According to the results of the Marshall stability test used for evaluating the moisture susceptibility of the HMA mixtures, the MSR values of specimens containing XLPE were higher than control mixture. So, the specimens containing XLPE showed an appropriate performance regarding moisture susceptibility.

5- Based on the MQ values, mixtures containing lower percentage of XLPE showed fine potential for resisting failure in rutting.

Overall, using recycled XLPE waste in HMA eliminates some of these wastes from nature. It is a suitable way to recycle them with low cost. In addition, it reduces the need for natural aggregates simultaneously. Finally, it is concluded that the use of XLPE wastes as aggregates can lead to the well dynamic behavior of the HMA mixture at 5°C; however, more research should be conducted to investigate the effect of XLPE on mixture resistance to other distresses.

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