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Eco-Friendly Asphalt Containing Recycled High-Density Polyethylene (HDPE): Performance Assessment and Cost Analysis

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Abstract: Utilization of the recycled waste materials for new products is considered as a viable solution for saving the environment. This study paper targets the performance evaluation of hot-mix asphalt made with the modified bitumen 60/70 containing 3 % and 5 % of recycled high-density polyethylene (HDPE) (by the weight of optimum bitumen). First, the properties of modified bitumen mixtures including specific density, penetration depth, ductility, and softening point were measured. Then, the properties of asphalt mixtures made with the modified bitumen including rutting depth and resilient modulus were measured. Findings indicated the suitability of recycled HDPE available in Iranian market in the development of eco-friendly asphalt mixtures. Results showed a 49 % decrease in penetration depth and a 15 % increase in softening point for the suggested modified bitumen mixture containing 3 % of recycled HDPE compared to those of control bitumen mixture, i.e. the bitumen mixture containing 0 % of recycled HDPE. Results also showed a 47 % decrease in rutting depth and a 113 % increase in resilient modulus of asphalt made with the bitumen mixture containing 3% of recycled HDPE compared to those of control asphalt mixture, i.e. the asphalt mixture containing 0 % of recycled HDPE. The results showed that the suggested asphalt mixture can be an appropriate option to be adopted not only in moderate climates but also in tropical climates as its characteristics become comparable to those of the bitumen 40/50 and the bitumen 30/40. Replacing a portion of bitumen by the recycled HDPE not only improves the characteristics of asphalt, but also has a positive impact on reducing the natural resource depletion and environmental pollution resulting from burning and/or the retention of plastic waste left in nature. The suggested eco-friendly asphalt is also cost effective.

Keywords: Eco-friendly asphalt, recycled polyethylene, rutting depth, resilient modulus

1. Introduction

In recent years, plastic waste has become a major worldwide concern due to the abundance of such non-biodegradable materials. Besides, the excessive use of natural resources has led to severe environmental issues. Utilizing the recycled plastic waste for new products is one of the approaches for reducing environmental pollution and saving natural resources [1].

In the past few years, taking advantage from plastic waste by adopting whether wet/dry or terminal blending methods has drawn specific attention to road construction industry; since on the one hand, it can bring quality

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enhancement for pavements along with reducing the immense cost of repair and maintenance, and on the other hand, results in reducing the bitumen's content and the reusing of recycled plastic waste [2].

By increasing the recycled plastic waste content, penetration resistance, softening point, viscosity, and resilience of bitumen increase [3]. Using recycled polymers can also decrease ductility and temperature sensitivity of modified bitumen. Adding a recycled polymer can also improve (decrease) the thermal sensitivity of bitumen [4]. In other words, the rheological properties of bitumen are less affected by the temperature variation.

A study shows that the incorporating of plastic waste would improve the rutting resistant of asphalt at high temperatures; further, it reduces the risk of thermal cracking of bitumen at low temperatures [5]. Rutting in asphalt pavement under heavy loads, particularly in tropical regions, can create numerous difficulties. Increasing the rutting depth can lead to a significant decline of serviceability [6]. Using recycled polyethylene terephthalate (PET) fibers by 0.4% causes a slight decrease in rutting depth and a slight increase in the number of loading cycles before failure at 50˚C [7]. By adding recycled polyethylene to bitumen mixtures, the penetration depth decreases while the ductility value and softening point increase [8]. Adding recycled polyethylene has also a positive effect on the compressive strength of asphalt mixtures [9].

Due to the limited studies carried out in Iran concerning the use of recycled polymers in the modification of bitumen and thus asphalt mixtures, conducting a comprehensive research is quite mandatory in such a context. This paper presents a study on the suitability of recycled high-density polyethylene (HDPE) in the development of eco-friendly asphalt mixtures.

The investigation method was experimental which performed in 2 phases. In phase 1, the tests were carried out on bitumen mixes containing 1 %, 3 % and 5 % of recycled HDPE to determine the relative density, penetration depth, ductility, and softening point. In phase 2, the tests were carried out on asphalt mixes made with the modified bitumen to determine the rutting depth and resilient modulus.

2. Materials

The materials used in this research include the bitumen 60/70, aggregates, and the recycled HDPE currently available in Iranian market. In this section, the specifications of the used materials are given.

2.1 Bitumen

The type of bitumen is selected noting some crucial factors such as climate conditions [10]. In this study, the bitumen 60/70, which is considered appropriate for regions with moderate climates like Tehran, was used. The characteristics of the bitumen used in this study are as given in Table 1.

2.2 Aggregates

Natural aggregates were used. The aggregate blend was composed of four separate fractions viz. 0–0.075, 0–6, 6–12 and 12–19 mm, having specific densities of 2.61, 2.43, 2.50 and 2.50, respectively, to conform to No.4 grading criteria as per reference [11] for a Topeka layer (see Fig. 1).

Table 1 - Characteristics of bitumen 60/70

Properties	Units	Tests	Requirements as per [10]	Results
Relative density	-	ASTM D70-03	-	1.01
Penetration depth at 25 °C	0.1 mm	ASTM D5-05	70- 60	61
Ductility at 25 °C	cm	ASTM D113-07	At least 100	More than 100
Softening point	C°	ASTM D36-09	56 – 49	49
Flash point	C°	ASTM D92-05	At least 232	299
Solubility in trichloroethylene	(m/m) %	ASTM D2042-01	At least 99	100

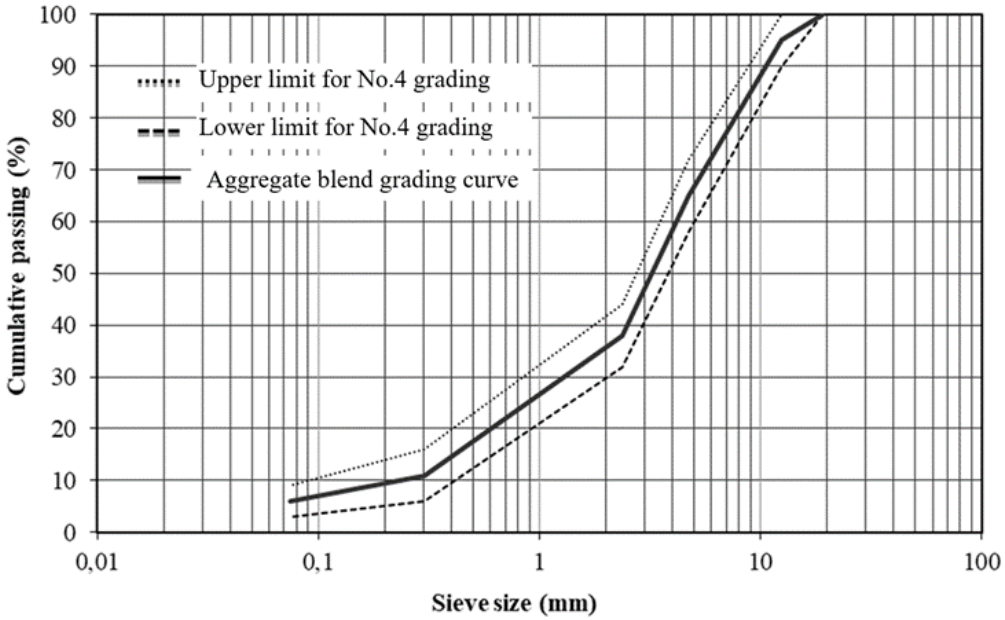


Fig. 1 - Gradation of aggregate blend

2.3 Recycled High-Density Polyethylene (HDPE)

Polyethylene is one of the most common polymers used in many industries as in the road construction due to its special characteristics such as proper chemical and mechanical resistance, processability, lightness, and low production cost [12]. Based on the specific density, polyethylene is classified into three main groups, i.e. low-density polyethylene (LDPE), medium-density polyethylene (MDPE), and high-density polyethylene (HDPE). HDPE has the highest chemical resistance, stiffness, and strength among the others [12]. In this study, a recycled HDPE in the form of granules, manufactured from plastic bottles, was used. The characteristics of the recycled HDPE are as given in Table 2.

Table 2 - Characteristics of recycled HDPE

Properties	Units	Tests	Results
Melting point	°C	Differential scanning calorimetry	Between 130-150
Mineral filler content	% (by weight)	Thermogravimetric Analysis	0
Density	g/cm^3	ASTM D1505-03	0.9377 ± 0.0087
Melt flow rate	g/10 min	ASTM D 1238-04	0.4 g/10

3. Mix Proportion and Preparation of Bitumen and Asphalt Mixtures

Four bitumen mixtures were prepared to study the effect of recycled HDPE on specific density, penetration depth, ductility, and softening point. In addition to the control mixture, three more mixtures respectively containing 1 %, 3 %, and 5 % of recycled HDPE were made. First, 900 g of bitumen was weighed and heated to 163 ˚C. Then, the mixing process was started. The recycled HDPE granules were gradually added to the bitumen while the temperature was kept around 163 ˚C. The mixing continued till obtaining a homogeneous mixture. Thereupon, the specimens were prepared and kept at room temperature for 24 hours.

Three asphalt mixtures were prepared to study the effect of recycled HDPE on rutting depth and resilient modulus. In addition to the control mixture, two more mixtures containing the modified bitumen with 3 %, and 5 % of recycled HDPE were made. First, 1200 g of aggregate blend with a grading curve, shown in Fig. 1, was prepared, and then placed in the oven at a temperature between 160 to 170 ˚C for 24 hours. Next, an optimum amount of bitumen was gradually added and mixed to the aggregates till obtaining a homogeneous mixture. It shall be noted that, following the ASTM D6927-05, the optimal bitumen content of asphalt mixtures containing 0 %, 3 %, and 5 % of recycled HDPE was determined equal to 5.5 %, 5.7 %, and 6 %, respectively [13]. Moreover, the absorption of bitumen by aggregates was obtained equal to 59 % [13]. Thereupon, the cylindrical test specimens were prepared in two sizes, viz. 100 × 60

mm for the resilient modulus test, and Marshal stability and flow test, and 150 × 60 mm for the rutting test. It shall be noted that in this paper, the focus will be on the rutting depth and resilient modulus of asphalt mixtures.

4. Tests On Bitumen and Asphalt Mixtures

4.1 Determination of Relative Density of Bitumen

The test was conducted following the ASTM D70-03 to determine the relative density of bitumen at 25 ˚C. The test results are as shown in Fig. 2.

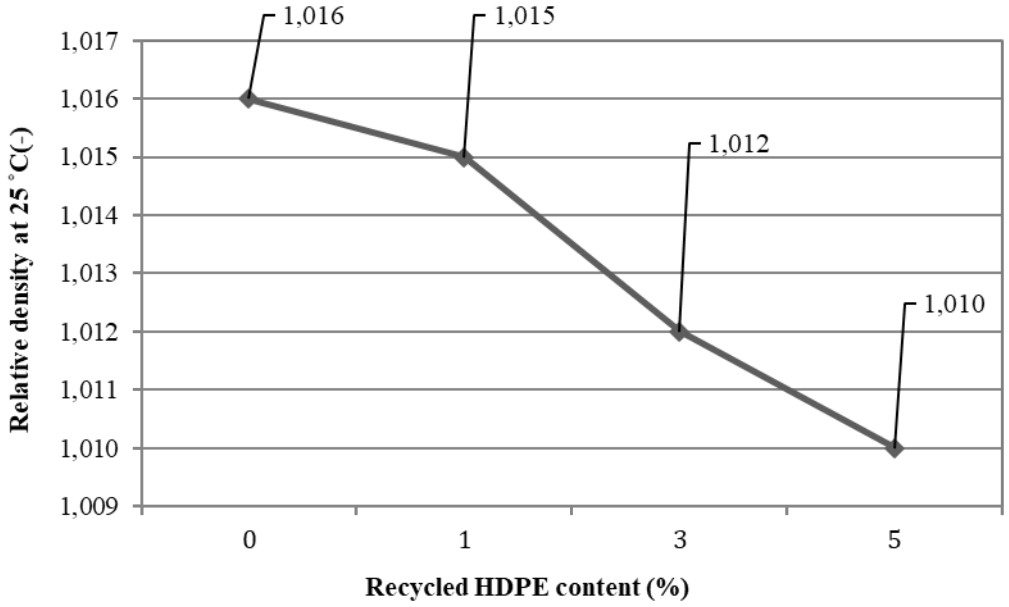


Fig. 2 - Relative densities of bitumen mixes containing different amounts of recycled HDPE

4.2 Determination of Penetration Depth of Bitumen

The test was conducted following the ASTM D5-05 to determine the penetration of bitumen at 25 ˚C as a measure of its consistency. Higher values of penetration indicate softer consistency. The test results are as shown in Fig. 3.

4.3 Determination of Ductility of Bitumen

The test was conducted following the ASTM D113-07 to determine the rupture length of bitumen at 25 ˚C as a measure of its tensile properties. The test results are as shown in Fig. 4.

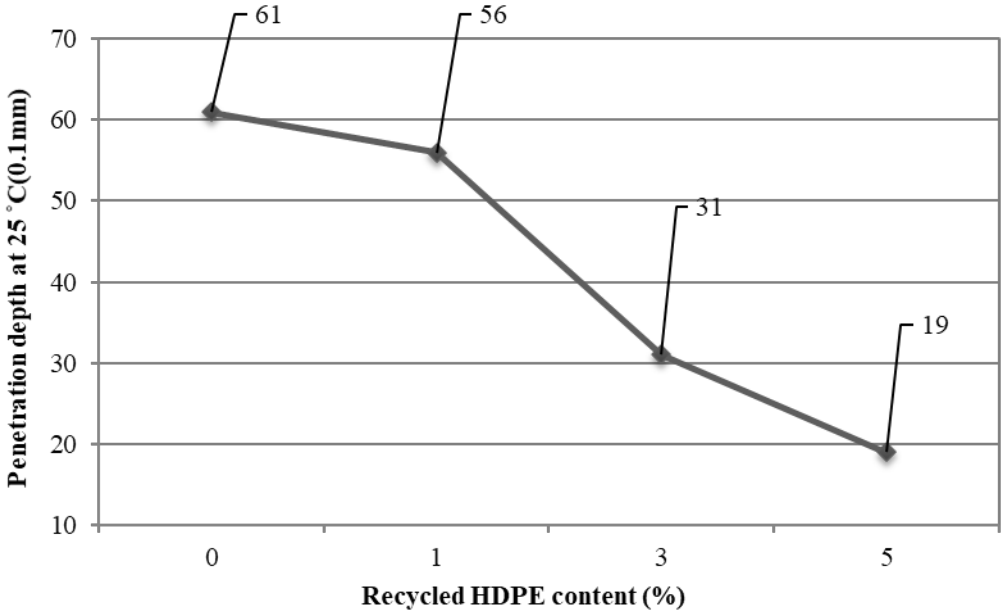


Fig. 3 - Penetration depths of bitumen mixes containing different amounts of recycled HDPE

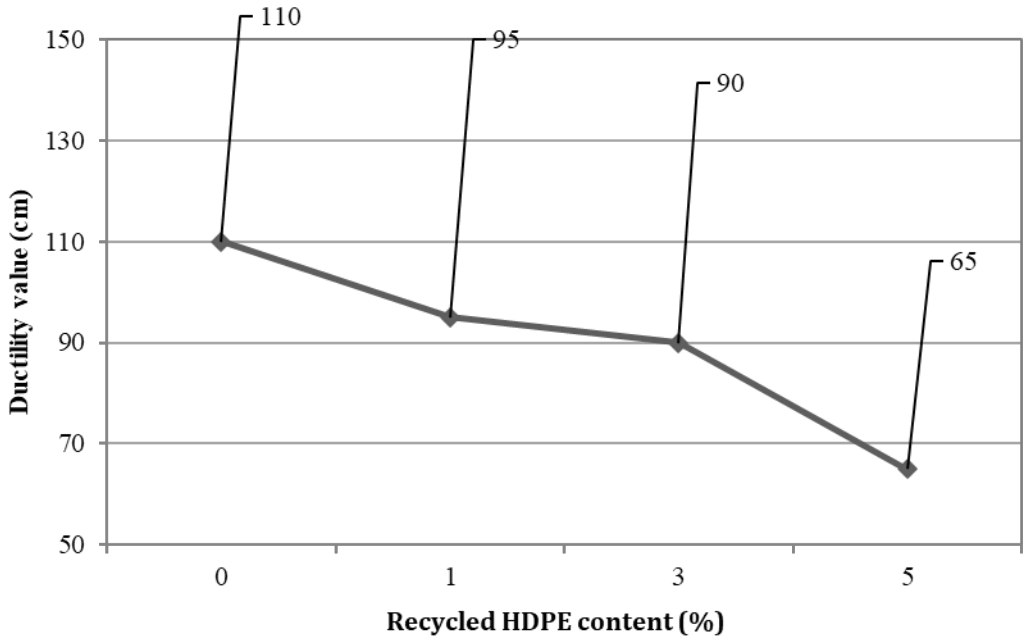


Fig. 4 - Ductility values of bitumen mixes containing different amounts of recycled HDPE

4.4 Determination of softening point of bitumen

The test was conducted following the ASTM D36-09 to determine the softening point of bitumen. The test results are as shown in Fig. 5.

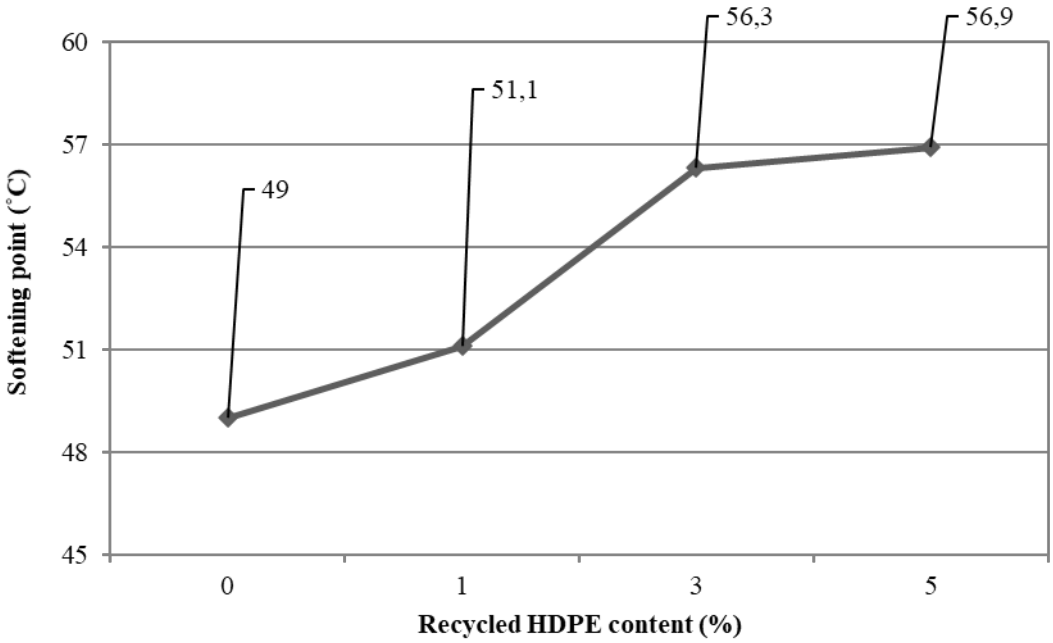


Fig. 5 - Softening points of bitumen mixes containing different amounts of recycled HDPE

4.5 Determination of rutting depth of asphalt

The test was conducted following AASHTO T324-04 to determine the rutting depth of asphalt after 10000 loading cycles at 55 ˚C. The test results are as shown in Fig. 6.

4.6 Determination of resilient modulus of asphalt

The test was conducted following the ASTM D4123-82(1995) to determine the resilient modulus of asphalt at 25 ˚C while the specimens were subjected to a half-sine loading cycle with the frequency of 1Hz.

The Poisson's ratio was considered equal to 0.35 for asphalt mixtures at 25 ˚C. The test results are as shown in Fig. 7.

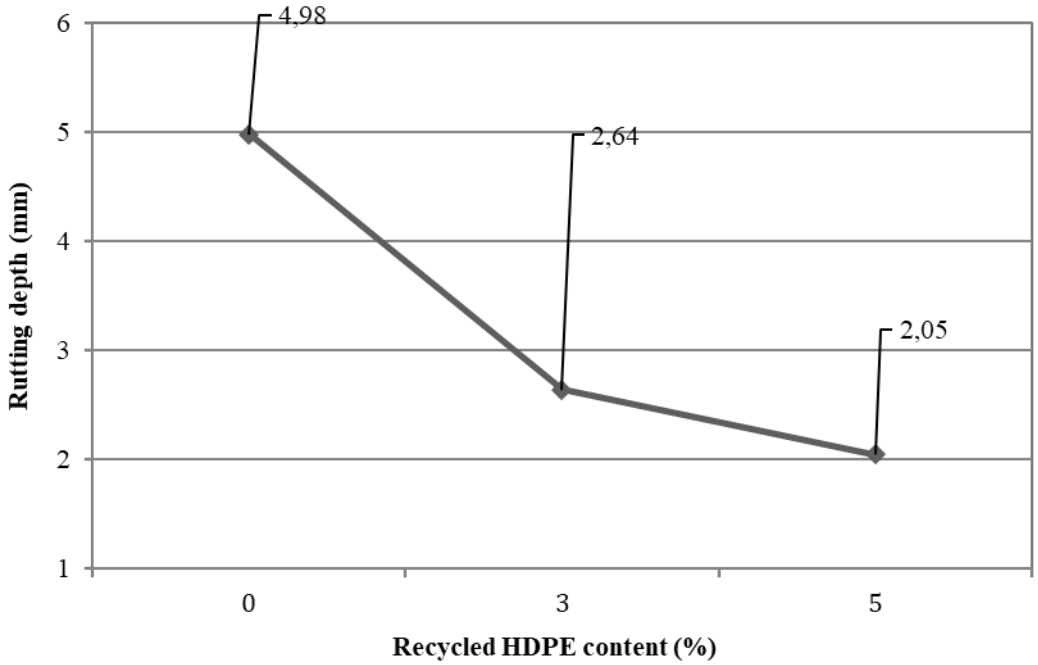


Fig. 6 - Rutting depths of asphalt mixes containing different amounts of recycled HDPE

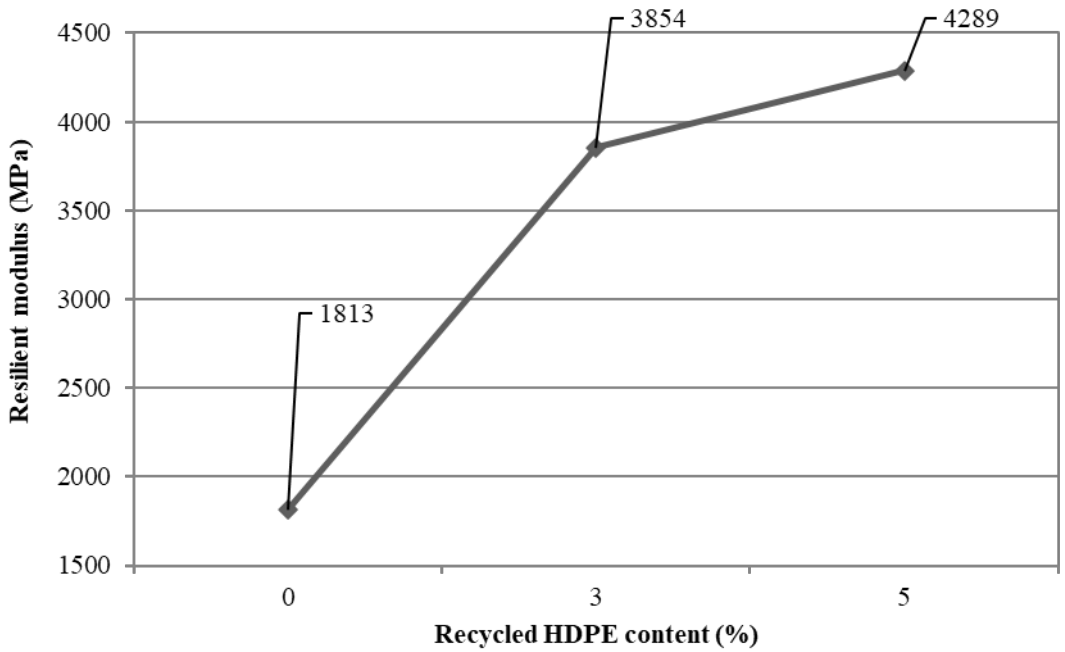
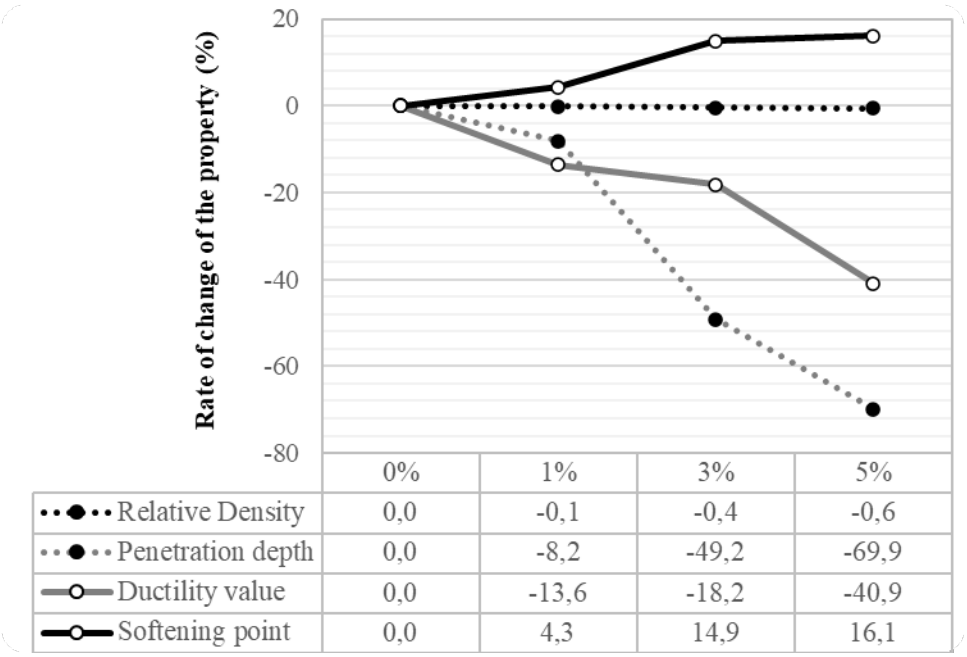


Fig. 7 - Resilient moduli of asphalt mixes containing different amounts of recycled HDPE

5. Discussion

The results of bitumen mixtures show that by adding recycled HDPE to bitumen, the density, penetration depth, and ductility (rupture length) decrease while the softening point increases. Moreover, by increasing the amount of recycled HDPE, the rate of change rises. Fig. 8 demonstrates that the rate of change of bitumen's properties with the recycled HDPE content is not constant. The least and the most changes are respectively observed in the density and penetration depth of bitumen mixtures. Adding 5 % of recycled HDPE leads to a fall in density, penetration depth, and ductility by about 0.6 %, 69 %, and 41 % respectively, and a rise in softening point by about 16 %. It shall be noted that

a fall in penetration depth and a rise in softening point for the mixtures containing recycled polymer were reported by Abdullah et al. [3].

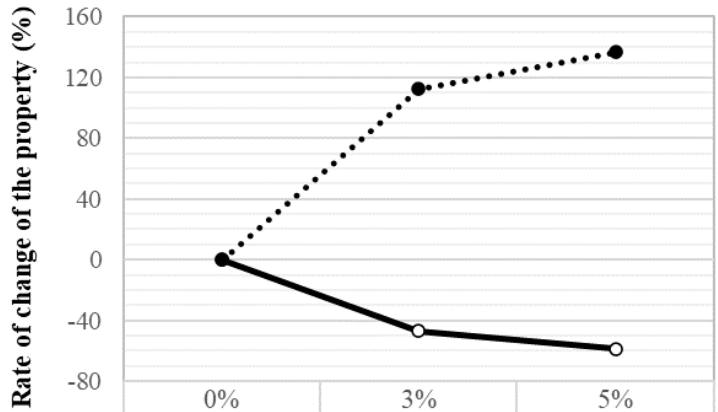


	0%	1%	3%	5%
Relative Density	0,0	-0,1	-0,4	-0,6
Penetration depth	0,0	-8,2	-49,2	-69,9
Ductility value	0,0	-13,6	-18,2	-40,9
Softening point	0,0	4,3	14,9	16,1

Fig. 8 - Effect of recycled HDPE content on the properties of bitumen mixtures

A decrease equivalent to 60.5 % in penetration depth and an increase equivalent to 8 % in softening point for the bitumen mixtures containing 6 % of recycled polymer were notified [3]. A decrease equivalent to 10 % in penetration depth and an increase equivalent to about 25 % in softening point for the bitumen mixtures containing 3 % of recycled polymer were also reported by Sarkar [14].

The results of asphalt mixtures show that by adding the recycled HDPE to asphalt mixtures, the rutting depth decreases while the resilient modulus increases. Moreover, by increasing the amount of recycled HDPE, the rate of change rises. Fig. 9 demonstrates that the rate of change of asphalt's properties with the recycled HDPE content is not constant. Adding 5 % of recycled HDPE leads to a fall in rutting depth and a rise in resilient modulus by about 59 % and 137 %, respectively. It shall be noted that a decrease equivalent to 68% in rutting depth for the asphalt mixtures containing 2 % of HDPE was reported by Ahmed and AL-Harbi [15]. An increase in resilient modulus equivalent to 89 % was notified for the asphalt mixtures containing 8 % of plastic waste [8].



	0%	3%	5%
Rutting depth	0,0	-47,0	-58,8
Resilient Modulus	0,0	112,6	136,6

Fig. 9 - Effect of recycled HDPE content on the properties of asphalt mixtures

Table 3 shows that by increasing the recycled HDPE content, the characteristics of modified bitumen mixtures have been improved in comparison with those of control mixture, except for the ductility. The ductility of modified bitumen mixtures containing 3 % and 5 % of recycled HDPE is 10 % and 35 % less than the minimum allowable value of 100 cm, indicated in ISIRI 12505, respectively. Because of a very low ductility of the bitumen mixture containing 5 % of recycled HDPE (65 cm), the optimum modified bitumen mixture is considered to be the one containing 3 % of recycled HDPE with a ductility equivalent to 90cm. Adding 3 % of recycled HDPE leads to a fall in penetration depth by about 49 %, and a rise in softening point by about 15 %.

Table 3 - Characteristics of the modified bitumen mixtures compared with bitumen 60/70, 40/50 and 30/40. Mix pricing was based on the US Doller (USD) to Iranian Rial (IRR) exchange rates on 25th June 2020; meanwhile, the price of the recycled HDPE was 500 US Doller per ton (USD/t)

Characteristics	Bitumen 60/70	Bitumen 40/50	Bitumen 30/40	Recycled HDPE content			
				0 %	1 %	3 %	5 %
Relative density (-)	1.01	1.01	1.01	1.016	1.015	1.012	1.01
Penetration depth (0.1mm)	60-70	40-50	30-40	61	56	31	19
Ductility value (cm)	At least 100	At least 100	At least 100	110	95	90	65
Softening point (°C)	49-56	52-60	55-63	49	51.1	56.3	56.9
Mix price* (USD/t)	175	225	225	175	178	185	191

The results also show that adding 3 % of recycled HDPE causes a significant reduction in rutting depth and an increase in the resilient modulus of asphalt mixtures by about 47 % and 113 %, respectively. Table 3 also presents the pricing of bitumen mixtures based on the cost of materials available in Iranian market. The cost of optimum mixture, i.e. the bitumen 60/70 containing 3 % of recycled HDPE, is merely about 6 % higher than that of the bitumen 60/70 and is approximately 18 % lower than that of either the bitumen 40/50 or the bitumen 30/40. The penetration depth of the suggested mixture is within the acceptable range for the bitumen 30/40 and its softening point is close to that of the bitumen 30/40 within the acceptable range for the bitumen 40/50. Therefore, the suggested mixture would also be an economic alternative for tropical climatic regions [16].

6. Conclusion

Results show that using recycled HDPE as a supplementary material in asphalt mixtures not only is a vital move towards directions dealing with the environmental aspects of sustainable development such as the environmental preservation and decreasing the natural resource consumption as well as the contamination risks out of leaving plastic waste in nature, but also towards directions dealing with the economic aspects of sustainable development such as the cost effectiveness of mix design and reducing the cost of maintenance and repair.

Tests on the modified bitumen 60/70 containing recycled HDPE show that by increasing the recycled HDPE content, the density, penetration depth, and ductility (rupture length) decrease while the softening point increases. Tests on asphalt mixtures made with the modified bitumen 60/70 show that by increasing the recycled HDPE content, the rutting depth decreases while the resilient modulus increases. The optimum modified bitumen mixture is identified the one containing 3 % of recycled HDPE having a relative density of 1.012, a penetration depth of 3.1 mm at 25 ˚C, a ductility of 90 cm, and a softening point of 56.3 ˚C while the asphalt mixture made with the optimum modified bitumen has a rutting depth of 2.64 mm, and a resilient modulus of 3854 MPa. In comparison with the bitumen 60/70, its penetration depth decreases by about 49 %, its ductility decreases by 18 %, and its softening point increases by about 15 %. The results also show that adding 3 % of recycled HDPE causes a significant reduction in rutting depth and an increase in the resilient modulus of asphalt mixtures by about 47 % and 113 %, respectively. The main concern with the suggested mixture was its ductility. It is observed that the ductility of modified bitumen mixtures containing 3 % of recycled HDPE is about 10 % less than the minimum allowable value of 100 cm [10]. Further research is currently ongoing toward this direction.

The modification of the bitumen 60/70 with recycled polyethylene (HDPE) at an optimal usage of 3 % leads to a mixture with characteristics close to those of the bitumen 40/50 or the bitumen 30/40; hence, there would be a possibility to use the suggested mix not only in regions with moderate climates but also in regions with tropical climates [16]. It is also cost effective. The cost of the suggested mixture, i.e. the bitumen 60/70 containing 3 % of recycled HDPE, is approximately 18 % lower than the cost of either the bitumen 40/50 or the bitumen 30/40 and is

merely about 6 % higher than that of the bitumen 60/70. Findings indicate the suitability of recycled HDPE available in Iranian market in the development of eco-friendly asphalt mixtures.

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