Laboratory studies to investigate the properties of CIR mixes containing steel slag as a substitute for virgin aggregates

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A B S T R A C T
This paper aims to evaluate the effectiveness of steel slag as a substitute for virgin aggregates on mechanical properties of cold mix recycling asphalt pavement. For this purpose, gradation requirements of two types of Reclaimed Asphalt Pavement (RAP) materials in Cold In Place Recycling (CIR) mixes were modified. Mixtures’ gradation requirements were satisfied by adding 20% and 10% of two types of new aggregates in accordance with Asphalt Institute CIR grading requirements. The results showed that the use of steel slag can enhance Marshall stability, resilient modulus, tensile strength, resistance to moisture damage and resistance to permanent deformation of CIR mixes. Use of anionic bitumen emulsion is recommended in preparing mixtures, because of its compatibility with them.

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1. Introduction

Reprocessed pavement materials consist of a reusable mixture of aggregate and asphalt binder known as Reclaimed Asphalt Pavement (RAP). Recycling of asphalt pavements is a valuable approach due to technical, economical, and environmental reasons [1–3]. So, use of RAP materials in asphalt mixtures has been favored over virgin materials in many countries.

Gradation of RAP materials, used in CIR mix design should be between blending chart limits [3,4]. Otherwise, they should be blended with virgin aggregates to satisfy the requirements.

Generally, there are two main sources of aggregates utilized in road construction, natural and artificial. To conserve natural resources and to reduce the potential environmental problems, material scientists and civil engineers try to open new avenues for replacing artificial aggregates with natural aggregates.

Steel slag is a by-product from steel making industry. The global amount of steel slag has been increasing continuously. It should be noted that in 2002, about 50 million tons of steel slag was produced worldwide, but in 2010 nearly 80 million tons of steel slag is discharged in China alone [5]. By the rapid expansion of the steelmaking industry in Iran, the amount of the steel slag in this region sharply increases like in other parts of the world. In Iran, most of the steel slag produced in Esfahan and Ahwaz Steel Manufacturing Facilities is usually sent to landfills for disposal. The disposal of steel slag occupies a significant portion of landfills and causes many serious environmental problems. This study aims to recognize the influences of steel slag on mechanical properties of CIR mixes as a substitute for virgin aggregate, which are used to satisfy the gradation requirements of the mixes. For this purpose, Marshall stability (ASTM D1559), resilient modulus (ASTM D4123), moisture sensitivity (ASTM D1075, AASHTO T283), and dynamic creep test (BSDD226) were conducted on eight different asphalt mixtures containing two types of RAP materials, two types of aggregate (steel slag and limestone), and two types of asphalt emulsions (anionic and cationic).

2. Background

Extensive researches have been conducted for the application of steel slag in broad areas of road construction [6]. Steel slag contains significant amounts of free iron, which gives the material high density and hardness and makes it a suitable artificial source of aggregates for road construction [7]. It can be used as an aggregate in surface layers and in unbound bases or sub-bases, due to its high strength and durability. Furthermore, it has high frictional and abrasion resistance, so it can be utilized on bridges,
intersections, bus lanes and parking areas, where high resistance is required [8]. Asi evaluated the skid resistance of asphalt concrete mixtures containing steel slag. The results indicated that asphalt concrete mixtures containing 30% steel slag have the highest skid number followed by Superpave, SMA, and Marshall mixtures, respectively. Feasibility of utilization of steel slag in asphalt concrete mixtures was investigated by Norman et al. [9]. They performed Marshall and stability tests on asphalt concrete mixtures containing steel slag. The results showed that the use of steel slag in asphaltic mixtures improved the mechanical properties of the mixes. Bagampadde and Al-Abdul Wahhab evaluated the effectiveness of steel slag aggregate by resilient modulus, split tensile strength, stability, fatigue, and permanent deformation tests [10]. In their study, it was concluded that mixes with steel slag in the coarse portion and limestone in the sand and filler portions prepared using polymer modified asphalt show high fatigue life and high resistance to permanent deformation. Kara et al. conducted a research to investigate the feasibility of utilization of steel slag in three levels of asphalt pavement as a bitumen base, binder and wearing course [11]. Their studies demonstrated that physical properties of steel slag satisfied the requirements for using in asphaltic mixture. Asi et al. investigated the feasibility of utilization of steel slag in asphalt concrete mixtures by indirect tensile strength, resilient modulus, rutting resistance, fatigue life, creep modulus, and stripping resistance tests [12]. It is found that replacing up to 75% of the limestone coarse aggregate by steel slag aggregate improved the mechanical properties of the mixes. Ahmedzade and Sengozb evaluated the effectiveness of steel slag coarse aggregate in hot mix asphalt concrete mixtures [13]. They conducted Marshall stability, indirect tensile stiffness modulus, creep stiffness, indirect tensile strength, and electrical resistivity tests. The results gained from their studies demonstrated that steel slag used as a coarse aggregate improved the mechanical properties and electrical resistivity of asphalt mixtures.

The main problem of using steel slag in road construction is volume expansion. It is the result of having high percentages of free lime and magnesium oxides that have not reacted with the silicate structures [14]. So when it hydrates, its volume increases and this swelling can lift the top layers. In addition, ignoring this issue could result in pavement cracking. Historically, the method of dealing with the free lime and magnesia has been to age the slag or problem of steel slag, the materials were washed to accelerate the hydration process of free lime and magnesia. In addition, the materials were used after two years of disposal. The range of chemical composition of steel slag is presented in Table 1. The values given in Table 1 are based on the information gained from Esfahan Steel Manufacturing Facility.

3. Materials

3.1. Aggregates

RAP material samples in this study were obtained from the following routes: (1) Azadegan freeway in Tehran province, (2) Ardabil-Khalil Khal route in Ardabil province. The gradation of obtained RAP materials was determined in accordance with ASTM C136.117 Test Method. Most projects demand that any oversize material should be removed and crushed [17]. Therefore, the plus 25 mm material was removed from both RAP material samples, and the gradations of the remainder of the samples were determined. The bitumen contents of the samples were determined using ASTM D2172. The RAP materials contained 3.5% and 3.9% of asphalt by weight for type 1 RAP (obtained from Tehran province), and type 2 RAP (obtained from Ardabil province), respectively. As shown in these figures the gradations of aggregates did not meet the required specifications of Ministry of Road and Transportations of Iran for Cold Mix Recycling [3]. Thus, new aggregate were added to satisfy the gradation requirements. The amounts of new aggregates were 20% and 10% by the weight of RAP materials, respectively. Fig. 1 presents the gradation of RAP materials, mix blends and specification limits.

In this study limestone was obtained from Bomehen mine in Tehran, Iran, and steel slag was obtained from Esfahan Steel Manufacturing Facility. According to the suggestion of Kneller et al. [15], to mitigate the expansion problem of steel slag, the materials were washed to accelerate the hydration process of free lime and magnesia. In addition, the materials were used after two years of age. The gradation of RAP materials, mix blends and specification limits is presented in Table 1.

3.2. Bitumen emulsion

Choosing of bitumen emulsion is important from compatibility perspective with aggregate and its gradation [3]. Since bitumen emulsions have positive or negative particle surface electric charge, they can show different characteristics while being blended with different aggregates. In this study, two asphalt emulsions were employed including a cationic slow setting (CSS–1) and an anionic slow setting (SS–1). Table 2 gives the specifications of these two bitumen emulsions.

3.3. Active additive – Portland cement

Pervious studies have shown that use of additives in CIR mixes can improve their performance [18]. In the present study, Portland cement type II (2% by the weight of aggregate) was selected as an active additive. Since it has a better influence on CIR mixes properties and it is more common additive used in CIR projects in Iran [18].

4. Mix design procedure

There are several procedures to determine the optimum emulsion and water content in CIR mixtures. But, there is no universally accepted mix design for cold mix recycling. In this study, the modified Marshall method (ASTM D1559) accepted by AASHTO was used [3]. The samples were prepared in such a way to have a 3% water content (consisting of emulsion water, RAP water 0.2% and the water added to the mixture). Bitumen emulsion was added...
to the mixture at percentages ranging from 2.5% to 4.5% by weight of total mixture at 0.5% increments. The mixtures were then compacted applying 50 blows per side with Marshall hammer. After compaction, all samples were cured in the oven for 24 h at a temperature of 60 °C. The cured samples were then kept for 24 h at room temperature in the molds and then were extruded and air cured for 5 days at room temperature. Using the maximum specific gravity and Marshall stability, optimum emulsions content was determined for samples. In the next step, the optimum moisture content was determined for samples prepared with optimum emulsion content and water contents ranging from 2.5% to 4.5% at 0.5% increments.

Maximum bulk specific gravity and average void content for each moisture contents are then determined. The only design criterion is the air void content, which should be between 9% and 14% [3]. The results for eight types of mixtures are shown in Table 3.

In the present study, samples were identified with labels composed of three characters. The first character of the label indicates the type of RAP materials. Second character indicates the type of blended aggregate, and the third one indicates the type of bitumen emulsion. (e.g. 1SA means RAP type 1 blended with slag aggregate and anionic emulsion). Marshall hammer was used for compacting Marshall test samples. Samples for resilient modulus, indirect tensile, moisture sensitivity, and dynamic creep tests were compacted by the Gyratory compactor. Same curing procedure was applied for all of the samples.

5. Testing program


Marshall stability and flow (ASTM D1559), bulk specific gravity (ASTM D2726), and air void content were determined in this test.

The ratio of stability (kn) to flow (mm) is known as the Marshall Quotient (MQ) (kn/mm) is also calculated. MQ can be used as a measure of the material’s resistance to permanent deformation in service. A higher value of MQ indicates a stiffer and more resistant mixture [19]. It is well recognized that the higher value of the MQ represents more resistance of material to shear stresses and permanent deformation.

5.2. Resilient Modulus (MR) test

Resilient modulus is the most important parameter used in the mechanistic design of asphalt pavements, performed based on elastic theory. Methods based on elastic theory require elastic properties of pavements as input. Resilient modulus of bituminous mixes, which is determined in accordance with ASTM D4123 method, is the most popular form of stress-strain measurements used to evaluate the elastic properties of these mixes [20,21]. It is well known that most paving materials are not elastic but experience some permanent deformation after each load application. However, if the load is small compared to strength of the material and is repeated for a large number of times, the deformation under each load cycle is proportional to the load and is nearly completely recoverable and therefore can be considered as elastic [22].

For each asphalt mixture mentioned in Section 3, five specimens having optimum emulsion and water contents were tested with Universal Testing Machine (UTM-5P). The specimens were tested at 25 °C causing a haversine load pulse at 1 Hz with 0.9 seconds rest time. The assumed Poisson’s ratio was 0.35 and the maximum applied load was 500 N with 200 repetition preconditioning loads.

5.3. Indirect Tensile Strength (ITS) test

The indirect tensile strength test is used to determine the tensile properties of the asphalt concrete, which can be related to the cracking properties of the pavement [23]. Indirect tensile test values are often used to evaluate the relative quality of materials. In indirect tensile strength test, a cylindrical sample is subjected to compressive loads between two loading strips, which generate a relatively uniform tensile stress along the vertical diametrical plane. Failure usually occurs by splitting along this loaded plane [24]. The tensile strength of the specimen is determined by the following equation: $\text{ITS} = 2P_{\text{max}}/\pi D t$, where $\text{ITS}$ is the tensile strength of specimens in kPa, $P_{\text{max}}$ is the applied load at failure in kN; $D$ is the diameter of the specimen in mm; $t$ is the thickness of the specimen in mm. Five specimens with optimum emulsion and water contents were prepared for each asphalt mixture mentioned in Section 3. The specimens were loaded at a deformation rate of 50 mm/min and at a temperature of 25 °C.

5.4. Resistance to moisture damage test

The moisture susceptibility of asphalt mixtures was evaluated by performing Marshall Conditioning (curing for 24 hours at a temperature of 60 °C), and AASTHO T283 Test.

For Marshall conditioning test, six samples from each mix were placed in the water bath at a temperature of 60 °C. After 40 minutes of immersion in the water bath, three samples from each mix were loaded at a rate of 50 mm/min. Then, the Marshall stability values were recorded. These samples were named as unconditioned samples. The other three samples from each mix were tested at a same rate for Marshall stability after 24 hours immersion in a water bath. These samples were named as conditioned samples. The Marshall Stability Ratio (MSR) was then compacted using the equation: $\text{MSR} = 100 \times (\text{MS2}/\text{MS1})$, where MS2 is the average Marshall stability for conditioned samples, and MS1 is the average Marshall stability for unconditioned samples.

For AASHTO T283 test, six samples from each mix were prepared. Three of them were conditioned by vacuum saturation (at 55–80% saturation level) followed by a freeze cycle (for 16 hours at a temperature of −18 °C), and subsequently having a warm-water soaking cycle (soaking in water bath at 60 °C for 24 hours). The other three samples from each mix were selected as unconditioned samples and tested without moisture conditioning. The

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Table 2

<table>
<thead>
<tr>
<th>Test type</th>
<th>CSS-1</th>
<th>SS-1</th>
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</thead>
<tbody>
<tr>
<td>Sabatt furol viscosity @ 25 °C (s)</td>
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<td>55</td>
</tr>
<tr>
<td>Storage stability test (%)</td>
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<td>0.5</td>
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<tr>
<td>Portland cement mixing test</td>
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<tr>
<td>Residue by distillation (%)</td>
<td>60</td>
<td>65</td>
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<tr>
<td>Penetration on residue @ 25 °C</td>
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<td>150</td>
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</table>

Table 3

<table>
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<tr>
<th>Sample ID</th>
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<th>Type of aggregate</th>
<th>Type of bitumen emulsion</th>
<th>Optimum bitumen</th>
<th>Optimum water</th>
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<tbody>
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<td>Aggregate</td>
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<td>RAP#1</td>
<td>Aggregate</td>
<td>Anionic</td>
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</tbody>
</table>
specimens were tested for indirect tensile strength by loading the specimens at a deformation rate of 50 mm/min. The indirect tensile strength ratio (TSR) was then computed using the equation: 

$$\text{TSR} = 100 \times \frac{(S2/S1)}{C3},$$

where S2 is the average indirect tensile stress of conditioned specimens, and S1 is the average indirect tensile stress of dry (unconditioned) specimens. A TSR of 0.8 or more has been utilized typically, as a minimum acceptable value for hot mix asphalt. Mixtures with tensile strength ratios less than 0.8 are moisture immune and mixtures with ratios greater than 0.8 are relatively resisted to moisture damage. Minimum acceptable TSR values for CIR mixtures have not been determined [25].

5.5. Dynamic creep test

The dynamic creep test is one of the methods to assess the resistance of bituminous mixes to flow rutting [26]. The test was performed in accordance with BS-DD226 Test Method. It is performed by applying a repeated pulsed uniaxial stress on asphalt specimens, and measuring the resulting deformation in the same direction using linear variable differential transducers (LVDT). Five cylindrical specimens 150 mm × 100 mm for each asphalt mixture mentioned in Section 3 were prepared at optimum emulsion and water content. The dynamic creep test was conducted by applying a dynamic stress of 50 kPa for 1 hour at 30 °C temperature. The Universal Testing Machine (UTM-5P) was used for this purpose. The tests were performed according to the following procedures: after capping the two sides of each specimen, it was placed in the loading machine under a conditioning stress of 10 kPa for 600 seconds. Then the conditioning stress was removed, a stress of 50 kPa was applied for 1800 cycles with 1 second loading and 1 second rest period and the axial deformation was measured using LVDT.

6. Results and discussion

6.1. Marshall stability and flow

The results of these tests are presented in Table 3. It should be noted that the values are average of three specimens. Difference in the air void contents is not a concern of decision as we can see from the results. The higher stability and lower flow are important criteria for Marshall tests. The Marshall stability is the ability of asphalt concrete to resist shoving and rutting under traffic. The Marshall flow of asphalt concrete is its ability to resist the gradual settlements and movements in the sub-grade without cracking [27].

The results indicate that the Marshall stability and bulk specific gravity increase in mixtures that contained steel slag and anionic bitumen emulsion. The asphalt concrete samples containing steel slag and anionic emulsion (1SA and 2SA mixtures) yield higher values of MQ than other mixtures as indicated in Table 4. The reason could be due to the compatibility of steel slag aggregate and anionic emulsion. Steel slag is a chemical compound of alkane series, so the particle of steel slag produces positive electrical surface charge in the presence of water [28]. Whereas the anionic emulsion has negative electrical surface charge, the negative ions adsorb the positive ones in a more compatible matrix. On the other hand, positive electric surface charge of cationic emulsion repulses the positive charge of steel slag. So, this results in lower quality mixtures and thus lower MQ value.

6.2. Resilient Modulus (MR) test

The resilient modulus test results for eight types of mixtures are shown in Fig. 2. The results indicate that addition of steel slag to satisfy the gradation requirements in CIR mixes requires anionic bitumen emulsion to produce higher resilient modulus. The use of steel slag in mixtures containing anionic emulsion resulted in an increase in resilient modulus of 8% and 14% as compared to samples with virgin aggregate. Replacing cationic emulsion with anionic emulsion in mixtures containing steel slag resulted in a reduction in resilient modulus of 16% and 20%.

6.3. Indirect Tensile Strength (ITS) test

The average tensile strengths of eight mixtures tested are shown in Fig. 3. The results indicate that mixtures containing steel slag and anionic emulsion show higher values of tensile strength at failure indirect tensile strength under static loading. This would further imply that modified mixtures appear to be capable of withstanding larger tensile stress prior to cracking. Tensile strengths of the mixtures containing virgin aggregates and different types of emulsions are nearly the same.

6.4. Resistance to moisture damage test

Marshall stability and indirect tensile values for both conditioned and unconditioned samples are given in Table 4. In addition, Table 5 gives the MSR and TSR values of the mixtures examined in tests. Both MSR and TSR values indicate that use of steel slag needs anionic emulsion to improve resistance to moisture damage of CIR.

![Fig. 2. Results of resilient modulus tests.](image)
mixtures. Mixtures containing steel slag and cationic emulsion are more susceptible than other mixtures to moisture damage. This could be due to less compatibility of steel slag aggregates with cationic emulsion. Both MSR and TSR values show that cationic emulsion decreases the resistance to moisture damage in mixtures containing steel slag. While, use of anionic emulsion in these mixtures results in significantly higher MSR and TSR values with all being above 0.8.

6.5. Dynamic creep test

The dynamic creep test results for RAP #1 and RAP #2 mixtures are shown in Figs. 4 and 5, respectively. The results of dynamic creep test show that the application of steel slag along with anionic bitumen emulsion leads to lower rut depth (17% and 21% as compared to mixtures with virgin aggregate).

7. Conclusion

This research was conducted to find the mechanical properties of CIR mixtures containing steel slag and virgin aggregate to satisfy the gradation requirements. Properties of eight different mixes from two types of RAP materials were evaluated. Based on the test results, the following conclusions were made:

1. The results of Marshall, resilient modulus and indirect tensile strength test show that the use of steel slag along with anionic bitumen emulsion increases the Marshall stability, bulk specific gravity, resilient modulus and tensile strength and reduces void content and flow of the recycled mixtures. But, mixtures of steel slag and cationic emulsion indicated the opposite results. This could be due to the compatibility of steel slag aggregates and anionic emulsion. It is also concluded that there is no significant difference in mixtures with aggregate and two types of bitumen emulsions.

2. MSR and TSR values of mixtures obtained from moisture susceptibility tests indicated that utilizing of steel slag and anionic emulsion can enhance the resistance of mixtures to moisture damage. Also, the results of dynamic creep test showed that these mixtures are more resistant to permanent deformation and have lower rut depth.

3. The use of steel slag as a substitute for virgin aggregate in CIR mixtures demands anionic bitumen emulsion to improve the mechanical properties of mixtures.

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References


