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Laboratory investigation of moisture susceptibility of warm-mix asphalt mixtures containing steel slag aggregates

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A number of completed or ongoing studies on warm-mix asphalt (WMA) and steel slag (SS) asphalt mixtures have been conducted all over the world. Moisture damage is one of the major concerns for both WMA and SS asphalt mixtures. This paper presents the results of a laboratory study aimed at verifying moisture susceptibility of WMA mixtures containing SS aggregates. The physical, chemical, and mechanical properties of aggregates and binders were evaluated to identify their effects on moisture susceptibility of asphalt mixtures. The moisture susceptibility of the asphalt mixtures was also evaluated by four different methods, including Marshall Stability Ratio, Resilient Modulus Ratio, Tensile Strength Ratio and Fracture Energy Ratio. The results generally indicated that use of coarse SS aggregate in WMA mixtures enhances the resistance of asphalt mixtures to moisture damage. Hence, use of steel slag aggregate in production of WMA mixture is recommended.

Keywords: warm-mix asphalt; sasobit; rediset; fracture energy; steel slag

Introduction

In the last two decades, asphalt technologists were constantly seeking new ways to improve pavement performance, increase construction efficiency, conserve natural resources, and advance environmental and economic stewardship (Kheradmand et al. 2013). To achieve these goals, more attention was paid to the sources that generate the costs and adversely affect environmental safety, including the heat sources required to process the materials and the materials cost (bitumen and aggregates) (Chiu et al. 2008).

To reduce the need for heat sources and to allow the traditional hot-mix asphalt (HMA) to be manufactured at lower temperatures, scientists have developed a number of new technologies for asphalt materials generally referred to as warm-mix asphalt (WMA), which have been proven to be cost effective and eco-friendly (Capitão et al. 2012, Rubio et al. 2012, 2013, Mallick and Bergendahl 2013). Moreover, to satisfy the great demand on natural aggregates for producing asphalt concrete and avoiding the exhausting exploitation of mountains and rivers, novel aggregates like steel slag (SS) were utilised (Ahmedzade and Sengoz 2009, Yildirim and Prezzi 2009, Sorlini et al. 2012, Ameri et al. 2013). It is noteworthy that the use of SS (as one of the most popular wastes used as road building material (Yildirim and Prezzi 2009, Ameri et al. 2013)) in production of WMA mixtures can lead to a more efficient approach that includes the simultaneous benefits of WMA technology application as well as industrial waste substitution.

Moisture damage is an important distress in asphalt mixtures, which leads to many concurrent surface defects such as rutting, corrugations, shoving, ravelling, cracking, etc. In general, the presence of water in asphalt mixtures weakens their structural capacity as the bond between the aggregates and the mastic is diminished (adhesive deterioration); also, the cohesive resistance of the mastic are adversely affected (cohesive deterioration) (Caro et al. 2008a,b). Thus, the properties of aggregate, binder, aggregate-binder interface and mixing temperature are potential parameters that can influence moisture damage in asphalt mixtures.

Moisture damage has been a primary concern in WMA mixtures. This is generally due to either the reduction in the mixing temperature, which adversely affects evaporation of the entrapped moisture in aggregate particles or to the inferior coating of aggregates because of high viscosity of binders (Prowell et al. 2007, Xiao et al. 2009, 2010a,b, 2012). In addition, SS contains oxides (CaO and/or MgO) that can result in volumetric instability after hydration in presence of moisture. This volumetric instability of SS in presence of moisture can also accelerate deterioration of the moisture damaged asphalt mixture containing SS (Wang et al. 2010). It is of vital importance to evaluate the moisture susceptibility in WMA mixtures containing SS aggregates.

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There are different recommended testing methods to estimate the moisture sensitivity of asphalt mixtures (e.g. Tensile Strength Ratio (TSR), Indirect Tensile Strength (IDT), etc.), whereby the AASHTO T283 is predominantly recommended. However, these tests may not be accurate enough for correct engineering judgement of mixture performance in presence of moisture. This inadequacy results from empirical nature of the tests that do not represent fundamental material characteristics, and lack of incorporating actual field data. To overcome the shortcomings of the empirical test methods, many researches have proposed new concepts associated with key material properties such as fracture parameters, surface energy, diffusion coefficients and adhesion characteristics to better understand the moisture damage characteristics of asphalt mixtures (McCann and Sebaaly 2001, Kanitpong and Bahia 2003, Airey et al. 2005, Kassem et al. 2006, Bhasin and Little 2007, Copeland 2007, Kringos and Scarpas 2008, Kim et al. 2012).

Objectives and scope of this study
The primary objective of this research study is to evaluate the moisture susceptibility of WMA asphalt mixtures containing Electric Arc Furnace (EAF) SS. To accomplish this goal, the binder (modified and unmodified), aggregates, and additives were evaluated by means of laboratory tests. Two WMA additives (Sasobit and Rediset) were used to produce WMA mixtures. In addition, multiple laboratory tests were conducted to characterise moisture susceptibility and moisture damage mechanisms in WMA mixtures containing SS aggregates and HMA as control mixtures.

Laboratory experimental programme and procedure for testing materials

Materials
Aggregates
Natural limestone (LS) and SS were used as aggregates to prepare asphalt mixtures. The crushed LS aggregates were collected from Asbcharan quarry located in eastern part of Tehran province. The SS used was EAF SS obtained from Ahvaz steel manufacturing facility. The gradation of the aggregates is shown in Figure 1. Appraisals of the physical, chemical and surface texture of the aggregates were conducted in this research study. The physical properties of the LS and SS aggregate are shown in Table 1. The chemical properties of both aggregates were analysed with XRF (X-ray fluorescence) and are presented in Table 2.

To have an explicit image from surface texture of the aggregates and compare their surface roughness, their surface texture was observed using scanning electron microscope (SEM). The captured SEM micro graphs of SS and LS are presented in Figures 2 and 3 respectively.

Asphalt binder and additives
For both HMA and WMA mixtures, a 60/70 penetration grade asphalt binder obtained from Pasargard Oil Company was used. The properties of the base bitumen are presented in Table 3.

To prepare WMA mixtures, Sasobit and Rediset were used as organic and chemical additives respectively. Sasobit is a long chain aliphatic hydrocarbon produced by Fisher-Tropsch synthesis from coal or natural gas. It forms a homogeneous solution with bitumen and produces a significant reduction in binder viscosity, which results in a reduction of 10–30°C in the mixing and compaction temperatures. Rediset is a surface active agent that improves wetting properties of aggregates by significantly reducing the surface tension of asphalt binder at temperatures below its typical mixing temperature (nearly 35°C below the typical mixing temperature). It functions as an anti-stripping agent to improve moisture resistance of asphalt mixtures (Banerjee et al. 2012, Capitão et al. 2012). Based on previous studies and also field trial experiences (Capitão et al. 2012, Rubio et al. 2012), the additive content used in this study was 2% by weight of binder for both additives (Figure 4).

<table>
<thead>
<tr>
<th>Test</th>
<th>Standard</th>
<th>LS</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>
<tr>
<td>Fractured faces (2 fractured face)</td>
<td>ASTM D-5821</td>
<td>92.3</td>
<td>97.6</td>
</tr>
</tbody>
</table>
Presence of some special functional groups in binders has a controlling effect on the interaction of bitumen with aggregate surface (Plancher et al. 1977). To have an explicit understanding about the functional groups in binders, functional group analysis for binders (base and modified bituminous binder) was used to obtain the functional groups of interest in the study. These data were collected using Fourier transform infrared (FTIR) spectroscopy. The spectra were obtained in wave numbers ranging from 3400 to 500 cm\(^{-1}\). Specifically, the absorbance peaks of interest were targeted in the carbonyl region (around 1705 cm\(^{-1}\)). From the infrared spectroscopy data, peaks of infrared absorbance in the region of 1710–1690 cm\(^{-1}\) corresponding to carbonyl stretch were used to characterise bituminous binders. The FTIR spectra for base bitumen, additives and modified bitumen are presented in Figures 5–9.

<table>
<thead>
<tr>
<th>Aggregate type</th>
<th>SiO(_2)</th>
<th>Fe(_2)O(_3)</th>
<th>Al(_2)O(_3)</th>
<th>CaO</th>
<th>MgO</th>
<th>Na(_2)O</th>
<th>TiO(_2)</th>
<th>K(_2)O</th>
<th>MnO</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS</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>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>

Figure 2. LS surface textures in different magnifications: (a) 100 ×, (b) 1000 × and (c) 3000 ×.
To have a better understanding of the cohesion of base and modified bitumen, the Dynamic Shear Rheometer (Smart Pave101, Anton Paar, Australia) was used to conduct frequency sweep tests on samples of the asphalt binders at 25°C. The asphalt binders were sandwiched between a lower fixed plate and an upper oscillation plate. An oscillatory torque was applied to the sample and the complex shear modulus ($G'$) was obtained for base and modified bitumen. Results of the frequency sweep test is presented in Figure 4.

In addition to frequency sweep test, the physical properties of asphalt, including softening point, penetration, ductility and viscosity were obtained in accordance with ASTM D36, ASTM D5, ASTM D113 and ASTM D2170 test procedures respectively, and are presented in Table 4.

**Mix design methodology**

In this research study, four types of aggregate compositions were used for preparation of asphalt specimens according to Table 5. The standard Marshall test method (ASTM D1559) was used to obtain the optimum bitumen content (OBC) for each of the selected aggregate compositions with 75 blows on each side of the 63.5-mm cylindrical specimens for compaction. The following standard procedures were applied to compact and test the specimens: the bulk specific gravity (ASTM D2726), the
maximum theoretical specific gravity (ASTM D2041), and the stability and flow of the mixtures (ASTM D1559). The OBCs obtained for each type of the selected aggregate compositions are presented in Table 5. Eight types of HMA and WMA specimens were fabricated due to the differences in aggregate compositions and their obtained OBC, and were labelled as shown in Table 6. To obtain the OBC for each type of the aggregate compositions, a total number of 84 (21 specimens for each of the four aggregate compositions) specimens were fabricated. Also, 28 specimens for each of the eight types of the specimens were fabricated and used for the moisture sensitivity testing programme. For AASHTO T283 test, the specimens were conditioned by vacuum saturation (at 55–80% saturation level) followed by freezing for 16 h at a temperature of −18°C and subsequent soaking in water bath at 60°C for 24 h.

Marshall stability test

For Marshall stability test, 10 specimens from each type were soaked in water bath at a temperature of 60°C. After 40 min of immersion in the water bath, five of the soaked specimens were randomly selected and loaded at a rate of 50 mm/min. Then, the Marshall stability values were recorded. These specimens were labelled as unconditioned.
specimens. The other five specimens were tested at the same rate for Marshall stability after being immersed in a water bath for 24 h and were labelled as conditioned specimens. The MSR was then calculated to evaluate moisture susceptibility using the following equation:

\[
\text{MSR} = \frac{\text{Marshall Stability}_{\text{Cond}}}{\text{Marshall Stability}_{\text{Uncond}}}.
\]

where Marshall Stability\text{Cond} is the average Marshall stability for conditioned specimens and Marshall Stability\text{Uncond} is the average Marshall stability for unconditioned specimens.

**Resilient modulus test**

It is well known that asphalt pavement materials are inelastic. However, if small loads compared to the strength
of the material are applied repetitively, the material behaves as nearly elastic, and shows recoverable deformation under each load repetition. Therefore, when the elastic theory is employed to analyse asphalt pavements, the resilient modulus is used in place of elastic modulus. Resilient modulus is the ratio of the repeated axial deviator stress to the recoverable axial strain (Huang 1993).

In this research study, the resilient modulus of asphalt mixtures was determined in accordance with Australian: AS 2891.13.1-1995. For each of the eight specimen types, ten replicate test specimens were fabricated. The specimens were randomly assigned to two groups of five. One group was kept dry as unconditioned at 25°C, and the other group was subjected to moisture conditioning process in accordance with AASTHO T283 conditioning procedure. Then all ten specimens were tested at a temperature of 25°C using a haversine load pulse at 1 Hz with a 0.1-s loading and 0.9-s rest period. The estimated poison ratio was assumed to be 0.35 and the maximum applied

![Figure 7. FTIR spectra for Rediset.](image1)

![Figure 8. FTIR spectra for Sasobit-modified bitumen.](image2)
load was set to 570 N with 100 repetitions for preconditioning. For all specimens, the retained RMR was defined as the ratio of mean resilient modulus of conditioned specimens to the mean dry resilient modulus of unconditioned specimens. This ratio was used to evaluate the moisture susceptibility of the mixtures. The RMR value of 70% was taken as the minimum acceptable value to ensure good performance against stripping of the mixtures (Lottman 1978).

**Indirect tensile strength test**

An important characteristic of asphalt concrete is its resistance to tensile loads and hence cracking. Although cracking of asphalt pavements is not immediately fatal, it certainly represents a type of tensile distress which is crucial when the adhesive and cohesive deterioration of the mixture occur in presence of moisture.

As one of the predominantly used methods, moisture susceptibility of asphalt mixtures is evaluated by performing AASHTO T283 test. Ten replicates for each type of specimens were selected. After dividing the specimens randomly into two groups, five were conditioned based on the AASHTO T283 test procedure. The other five samples were kept dry and tested without moisture conditioning. To obtain ITS in current research study, a cylindrical specimen is subjected to compressive loads between two loading strips at a deformation rate of 50 mm/min at 25°C. This type of vertical diametral plane loading generates a relatively uniform tensile stress along the plane. The loading is continued until failure and splitting of the specimen along the loading plane. Equation (2) is used to calculate the ITS value for each test specimen:

\[
\text{ITS} = \frac{2P_{\text{max}}}{\pi td},
\]

where \(P_{\text{max}}\) is the maximum applied load (kN), \(t\) is the thickness of the specimen (mm) and \(d\) is the diameter of the specimen.

The TSR is defined as the average ITS for the conditioned specimen to the average ITS for the dry specimen (in ordinary dry condition) and expressed as follows:

\[
\text{TSR} = \frac{\text{ITS}_{\text{Cond}}}{\text{ITS}_{\text{Uncond}}},
\]

A TSR value of 0.7 is typically specified as a minimum acceptable value. Mixtures with TSR values greater than 0.7 are considered acceptable against moisture damage.

### Table 4. Physical properties of base and modified bitumen.

<table>
<thead>
<tr>
<th>Test</th>
<th>Standard</th>
<th>Unit</th>
<th>Base bitumen</th>
<th>Sasobit-modified bitumen</th>
<th>Rediset-modified bitumen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softening point</td>
<td>ASTM D36</td>
<td>°C</td>
<td>49</td>
<td>63</td>
<td>62</td>
</tr>
<tr>
<td>Penetration</td>
<td>ASTM D5</td>
<td>mm</td>
<td>62</td>
<td>32</td>
<td>34</td>
</tr>
<tr>
<td>Ductility</td>
<td>ASTM D113</td>
<td>cm</td>
<td>100</td>
<td>110</td>
<td>112</td>
</tr>
<tr>
<td>Kinematic viscosity @ 135 °C</td>
<td>ASTM D2170</td>
<td>mm²/s</td>
<td>420</td>
<td>378</td>
<td>390</td>
</tr>
</tbody>
</table>
than 0.7 are relatively less prone to moisture damage (Lottman 1978).

**Fracture energy calculation method**

To evaluate the moisture susceptibility of the asphalt mixtures, the fracture energy to failure was calculated for conditioned and unconditioned specimens of the ITS test. The fracture energy is defined as the work done to fracture the specimen. It is equal to the area under the load-deflection curve at failure load. The total fracture energy is defined as the total area under the load–deformation curve (as shown in Figure 10) and can be calculated by the following equation (Hamed 2010):

\[
\text{Fracture energy} = \int_0^{\delta_{\text{max}}} \frac{P(\delta) \, d(\delta)}{HD},
\]

where fracture energy is total fracture energy at failure (J/m²), \(P\) is load (N), \(\delta\) is deformation (mm), \(H\) is thickness of the specimen (mm) and \(D\) is diameter of the specimen (mm). As a parameter to evaluate moisture susceptibility of mixtures, FER is calculated as follows:

\[
\text{FER} = \frac{\text{Fracture energy}_{\text{Cond}}}{\text{Fracture energy}_{\text{Uncon}}},
\]

where fracture energy\(_{\text{Cond}}\) is the fracture energy at failure for conditioned specimens and fracture energy\(_{\text{Uncond}}\) is the fracture energy at failure for unconditioned specimens.

**Results and discussions**

**Aggregates effects on moisture susceptibility**

The physical, chemical and surface texture properties of aggregates directly affect moisture susceptibility of asphalt mixtures. The physical properties of aggregates are predominantly related to their chemical structure and the chemical properties of their consisting elements (Jamieson et al. 1995, Hefer and little 2005). As it is observed in Table 1, SS aggregates showed lower abrasion loss than LS. This is due to the higher amount of \(\text{Fe}_2\text{O}_3\) and \(\text{SiO}_2\) in chemical composition of SS. The higher resistance of SS aggregates against abrasion would result in better crushing resistance of SS aggregates under compaction and traffic loads, preserved angularity and aggregate interlock and better cohesion in lithic skeleton of the asphalt mixtures. This improved cohesion leads to better resistance against deformations and prevents acceleration of moisture damage in asphalt mixtures containing SS aggregates.

The overall affinity of the aggregates for bitumen is evaluated by alkalinity (CaO/SiO\(_2\) ratio) of the aggregates. Thus, a higher CaO/SiO\(_2\) ratio for LS than SS characterises the LS as a substantially alkaline aggregate, and therefore, suitable to guarantee the necessary adhesion with the weakly acidic bitumen in absence of moisture.

However, in presence of water, the situation is different. Carboxylic acids in bitumen readily bond with metal oxides (such as iron oxides) and siliceous aggregate surfaces and are easily displaced by water (Hefer and little 2005). Therefore, the higher amounts of oxides like \(\text{SiO}_2\), \(\text{Fe}_2\text{O}_3\), \(\text{MgO}\) and \(\text{Al}_2\text{O}_3\) in SS aggregates could lead to a higher possibility for moisture susceptibility of asphalt mixtures containing SS. It is noteworthy that SS

---

**Table 5. Aggregate gradation types.**

<table>
<thead>
<tr>
<th>Gradation type</th>
<th>Aggregate composition</th>
<th>OBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Steel slag as fine and coarse aggregate</td>
<td>5.2</td>
</tr>
<tr>
<td>B</td>
<td>Steel slag as coarse aggregate + LS as fine aggregate</td>
<td>4.57</td>
</tr>
<tr>
<td>C</td>
<td>LS as fine and coarse aggregate</td>
<td>4.34</td>
</tr>
<tr>
<td>D</td>
<td>Steel slag as fine aggregate + LS as coarse aggregate</td>
<td>4.71</td>
</tr>
</tbody>
</table>

**Table 6. Types of specimens.**

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA</td>
<td>HMA containing type A aggregate</td>
</tr>
<tr>
<td>HB</td>
<td>HMA containing type B aggregate</td>
</tr>
<tr>
<td>HC</td>
<td>HMA containing type C aggregate</td>
</tr>
<tr>
<td>HD</td>
<td>HMA containing type D aggregate</td>
</tr>
<tr>
<td>SB</td>
<td>WMA mixture with type B aggregate + Sasobit-modified bitumen</td>
</tr>
<tr>
<td>SC</td>
<td>WMA mixture with type C aggregate + Sasobit-modified bitumen</td>
</tr>
<tr>
<td>RB</td>
<td>WMA mixture with type B aggregate + Rediset-modified bitumen</td>
</tr>
<tr>
<td>RC</td>
<td>WMA mixture with type C aggregate + Rediset-modified bitumen</td>
</tr>
</tbody>
</table>

**Figure 10. Fracture energy definition.**
aggregates are more prone to stripping in the vicinity of moisture. However, if SS is completely covered with sufficient and sound coating of bitumen, moisture cannot reach its surface and the possibility of stripping would decrease significantly.

In addition to the physical and chemical properties, surface texture of aggregates has significant effect on adhesion of binder to aggregate surface. First, mechanical gripping of the bitumen into the cavities, pores and asperities of the aggregate surface on a macroscopic scale improves adhesion. This improvement in adhesion is demonstrated through three major mechanisms, including physical ‘lock and key’, redistribution of stresses and increased surface area (Pocius 1997). Second, when aggregates are crushed or cleaved, the new surface attracts contaminants such as water and organics to the surface, also serving as bonding sites for functional groups in bitumen. Therefore, the higher amount of fractured faces in SS than LS (Table 1) would increase the possibility of attraction of water and organics to the surface of SS aggregates and leads to higher moisture susceptibility in mixtures containing SS. However, it should be noted that contrary to the natural LS, SS is fairly free of any clay and organic contaminates due to the nature of their production process. Therefore, there is lower moisture damage potential for asphalt mixtures containing SS aggregates, which are soundly and sufficiently coated with bitumen.

Also, in spite of the lower affinity for bitumen in dry conditions and the higher possibility of moisture damage in presence of water, SS aggregates have higher amount of pores, cavities and asperities in their surface texture than LS, as demonstrated in Figures 2 and 3. This rough surface texture of SS will lead to a higher aggregate-bitumen surface interlock, an inter-structural redistribution of stress and an increase in surface area that eventually leads to better adhesive properties for SS. Also, the lower viscosity of the modified binders used in this research study (Table 4) leads to a better penetration of binder into the pores in the SS aggregate surface, resulting in better physical interlocking between the binder and the surface of SS aggregates and better durability of the mix in presence of moisture.

**Binders effects on moisture susceptibility**

The mechanical properties of bitumen affect cohesion of binder, while the chemical properties affect the adhesion of bitumen to aggregates.

The results of frequency sweep test are presented in Figure 4. The results show that the modified binders have higher complex shear modulus than the base bitumen. In Sasobit-modified binder, the higher complex shear modulus could be attributed to the fact that when the hot binder cools, Sasobit crystallises, forming a lattice structure of microscopic particles, increasing the binder stiffness and its resistance to deformation. Formation of the same lattice structure as Sasobit could also account for the reason for higher complex shear modulus of the Rediset-modified binder. Also, based on the physical properties of binders presented in Table 4, modified binders showed lower penetrations, which can be due to the same reason as for improved stiffness.

It is essentially the minor acidic components such as carboxylic acids, anhydrides, ketones and 2-quinolone types that are the most highly concentrated in the adsorbed fraction of bitumen on aggregate surface and could be crucial for moisture damage evaluation of asphalt mixture (Petersen 1986, Morgan and Mulder 1995). As the results of the FTIR test illustrate (Figures 5–9), the base and the modified bitumen do not have a significant peak in the target infrared absorbance region. Thus, the base and the modified bitumen used in this research study are not chemically moisture sensitive. It is noteworthy that even though Sasobit had some significant peak in the target region (Figure 6), the Sasobit-modified binder was not chemically moisture sensitive.

Other than the mechanical and chemical properties of bitumen, the bitumen content in the mixture significantly affects the moisture susceptibility. Higher OBC has a positive effect on increasing the bitumen coating thickness around the aggregates. This better coating of aggregates would effectively decrease the possibility of moisture reaching the aggregate-bitumen interface, and increase moisture resistance of the mixture. Therefore, higher OBC in mixtures containing SS (Table 5) would result in better performance against moisture. Also, higher ductility of the modified binders (Table 4) would lead to better coating capability for these binders and better resistance against moisture damage in WMA mixtures.

**Mixture moisture susceptibility evaluation results**

Moisture susceptibility of asphalt mixtures is evaluated by means of four different methods, including MSR, RMR, TSR and FER. The test results are presented in Figures 11–18. Among HMA specimens, as the results illustrate, although the HC-type specimens did not have better Marshall stability, resilient modulus, ITS, and fracture energy than other types of HMA specimens both in unconditioned and conditioned states, they showed better moisture resistance among HMA specimens. This can be attributed to the higher CaO/SiO$_2$ ratio in LS than in SS aggregates that guaranties better adhesion of binder to LS aggregates. Also, among HMA specimens containing SS (HA-, HB- and HD-type specimens), the HB-type specimens showed the best moisture resistance. Based on the gradation of aggregates represented in Figure 1, the fine portion of the aggregates has greater mass and greater
specific surface area than coarse portion of the aggregates. Therefore, the higher moisture resistance of HB-type specimens is due to the greater amount of available LS aggregate surface per unit mass of the aggregate for interaction with bitumen in HB-type specimens. This indicates that it is better to substitute SS aggregates in the coarse portion of the LS lithic skeleton. On the other hand, SS is more prone to moisture damage. Thus, when SS aggregate is used as the fine portion of the lithic skeleton in HD-type specimens, there is a greater amount of moisture sensitive active sites of SS per unit mass of the aggregate, which leads to a weaker resistance of the HD-type specimens against moisture than other HMA specimens.

Figure 11. Marshal stability test results.

Figure 12. MSR values.

Figure 13. Resilient modulus test results.
As the results illustrate, WMA specimens showed better Marshall stability, resilient Modulus and ITS in both unconditioned and conditioned states than HMA specimens. This can be attributed to higher complex shear modulus for modified binders used in WMA mixtures. Moreover, the results specify better compatibility of SS aggregates with WMA-modified binders than base bitumen in terms of moisture resistance. Also, RB-type specimens generally showed better moisture resistance than SB- and HB-type specimens with the same aggregates. This implies a better cohesion, adhesion and aggregate-binder compatibility in RB-type specimens, which results in a better performance against moisture.

Although WMA specimens containing SS aggregates (SB- and RB-type specimens) showed lower Marshall stability, resilient modulus, ITS and fracture energy than WMA specimens containing LS (SC- and RC-type specimens), they showed better moisture resistance behaviour. This behaviour can be attributed to the factors: rough SS surface texture, dry and free of clay and contaminate SS aggregates and higher OBC that positively influence moisture resistance of WMA specimens containing SS aggregates (SB- and RB-type specimens). Thus, substitution of SS aggregates as the coarse portion of the lithic skeleton in WMA mixtures would lead to improvement in moisture resistance.
As the results show, although different conditioning methods and moisture resistance criteria were used in these test procedures, the results have nearly the same trends. The minor differences in obtained results can be attributed to different loading and conditioning mechanisms used in moisture susceptibility testing procedures, and can be referred to as the shortcomings of the experimental methods in evaluating moisture damage. Thus, provision for a unique test method and procedure in evaluating of moisture susceptibility of asphalt mixtures is the perquisite for an accurate engineering judgement.

Figure 16. TSR values.

Figure 17. Fracture energy values.

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

- Based on the XRF test results obtained in this research study, SS aggregates have lower alkalinity and lower affinity to bitumen than LS aggregates. Thus, SS aggregates have higher possibility of moisture damage.
- Based on the SEM images, SS has more rough and porous surface texture than LS, which leads to higher OBC and better coating of aggregates with binders.
better adhesion of SS to bitumen and improved moisture resistance.

- Based on FTIR test results, Sasobit- and Rediset-modified binders did not show any significant potential for moisture sensitivity.

- Based on moisture sensitivity tests results of the mixtures, replacing SS aggregate as coarse portion in the lithic skeleton of HMA mixtures did not improve moisture resistance while moisture resistance of WMA mixtures improved by using SS as coarse portion of aggregates. This is in spite of the lower adhesion and bitumen affinity of SS than LS.

- Based on the finding of this research study, WMA mixtures containing EAF steel slag as coarse portion of aggregates can be recommended for use in most developed and developing countries with increasing numbers of steel production industries and tropical regions with limited natural aggregate sources, great amount of annual construction, reconstruction and repairs of road pavements.

References


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