Laboratory evaluation of warm mix asphalt mixtures containing electric arc furnace (EAF) steel slag

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HIGHLIGHTS

- Steel slag aggregates improved the Marshall stability of hot mix asphalt mixtures.
- Moisture susceptibility of warm mixtures containing steel slag was improved.
- Warm mix asphalt mixtures containing steel slag aggregates showed higher resilient modulus.
- Steel slag aggregates improved resistance to permanent deformation in warm mixtures.

ABSTRACT

This paper presents the results of a laboratory study which was aimed to verify possibility of using electric arc furnace (EAF) steel slag (SS) in substitution of natural limestone (LS) aggregates in warm mix asphalt (WMA) mixture. The SS was used as fine and coarse portion of aggregate gradation in HMA mixtures, and as coarse portion of aggregate gradation in WMA mixture. The surface texture of both LS and SS aggregates was observed through scanning electron microscope (SEM). The results illustrated that the porosity and the roughness of the SS aggregate are higher than that of the LS aggregate. Moreover, laboratory tests results indicated that use of coarse SS aggregate in WMA mixture enhances Marshall stability, resilient modulus, tensile strength, resistance to moisture damage and resistance to permanent deformation of the mixture. Hence use of coarse electric arc furnace steel slag aggregate in production of WMA mixture is recommended.

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1. Introduction

In recent years the concept of “comprehensive development” has evolved to the more developed idea of “sustainable comprehensive development”. The concept of sustainable development tries to make equilibrium among various fundamental factors including environment, economy, security, and social issues, which must be considered for the conservation of the nature as inheritance for future generations [1–3].

Transportation system has a decisive role in comprehensive sustainable development of a country. Nowadays an efficient transportation system has vital importance for economic development. As a constituent element of the national infrastructure, the transportation system satisfies human and economic needs in terms of freight transportation and passenger carriage. Actually the system is the basic element of supply chain of all industries which is used by all economic and non-productive activity sectors without any exception [4–6].

Road pavement can be considered to be one of the fundamental elements of the transportation system. Significant amounts of bitumen and natural aggregates are used in the construction of asphalt concrete pavements. Considering the compatibility of asphalt concrete pavements construction with the principles of sustainable development, researchers are seeking for new ways to reduce construction cost, and lower emissions.

The economic costs and adverse environmental effects of asphalt concrete pavement construction generate from two important sources; first and the most important is the heat sources required to process the paving materials, and the second is the ingredients cost (bitumen and aggregates) [7].

The energy consumption and the release of pollutant gasses is the consequence of drying and heating mineral aggregate and bitumen at temperatures above 140 °C [8,9]. Therefore, scientists have developed a number of new technologies for asphalt pavement
materials generally referred to as warm mix asphalt (WMA), which produce asphalt mixture in the temperature range of 100–140 °C, without compromising the workability and mechanical performance attained [8,9]. There is also numbers of benefits in warm-mix asphalt production including: Environmental benefits (Lower plant emissions and fumes), Economic benefits (Reduced energy consumption and financial cost), Paving benefits (Improved workability and compaction efficiency, provision of longer haul distances, and quicker turnover to traffic due to shorter cooling time, and Production benefits (Increased Recycled Asphalt Pave-ment (RAP) content and location of plant site in urban areas) [10–15].

On the other hand to satisfy the need for natural stone materials, which is needed for construction, reconstruction, and repairs of road pavements, a wide range of industrial waste as secondary resources have been utilized.

Among wastes used as road building material, steel slag (SS) is one of the most popular one, due to certain environmental saving properties including: preservation of natural ecosystem by means of reducing the amount of dumped wastes, and allowing reducing the consumption of natural aggregate in asphalt concrete pavements production every year [16–21].

Due to economic and environmental advantages, WMA has been used to produce different kinds of asphalt mixtures, such as polymer-modified asphalt, sulfur modified asphalt, stone matrix asphalt (SMA), dense graded asphalt, crumb rubber modified (CRM) asphalt, and in some cases with different aggregates such as asphalt mixture containing recycled asphalt pavement (RAP) [8]. Therefore different WMA mixtures have different performance characteristics depending on the material used in them.

As a result, production of asphalt mixture which contains SS as an aggregate by means of WMA technologies is a more efficient approach that includes WMA technology application as well as industrial waste substitution benefits simultaneously.

It is reminded that application of SS in the mixture can be recommended if its use does not have significant negative effect on the performance of the produced asphalt concrete pavement, even though having grate cost and emission reduction cover the minor reduction in the performance characteristics. The objectives of this research study are to conduct laboratory tests on WMA mixtures containing SS aggregates and to evaluate its performance for producing a WMA mixture that is more environmentally friendly.

2. Materials and experimental procedures

The testing program for this study was divided into three main phases. In the first phase the four different aggregate gradations that are shown in Table 1, was selected. Then mixtures of HMA concrete were prepared in accordance with the Marshall method (ASTM D1559) to obtain optimum bitumen content (O.B.C) for each of the selected gradations, based upon the maximum bulk specific gravity, maximum Marshall stability and 4% air void [22]. In the second phase Marshall, ITS and dynamic creep tests were conducted on each of the HMA specimens with the (O.B.C) as controlling mixtures. In the third phase, the WMA specimens were prepared and tested.

2.1. Materials

For both HMA and WMA mixtures a 60/70 Penetration grade bitumen obtained from Pasargad Oil Company was used. The properties of the bitumen are presented in Table 2. The crushed limestone (LS) aggregates used in this study for both HMA and WMA mixtures were collected from Ashbaran quarry located in eastern part of Tehran province, city of Rudehen. The gradation of the aggregates used in this research study is shown in Fig. 1. The steel slag used was electric arc furnace steel slag which was obtained from Ahvaz steel manufacturing facility. The physical properties of the LS and SS aggregates are shown in Table 3.

Table 2

<table>
<thead>
<tr>
<th>Test Standard test</th>
<th>Unit</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity (25 °C)</td>
<td>ASTM D70</td>
<td>g/cm³</td>
</tr>
<tr>
<td>Flash point (Cleveland)</td>
<td>ASTM D92</td>
<td>°C</td>
</tr>
<tr>
<td>Penetration (25 °C)</td>
<td>ASTM D5</td>
<td>°C</td>
</tr>
<tr>
<td>Ductility (25 °C)</td>
<td>ASTM D113</td>
<td>cm</td>
</tr>
<tr>
<td>Softening point</td>
<td>ASTM D36</td>
<td>°C</td>
</tr>
<tr>
<td>Kinematic viscosity @ 120 °C</td>
<td>ASTM D2170</td>
<td>mm²/s</td>
</tr>
<tr>
<td>Kinematic viscosity @ 135 °C</td>
<td>ASTM D2170</td>
<td>mm²/s</td>
</tr>
<tr>
<td>Kinematic viscosity @ 150 °C</td>
<td>ASTM D2170</td>
<td>mm²/s</td>
</tr>
<tr>
<td>Penetration index (PI)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Penetration</td>
<td>(Pen25)</td>
<td></td>
</tr>
<tr>
<td>Penetration number (PVN)</td>
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</tbody>
</table>

As a common WMA additives [8,9] Sasobit was used as WMA organic bitumen modifier. For WMA mixtures, first base bitumen was blended with Sasobit, and then the modified binder was used for preparation of WMA mixtures with optimum bitumen content. Properties of the Sasobit used in this study are presented in Table 5.

2.2. Sample preparation

Four types of aggregate compositions were used in this research study for preparation of specimens according to Table 1. For preparation of HMA specimens, the aggregates were heated in an oven for 24 h at the temperature of 165 °C, and then the heated bitumen was added into the aggregates. For WMA mixtures the aggregates were heated at 135 °C (Which is the temperature for the production of WMA with Sasobit) and then the modified bitumen was added.

Replacing both the fine and coarse aggregate fraction of the mixtures by 100% SS results in excessive void, bulking problems, and increases the internal volume expansion risk and high bulk density [23]. To alleviate these problems and according to the test results conducted on HMA mixtures in phase two of this study, the type B aggregate was selected to fabricate WMA test specimens containing SS aggregate.

2.3. Testing program

2.3.1. Marshall stability, flow and Marshall quotient test

Marshall stability and flow test was conducted on specimens with various bitumen contents and the optimum bitumen content was determined in accordance with ASTM D1559 and their Bulk specific gravities and air void contents were measured in accordance with ASTM D2726. In addition the Marshall quotient (MQ) (the ratio of stability (KN) to flow (mm)) was also calculated. Higher MQ value indicates that the mixture has better resistance to shear stresses and permanent deformation [24].

2.3.2. Resilient modulus test

When the elastic theory is employed to analyze pavements, the resilient moduli of asphalt surface, base and subgrade materials in flexible pavements are used in place of elastic modulus. Resilient modulus is the ratio of the repeated axial

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of 7 ± 1% were selected. Three specimens were conditioned by vacuum saturation at
0.1 s loading time and 0.9 s rest period. The estimated poisons ratio was 0.35 and
the maximum applied load was 570 N with 100 repetitions for preconditioning
and cracking [26]. Although cracking of asphalt pavements is not immedi-
ately fatal, but certainly represents a type of tensile distress. The tensile strength
is determined by indirect tensile strength (ITS) test. In this research study the resil-
ience modulus of mixtures was determined in accordance with Australian: AS

For both WMA and HMA mixtures five specimens with optimum bitumen con-
tent were tested at temperature of 25 °C using a haversine load pulse at 1 Hz with
the tensile strength of the specimens in ordinary dry condition and may be ex-
pressed as follows:

\[ \text{TSR} = \frac{\text{Wet ITS}}{\text{Dry ITS}} \]  

where WetITS is the average ITS value for conditioned specimens and DryITS is the
average ITS value for unconditioned specimens. A TSR value of 0.7 is typically spec-
ified as a minimum acceptable value and mixtures with TSR values more than that
are relatively resisted to moisture damage [29].

2.3.3. Indirect tensile strength (ITS) test
An important characteristic of asphalt concrete is its resistance to tensile loads
and hence cracking [26]. Although cracking of asphalt pavements is not immedi-
ately fatal, but certainly represents a type of tensile distress. The tensile strength
of the asphalt concrete is determined by indirect tensile strength (ITS) test. In this
test, a cylindrical specimen is subjected to compressive loads between two loading
strips, loading the vertical diametrical plane and generating a relatively uniform
tensile stress along the plane. The loading is continued to the failure and splitting
the specimen along the loading plane. The following equation is used to calculate
the ITS value for the specimen:

\[ \text{ITS} = \frac{2P_{\text{max}} t}{\pi d^2} \]  

where \( P_{\text{max}} \) is the maximum applied load (KN), \( t \) is thickness of the specimen (mm), \( d \)
is diameter of the specimen. For each type of the mix, five specimens were loaded at
deflection rate of 50 mm/min at 25 °C.

2.3.4. Resistance to moisture damage test
Presence of moisture in asphalt concrete can weakens bonds between the
aggregate and bitumen leading to adhesive and also cohesive deterioration of the
mixture and decrease in load carrying capacity of asphalt pavement [27,28]. In this
research study the moisture susceptibility of asphalt concrete is evaluated by per-
forming AAHTO T283 test. Six specimens for each mixture type with air void level
of 7 ± 1% were selected. Three specimens were conditioned by vacuum saturation at
55–80% saturation level, followed by freeze–thaw cycle (16 h at −18 °C and subse-
quent soaking in water bath at 60 °C for 24 h). The other three specimens were re-
mained dry and were tested without moisture conditioning.

The tensile strength ratio is the tensile strength of the conditioned specimens to
the tensile strength of the specimens in ordinary dry condition and may be ex-
pressed as follows:

\[ \text{TSR} = \frac{\text{Wet ITS}}{\text{Dry ITS}} \]  

where WetITS is the average ITS value for conditioned specimens and DryITS is the
average ITS value for unconditioned specimens. A TSR value of 0.7 is typically spec-
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2.3.5. Dynamic creep test
Rutting in asphalt concrete pavements under traffic loading occurs predomi-
antly at elevated temperatures. Rutting in the asphalt surface layer is more sensi-
tive to resistance of the layer to shape distortion due to plastic flow than it is to the
layer resistance to densification or volume change [30]. Based on the consider-
ations, the dynamic creep test in this research study was conducted in accordance
with US.NCHRP 9-19 [31] Superpave W2 to evaluate the propensity for rutting in
the mixtures. The test was conducted at 30 °C. The stress of 450 Kpa was used as
deviator stress with 0.1 s loading and 0.9 s rest time for each loading pulse cycle.
A typical creep test curve drawn for a sample in this research study is shown in
Fig. 2. As the figure illustrates, the curve can be divided into three distinct regions.
In the primary stage of permanent deformation (up to around 1500 cycle), a
decreasing rate of plastic deformations, which is predominantly associated with
high initial level of rutting and volumetric change can be observed. In the secondary
stage (nearly from 1500 to 7000 cycle), a constant rate of plastic deformation and
rutting change is exhibited that is also associated with volumetric changes. How-
ever, shear deformations increase at increasing rate in this stage. In tertiary stage
(after 7000 cycle), high level of rutting predominantly associated with plastic
(shear) deformations under no volume change is observed. Flow number, which
is defined as the number of cycle in which permanent strain in the mixture dramat-
ically increases (the transition point from secondary to tertiary stage) [31], was
used as criterion to compare the mixtures potential to rutting.

3. Results and discussions


Table 6 presents the Marshall test properties including (O.B.C) of all HMA mixtures tested in this research study. The values are obtained from replicate of three test specimens. It is observed that addition of SS increases the optimum bitumen content of the mix-
tures. This is attributed to the porous surface texture of SS, which was clearly demonstrated by the SEM images captured from both limestone and SS surface texture shown in Figs. 3 and 4. The (O.B.C) for type D mixture is higher than that for type B mixtures. This is due to higher porous specific surface area steel slag used as fine portion of the aggregates in type D mixtures.

Bulk specific gravity and Marshall stability and flow results for HMA specimens are also presented in Table 6. The results in Table 6 show that mechanical and also physical properties of the mix-
tures produced with SS are higher. Predominately this is due to the higher bulk specific gravity of SS.

Based upon the results presented in Table 6, Marshall stability and flow of the HMA mixture increase simultaneously if the coarse portion of the aggregates is replaced with SS leading to larger value for MQ of the mix. In general, SS aggregates have higher angularity, angle of internal friction, and higher bulk specific gravity relative to other natural stones [20]. This higher internal angle of friction leads to better aggregate interlock and makes SS a suitable aggre-

<table>
<thead>
<tr>
<th>Aggregate type</th>
<th>Oxide content (%)</th>
<th>SiO2</th>
<th>Fe2O3</th>
<th>Al2O3</th>
<th>CaO</th>
<th>MgO</th>
<th>Na2O</th>
<th>TiO2</th>
<th>K2O</th>
<th>MnO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td></td>
<td>17.25</td>
<td>0.93</td>
<td>2.11</td>
<td>43.01</td>
<td>0.75</td>
<td>0.08</td>
<td>0.107</td>
<td>0.66</td>
<td>0.046</td>
</tr>
<tr>
<td>EAF steel slag</td>
<td></td>
<td>18.72</td>
<td>35.16</td>
<td>2.75</td>
<td>25.58</td>
<td>7.50</td>
<td>0.29</td>
<td>1.595</td>
<td>0.13</td>
<td>0.304</td>
</tr>
</tbody>
</table>

Fig. 1. Gradation of designated aggregate.

Table 3
Physical properties of aggregates.

<table>
<thead>
<tr>
<th>Test</th>
<th>Standard</th>
<th>Limestone</th>
<th>Steel slag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los angeles abrasion (%)</td>
<td>ASTM C-535</td>
<td>22.6</td>
<td>14.2</td>
</tr>
<tr>
<td>Specific gravity (coarse agg.)</td>
<td>ASTM C-127</td>
<td>2.49</td>
<td>3.01</td>
</tr>
<tr>
<td>Specific gravity (fine agg.)</td>
<td>ASTM C-128</td>
<td>2.48</td>
<td>3.06</td>
</tr>
</tbody>
</table>
gate for improving the rutting resistance of pavement layers. These unique properties of SS have attributed to larger value of MQ parameter indicating higher resistance to shear stresses and permanent deformations.

3.2. Resilient modulus (MR)

The test results for resilient modulus values of four types of HMA and two types of WMA mixtures are presented in Fig. 5. The results indicate that in general, the WMA mixtures have higher resilient modulus values than HMA mixtures. By comparing the WC type specimens with C type ones that both used the same type and grading of aggregates, the WC specimens have higher resilient modulus. The Sasobit modified binder is stiffer and has better tensile strength [32]. Thus, the improvement in resilient modulus of WMA mixtures is attributed to the stiffer Sasobit modified binder. The same results were obtained comparing WB and B specimens. Among WMA specimens, WB type specimens that contain SS have lower resilient modulus values than WC type specimens. The SS used in this study has lower CaO/SiO₂ value than limestone, which results lower aggregate-binder adhesion. Thus, the decrease in resilient modulus values resulted by addition of SS to WMA mixtures is related to the chemical composition of SS and limestone used in this research. But it should be noted that, despite having lower resilient modulus than WC type specimens, the WB type specimens have higher resilient modulus than all types of HMA specimens.

3.3. Indirect tensile strength (ITS)

The average tensile strength values for all six types of HMA and WMA mixtures are represented in Fig. 6. As the results indicate, among HMA specimens, the type C ones, which contain only limestone aggregates, have higher tensile strength values than others. This is due to the better adhesion of limestone aggregates to binder than SS, which generates from chemical composition of the aggregates (higher CaO/SiO₂ value for limestone).
In general, the WMA mixtures have better tensile strength than HMA mixtures. The higher tensile strength values of WMA mixtures are attributed to better tensile performance of Sasobit modified binder.

3.4. Resistance to moisture damage

The tensile strength values for the six types of mixtures are depicted in Fig. 6 for both dry and conditioned specimens. Based upon the results presented in Fig. 6, the dry and conditioned tensile strength for both WB and WC type mixtures are higher than that of HMA mixtures. Fig. 7 shows the results of TSR values for six types of HMA and WMA specimens in this study. The moisture susceptibility of WMA mixtures is an important issue considering their lower mixing and compaction temperature. Based upon the TSR values obtained, the WMA mixtures have better moisture damage resistance than HMA mixtures. Among WMA mixtures the WB type specimens containing SS as coarse aggregate have higher TSR values than WC type ones. This is attributed to the higher bitumen content and better coating of aggregates by bitumen. The type D specimens have higher TSR values than other three types of HMA specimens, which is attributed to the low air void content and high optimum bitumen content value for this type of specimens. The lower air void content in type D specimens decreases the water penetration into the mixture. At the same time the higher bitumen content results better coating of aggregates in this type of mixtures.

3.5. Permanent deformation (dynamic creep)

The dynamic creep test results are presented in Fig. 8. Aggregate interlock and bitumen stability are two important factors affecting

<table>
<thead>
<tr>
<th>Mixture type</th>
<th>Bulk specific gravity</th>
<th>Air void content (%)</th>
<th>O.B.C (%)</th>
<th>Marshall stability (KN)</th>
<th>Flow (mm)</th>
<th>MQ (KN/mm)</th>
<th>VMA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.77</td>
<td>4.81</td>
<td>5.2</td>
<td>11.33</td>
<td>3.8</td>
<td>2.98</td>
<td>12.95</td>
</tr>
<tr>
<td>B</td>
<td>2.54</td>
<td>4.51</td>
<td>4.57</td>
<td>10.81</td>
<td>3.3</td>
<td>3.28</td>
<td>10.73</td>
</tr>
<tr>
<td>C</td>
<td>2.35</td>
<td>4.47</td>
<td>4.34</td>
<td>9.06</td>
<td>2.9</td>
<td>3.12</td>
<td>10.17</td>
</tr>
<tr>
<td>D</td>
<td>2.56</td>
<td>4.12</td>
<td>4.71</td>
<td>8.83</td>
<td>3.1</td>
<td>2.85</td>
<td>11.49</td>
</tr>
</tbody>
</table>
the creep performance of asphalt concrete. Modification of binder with Sasobit stiffens the modified binder. Moreover, addition of SS to the lithic skeleton of the mixtures increases the aggregate interlock and improves the resistance of the mixture to vertical loading permanent deformations. The dynamic creep test results in Fig. 8 indicates that in general, the WMA mixtures have significantly better resistance to permanent deformations than HMA mixtures which is attributed to stiffer Sasobit modified binder used in WMA mixtures.

The simultaneous affection of stiffer modified binder and better aggregate interlock in WB type mixtures resulted significant enhancement in resistance to permanent deformation. Thus, this type of SS warm mix asphalt mixture is a good choice for application as a rutting resistant asphalt mixture.

4. Conclusion

On the basis of the limited tests results obtained in this research study, the following conclusions are drawn:

- Based on the Marshall test results replacing the coarse portion of the aggregate in HMA mixture with the coarse portion of the SS aggregate leads to a concurrent increase in the Marshall stability and flow with an improve MQ parameter.
- Based on other tests results of this research study the advantageous of using coarse SS aggregate in production of WMA mixture are:
  (a) Better adhesive properties, better resistance to moisture damage and hence a more durable mixture.
  (b) Better aggregate interlocking, higher cohesive property and hence better resistance to permanent deformation.
  (c) Higher MQ parameter and hence more flexible and energy absorbing mixture.

References


