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Analysis and Comparison of Performance Characteristics of Asphalt Mixtures Containing Steel Slag and rPET

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ABSTRACT

Asphalt mixtures are composed of two components, namely aggregate and bitumen, so many structural weaknesses of an asphalt mixture can be resolved by modifying these components. In the past, various research works have been done to improve these weaknesses using a versatile spectrum of different materials. Among others, recycled materials have attracted more attention thanks to their further environmental benefits. On this basis, in the present work, steel slag and recycled polyethylene were used with different compositions at different percent dosages. In order to evaluate the effects of these two materials, we used the resilience modulus test, Marshall Resistance test, dry and wet indirect traction tests, and moisture sensitivity test. Results showed that the incorporation of both materials in a mixture provides for a better output than the use of either of them alone. Indeed, the blending of these two materials helps address the weaknesses of either of them.

Keywords: Steel slag, Recycled polyethylene, Asphalt mixture, Performance Characteristics

1. INTRODUCTION

The lifetime of road pavements is among the most important and effective parameters for the economy of a country. Hence, one of the initial objectives of the design and execution of asphalt pavements for the roads is to achieve the best performance in terms of durability and stability under optimum conditions. The pavement quality depends on various factors, including constituent materials like stone materials (aggregates) and bitumen [1]. Aggregates include the greatest percentage of the mixture, and any change in their type and structure could affect the characteristics of the ultimate mixture. On the one hand, while bitumen has a much lower weight than aggregates, but has a very important role in the performance of asphalt pavements [2]. Changes in the main structure of constituent materials of asphalt mixture are applied with the aim of modifying and improving the mixture properties and are more directed toward the use of additives with specific objectives [3]. Although researches on the applicable materials used for pavements are very extensive, in a general classification, one could state that such polymers as SBS, SBR, nanomaterials like nano clay, zycotherm, nano lime, recyclable materials like rubber powder, and recyclable polyethylene are among the most important materials that are used for bitumen modification [4,5]. On the other hand, recycled asphalt pavement (RAP) and artificial aggregates such as light polyethylene aggregates and slag are accounted as the main replacement materials for modifying the aggregates [6-9]. Among these materials, the recyclable materials, while improving some properties of the mixture, have many environmental advantages as they prevent the accumulation of waste materials and mitigate environmental damages [9]. Steel slag and Recycled Polyethylene Terephthalate (rPET), as two recyclable materials that could be used in asphalt, have been utilized in different ways in the research works. But in the mentioned research, the effect of simultaneous use of the two materials in combined form has not been investigated. Hence, in this research, the properties of asphalt mixtures containing different percentages of the materials are investigated. Steel slag is one of the by-products of the steel industry, which has many valuable materials and compounds like calcium oxide, magnesium oxide, iron, phosphorous, manganese, and silicon, among its components. Steel slag is not applicable directly and is accumulated as waste. Storage of these materials has many restrictions due to their huge volume, in addition to serious environmental hazards [10]. Steel slag is divided into two groups of Electric Arc Furnace (EAF) and Basic Oxygen Furnace (BOF) [11]. High specific weight, angularity, hard surface texture, high strength, and durability of steel slag are among the factors that improve the mechanical properties of asphalt mixtures [12].In contrast, an increase in optimal bitumen amount due to the high surface porosity of the slag and an increase of void space due to the use of coarse slag are among the disadvantages of the use of slag in asphalt mixtures [13]. Goli et al. have investigated the rutting and moisture susceptibility of asphalt mixtures containing slag. The results of this research showed that the use of slag as a replacement for aggregates improves rutting resistance, reduces moisture susceptibility, and improves the fatigue life of asphalt mixtures [14]. Ghazizafeh et al. also compared the BOS and EAF slags using the Marshall stability and Fatigue life tests. The results of these researchers' study showed that the use of EAF slag in asphalt mixtures is much better than BOS slag [15]. Zia et al. replaced limestone aggregates with steel slag at 25, 50, and 75% and performed the aggregate and mechanical performance tests on asphalt mixtures. The results of this research showed that the use of slag instead of limestone aggregates exhibits better results in terms of such parameters as breakage percentage, Los Angeles abrasion, total index, surface texture, and uncompacted void content (percentage). On the other hand, the results of performance tests like resilient modulus show the better performance of asphalt mixtures containing slag [16]. On the other hand, the rPET obtained from mineral water bottles with the Persian commercial name Polyethylene terephthalate is converted into granule in a recycling process and finally is used as powder. Polyethylene terephthalate, which is used for making plastic bottles and hard chambers and package of nutrients, are categorized in the group of highly recyclable plastics. But more than half of this plastic which is used for producing bottles is not collected for recycling purposes. Research is performed on the use of rPET in asphalt mixtures by a number of researchers, and there are reports of improvement in such properties as resilient modulus in these studies [17-19].In one of these research, Ameri et al. investigated the simultaneous use of rubber powder and rPET in asphalt mixtures. The results of this study showed that the use of both rubber powder and rPET could compensate for some other weaknesses but concerning moisture susceptibility, it is better to use another material as a replacement [20]. On this basis, in this research, the effect of adding rPET to bitumen and using slag as a partial replacement for aggregates on the performance characteristics of asphalt mixtures is investigated.

2. MATERIALS AND METHODS

2.1. MATERIALS

The aggregates used in this research were prepared from the Asbcheran mine located in Damavand township according to the characteristics given in Table 1. Also, use was made of the bitumen with 60/70 penetration grade produced by Pasargad Co. in Tehran. Isfahan Steel Company prepared the slag materials used in this research. Table 2 shows the results of the XRF test on these materials. Also, the rPET material used in powder form is a product of Malaysia with the commercial name BG1021.

Table 1. Aggregate properties

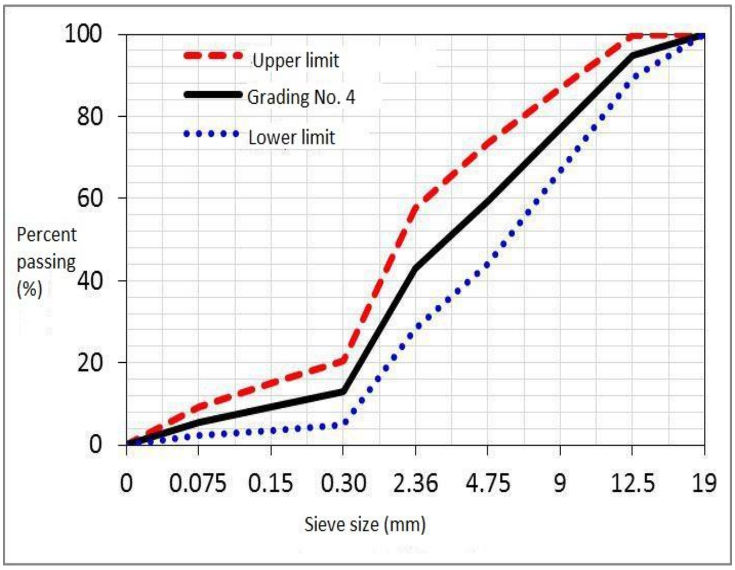
Aggregate Test	Aggregate	Test Method
Bulk specific gravity	2.484	ASTM C127
Absorption course aggregate (%)	2.1	ASTM 127
Absorption fine aggregate (%)	4.3	ASTM 128
Los Angeles abrasion Loss (%)	23	AASHTO T96
Tow Fracture faces (%)	93	ASTM D5821

Table 2. Results of XRF test on the used slag

Na_2O	CaO	MgO	Fe_2O_3	Al_2O_3	SiO_2
0.68	32.57	5.58	26.13	5.52	20.23

For mixing the rPET, use was made of High Shear equipment. The mixing is performed under 4200 cycles per minute for 30 minutes and at 160 °C temperature. Grading of the aggregates and the steel slag used in this research are all according to continuous grading No. 4 given in publication No. 234 of Iran. The boundary between fine grains and coarse grains is considered sieve No.4 with 4.75mm diameter. The range for continuous grading No.4 given in publication No. 234 is shown in Figure 1.

Figure 1. Grading of the used materials



Considering the difference between the specific weight of the slag and that of aggregates, weight replacement of aggregates causes a difference in the height of specimens. Thus the error of non-similarity (non-homogeneity) would appear between compared specimens. For this reason and to account for the similarity of specimens during the comparison process, in this research, the volumetric replacement method is adopted. Ultimately the final specimens studied in this research are investigated through 15 different schemes, as introduced in Table 3. Also, Figure 2 shows two images of the two recycled materials used in this research.

Table 3. Combination and naming of the mixtures

No	Sample name	Slag percentage	rPET percentage
1	AC	0	0
2	ST25	25	0
3	ST50	50	0
4	ST75	75	0
5	ST100	100	0
6	RPET 7.5	0	7.5
7	RPET 15	0	15
8	ST 25 RPET7.5	25	7.5
9	ST 25 RPET15	25	15

10	ST 50 RPET7.5	50	7.5
11	ST 50 RPET15	50	15
12	ST 75 RPET7.5	75	7.5
13	ST 75 RPET15	75	15
14	ST 100 RPET7.5	100	7.5
15	ST 100 RPET15	100	15

Figure 2. Used recycled materials A: steel slag, B: rPET

2.2. EXPERIMENTS

2.2.1. Preparation of Specimens

For preparing the specimens, first, the optimal bitumen for the control specimen using the Marshall Mix design method was obtained equal to 5.2. Then, all the specimens were compacted using the optimal bitumen of the control specimen and application of a gyratory compactor according to ASTM 3387 Standard [21].

2.2.2. Marshall Stability

Marshall Stability is significantly affected by the angle of internal friction of the materials and the bitumen viscosity at 60℃ temperature. The Marshall stability is obtained using the Marshall Stability test according to ASTM D1559. This test is generally used for investigating the strength of a mixture [22].

2.2.3. Resilient modulus

The resilient modulus test is an indirect test that is performed using the UTM5 apparatus according to ASTM D4123. The output of this test is used for determining the resilient modulus needed for the calculation of pavement thickness. The test is performed by applying a semi-sinusoidal load of 400N with 0.5 seconds of loading and 1.5 s of unloading [23].

2.2.4. Indirect tensile and moisture susceptibility tests

The most common test for determining the moisture susceptibility of asphalt mixtures is the use of the modified Lottman method based on AASHTO T283. In this method, first, the specimens with a void content of 6-8% (in this research is taken as equal to 7%) were prepared in two series using the gyratory compactor. Then, the indirect tensile strength of the specimens in the second series in wet conditions (the specimens after saturation by the vacuum pump, were kept at -16°C temperature for 16 hours, and then were kept at 60°C temperature for 24 hours and ultimately were tested at 25°C temperature) was measured. Finally, by dividing the wet indirect tensile strength by the dry indirect tensile strength, the parameter TSR is obtained, which demonstrates the moisture susceptibility of the asphalt mixture [24].

3. RESULTS AND DISCUSSIONS

3.1. INDIRECT TENSILE STRENGTH

As was stated in the section that introduced the test, it is done in two states, wet and dry conditions. The results of this test in the two abovementioned states are presented in Figure 3. As is seen from the results, an increase in the steel slag percentage causes an increase in the indirect tensile strength value in wet and dry conditions. Also, the addition of rPET increases the dry indirect tensile strength, but an increase in the wet indirect tensile strength is very small. But the results of the combined use of steel slag and rPET with different percentages are different. In the dry state, first, an increase in strength has occurred, but with increasing the amount of slag, changes are non-significant with respect to the case that only slag is used; also, by increasing the amount of rPET, a small reduction is observed. In the wet state, the trend is similar, but a considerable reduction is not seen by increasing the amount of rPET.

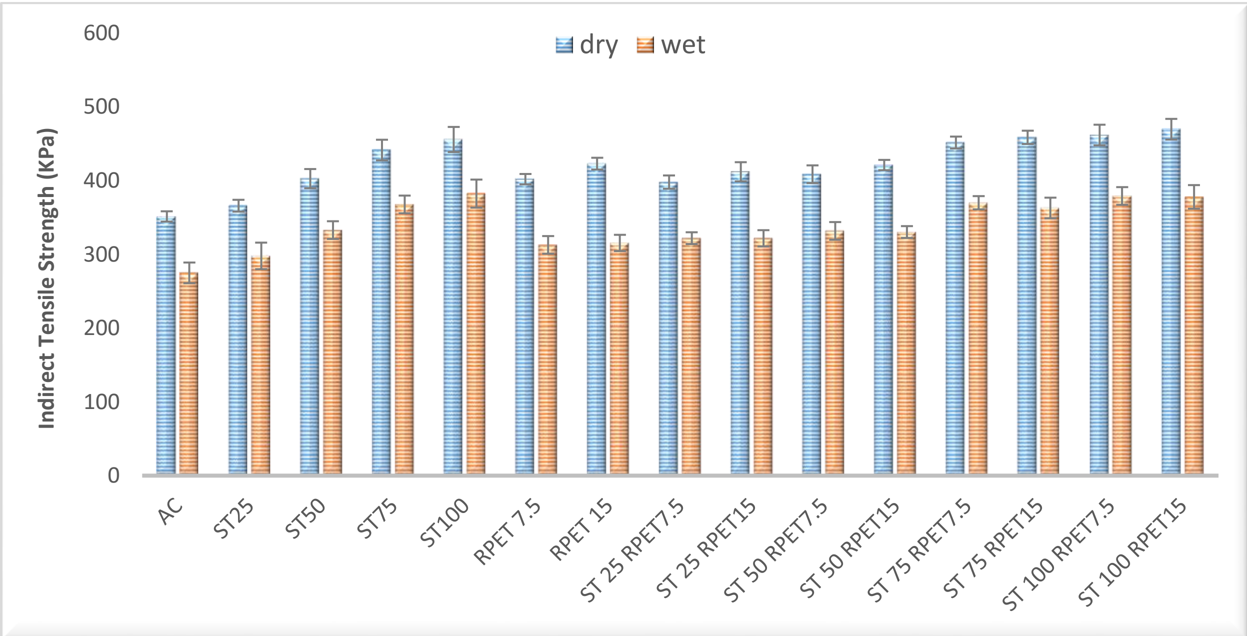


Figure 3. Indirect tensile strength for the two wet and dry conditions.

3.2. MOISTURE SUSCEPTIBILITY

The TSR parameter is among the secondary results of the indirect tensile test. This coefficient is a very important parameter in determining the moisture susceptibility of asphalt mixtures. The TSR parameter is calculated by dividing the wet indirect tensile strength by dry indirect tensile strength (in percentage), and the minimum acceptable value for it is determined based on different available standards. The results obtained from investigating this parameter for the research specimens are given in Figure 4. As is seen from the results, the steel slag has a major role in improving moisture susceptibility, but adding rPET causes a reduction in the TSR parameter, and by a further increase of rPET the reduction is intensified.In the combined state, improvement of the moisture susceptibility due to the addition of steel slag slightly overcomes the reduction of moisture susceptibility due to the addition of rPET and has limited the changes. The maximum improvement in terms of the TSR parameter belongs to 100% steel slag, and in the combined state belongs to 100% steel slag and 7.5% rPET. Improvement in the moisture susceptibility due to the use of steel slag in the previous studies had been attributed to the surface characteristics of this material which causes improvement in moisture susceptibility. On the other hand, the addition of rPET, according to the previous research, causes the hardening of the mixture, which leads to the setting of the mixture under the effects of thaw-freeze cycles.

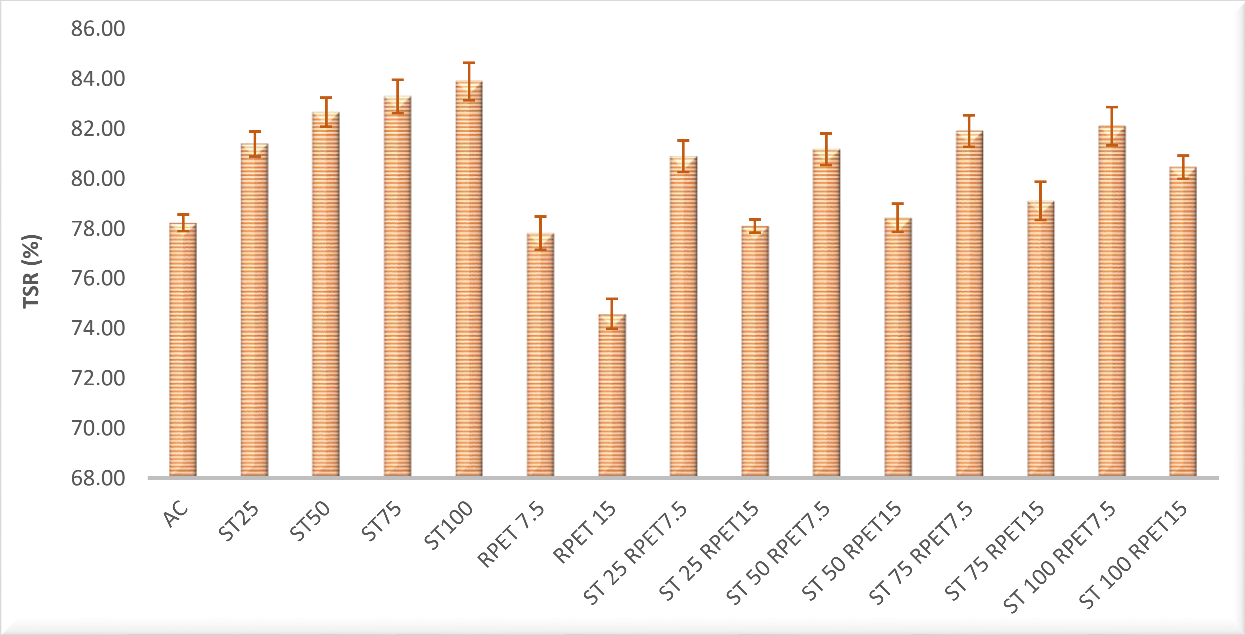


Figure 4. TSR results of the specimens

3.3. MARSHALL STABILITY TEST

The Marshall stability is significantly affected by the angle of internal friction of the materials and bitumen viscosity at 60°C temperature. Generally, it could be stated that the Marshall stability value exhibits the capability of asphalt mixture in resisting rutting failure and bumping under heavy loads. The results of the Marshall stability test are given in Figure 5. As is seen from the results, the addition of slag increases the Marshall stability with a steeper slope. Also, the addition of rPET has caused a small increase in the Marshall stability value. But increasing the amount of rPET from 7.5% to 15% causes a slight reduction in the Marshall stability value. In the combined state also, this trend is somehow observed so that the maximum value of Marshall stability corresponds to the specimen that contained 100% steel slag and 7.5% rPET. The reason for these changes due to the increased amount of steel slag is attributed to the higher density and greater strength of steel slag against compression. Considering the rPET, using this material increases the hardness of the mixture, and by increasing the percentage, the bitumen becomes so hard that it negatively affects the overall compressive strength of the mixture.

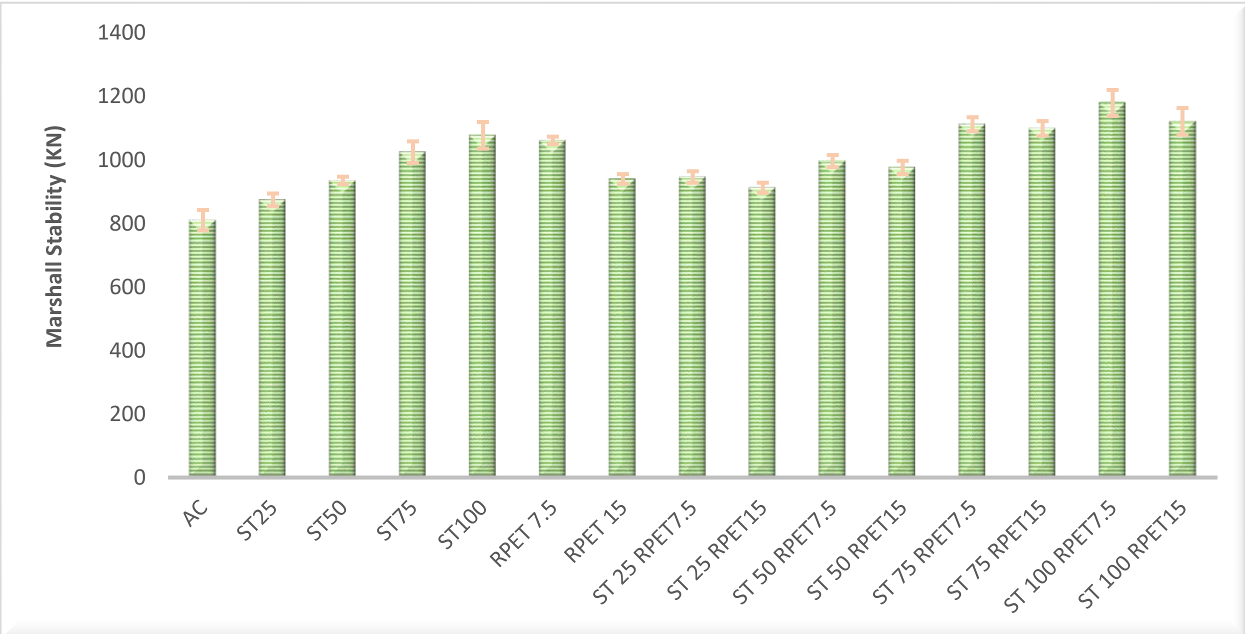


Figure 5. Results of the Marshall stability test of the modified and non-modified specimens

3.4. RESILIENT MODULUS

The resilient modulus test is a non-destructive test and is performed by applying a load with low intensity. This test yields the main parameter needed for pavement calculations. The resilient modulus value, which is the output of this test, is denoted by Mr and represents the maximum energy that the volume unit of an asphalt mixture could sustain without permanent deformation. The results of the residual modulus test for the studied specimens are given in Figure 6. As is seen, both materials have caused an increase in the resilient modulus of asphalt mixtures. The increase has been continued by the gradual addition of steel slag with a mild slope. On the other hand, the addition of rPET causes an increase in resilient modulus similar to when 100% steel slag is added. In the state of combined use of materials, the impact of the steel slag (due to the higher volume of this material and as the result of further distribution of it in the volume unit of the specimen) is higher than that of the rPET and has affected the resilient modulus value in the combined state.

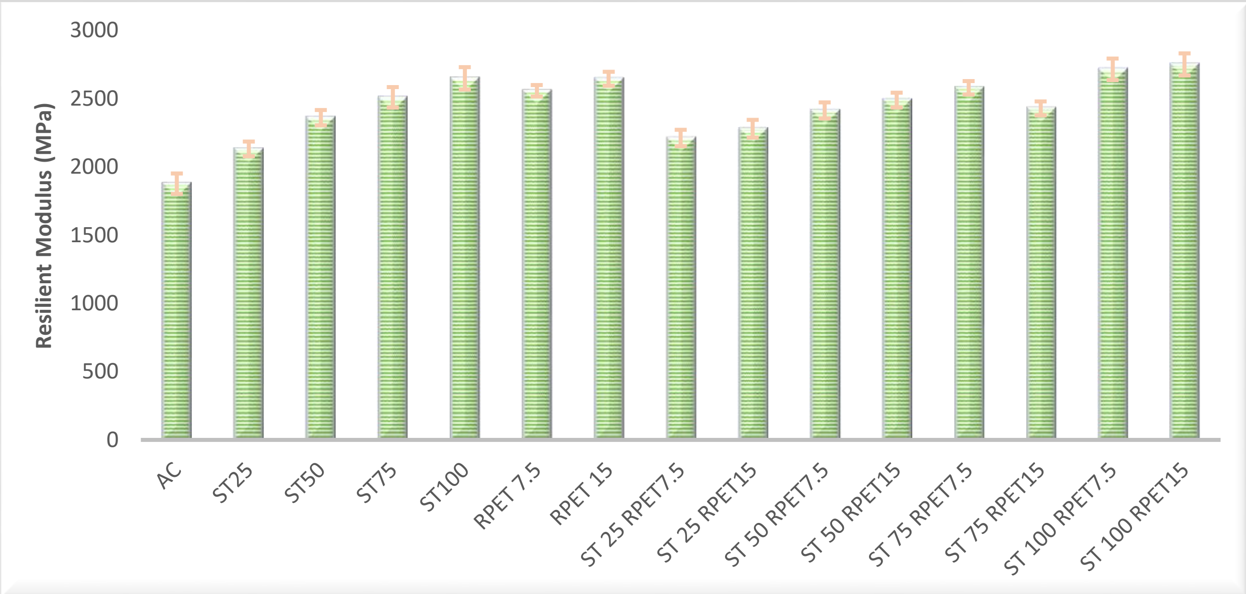


Figure 6. Results of the resilient modulus test

4. CONCLUSION

In this research, the characteristics of asphalt mixtures containing rPET and steel slag are compared and investigated. The main results of this research are as follows:

1- The indirect tensile test in both the wet and dry states showed that adding slag increases the strength in both states. But, adding rPET has maximum impact on the dry tensile strength and negligible impact on the wet indirect tensile strength.

2- The moisture susceptibility of the asphalt mixture is improved as a result of adding the slag. But considering the increase of mixture hardness due to the addition of rPET, the moisture susceptibility is reduced. In the specimens that contained both additives, the increasing effect of steel slag is greater than the decreasing effect of rPET.

3- The Marshall stability of the mixture has increased due to the addition of both materials. Also, by e combined addition of the two mentioned materials, we observe an increase in the Marshall stability value with a milder slope.

4- Considering the increase in hardness due to addition of both materials, the resilient modulus value also increases with an increase in the amount of both materials.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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