Experimental investigation of stone matrix asphalt mixtures containing steel slag

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Abstract Significant quantities of steel slag are produced as by-product every year from steel industries in Iran. Although it can be used as an artificial source of aggregates, it is 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 investigate the feasibility of utilizing steel slag aggregates in Stone Matrix Asphalt (SMA) mixtures. The results show that the use of steel slag as the coarse portion of aggregates can enhance Marshall stability, resilient modulus, tensile strength, resistance to moisture damage and resistance to the permanent deformation of SMA mixtures.

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1. Introduction

Stone Matrix Asphalt (SMA) is a hot mixture asphalt that was developed in Germany in the late sixties. SMA has been utilized in other European countries for more than two decades to provide higher rutting resistance as well as studied tyre wear [1]. Because of its success in Europe, the United States of America (USA) also launched the construction of SMA pavements in some states, in collaboration with the Federal Highway Administration [2,3]. Recent studies have shown that more than 28 states in the USA utilize SMA because of its increased durability, up to 20%–30%, compared to conventional mixtures [4].

SMA is a gap graded aggregate-asphalt hot mixture which maximizes the coarse aggregate fraction. Utilizing the SMA mixture provides us with a stable stone-on-stone skeleton that is held together by a rich mixture of asphalt cement, filler, and stabilizing additive [5].

SMA has shown high resistance to permanent deformation due to having a high coarse aggregate content which interlocks to form a stone skeleton [2]. Also, SMA has indicated enhanced durability as a result of higher bitumen content, and lower air voids content [3]. Other advantages associated with the use of SMA include high resistance to reflective cracking, improvement against aging and reduced traffic noise [6]. However, the main disadvantages of SMA mixtures are related to its binder drainage and higher primary cost [6]. Adding of a small quantity of fibers or polymer modifiers is recommended to prevent the drainage of binder during transport and placement [7]. A typical SMA mixture composition contains 70%–80% coarse aggregate, 8%–12% filler, 6.0%–7.0% binder, and 0.3% fibre [8].

Generally, two main sources of aggregate are used in construction projects: natural and artificial. In recent years, to conserve natural resources and to reduce environmental problems, material scientists and engineers have been encouraged to utilize artificial aggregates instead of natural ones.

Steel slag is a by-product of the steel making process. Previous studies have shown that the global amount of steel slag has been increasing rapidly. It should be noted in the text that in 2002, the total amount of steel slag produced was about 50 million tons, worldwide. But, in 2010, nearly 80 million tons of steel slag was produced in China alone [9]. By the continual expansion of the steel making industry in Iran, the quantity of produced steel slag in this country has sharply increased, as in other parts of the world. In Iran, most of the steel
slag produced in steel manufacturing facilities is discharged in landfills. Disposal of steel slag occupies a considerable portion of landfills and causes serious environmental problems.

This study aims to explore the feasibility of steel slag aggregates for SMA mixtures through laboratory studies, and compares the test results with mixtures containing natural aggregate. For this purpose, Marshall stability, moisture sensitivity, loss of Marshall stability, resilient modulus, and dynamic creep test were conducted on five different asphalt mixtures containing two types of steel slag and one type of natural aggregate (limestone).

2. Background

Utilization of steel slag in industrial projects is a valuable approach for technical, economical, and environmental reasons. Steel slag aggregates are highly angular in shape and have a rough surface texture. Processed steel slag has favorable mechanical properties for aggregate use, including good abrasion resistance, hardness, and high bearing strength [10]. Steel slag has been successfully used as aggregate in surface layers of pavements, as well as in unbound bases and subbases.

Asi studied the skid resistance of asphalt concrete mixtures containing steel slag [11]. The results showed that asphalt concrete mixtures containing 30% steel slag have the highest skid number, followed by Superpave, SMA, and Marshall mixtures, respectively. To investigate the feasibility of utilization of steel slag in asphalt concrete mixtures, Norman et al. performed Marshall and stability tests [12]. They concluded that the use of steel slag in asphaltic mixtures improved the mechanical properties of the mixes. The effectiveness of steel slag aggregates in asphalt mixtures was investigated by Bagampadde et al. [13]. They conducted resilient modulus, split tensile strength, stability, fatigue, and permanent deformation tests. The results indicated 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. Wu et al. studied the mechanochemical and physical changes of the steel slag utilized in SMA mixtures by performing XRD, SEM, TG and mercury porosimeter analysis and testing methods. The results showed that the utilization of steel slag in SMA mixtures is a new and cost-effective approach for aggregate resources [14,15]. Ahmedzade and Sengozb investigated the effectiveness of steel slag coarse aggregate in hot mix asphalt concrete mixtures [16]. They conducted Marshall stability, indirect tensile stiffness modulus, creep stiffness, indirect tensile strength, and electrical resistivity tests. In their study, it was demonstrated that steel slag used as a coarse aggregate improved the mechanical properties and electrical resistivity of asphalt mixtures. In our previous research, we investigated the properties of cold in-place recycling mixes containing steel slag as a substitute for virgin aggregates [17]. We performed Marshall stability, resilient modulus, tensile strength, and resistance to permanent deformation tests. The results indicated that the use of steel slag, along with anionic bitumen emulsion, can improve the mechanical properties of recycling mixtures.

The main problem associated with the use of steel slag is its volume expansion. There is general agreement in the technical literature that the hydration of free lime and magnesia is largely responsible for the expansive nature of steel slag aggregates [18]. Reacted with moisture, the hydration process commences and the aggregate’s volume increases. Ignoring this issue could result in pavement cracking. Aging and washing slag aggregates is an effective approach towards mitigating this problem [19]. Also, steel slag aggregate use should be limited to either coarse or fine aggregate, but not both [20].

3. Materials

3.1. Aggregate

This study included one type of limestone aggregate (as coarse, fine, and filler fraction) and two types of steel slag (as a substitute for the coarse or fine fraction of limestone aggregate). Limestone aggregate was obtained from a mine around Shiraz, Iran. Steel slag aggregates were obtained from Esfahan and Mobarake Steel manufacturing companies. Recommended by previous studies, to mitigate the expansion problem of steel slag, the aggregates were washed to accelerate the hydration process of free lime and magnesia. Furthermore, the aggregates were utilized after two years of disposal. The properties of the limestone and steel slag aggregates are presented in Table 1. Figure 1 shows the gradation limits for SMA mixtures. In this study, the selected gradation was in the middle of upper and lower limits.

3.2. Asphalt cement

The asphalt cement used in this study was obtained from the Tehran oil refinery. The asphalt was 60/70 Penetration Grade, which is a common asphalt regarding regional factors. Standard laboratory test results for asphalt cement are presented in Table 2.

3.3. Additive

Previous studies have shown that the use of additives in SMA mixes can prevent the drainage of binder. But, there is no universally accepted additive used in SMA mixtures. In this study, Stireen–Butadien–Stireen copolymer (SBS) was utilized as a modifier, since it has higher resistance to permanent deformation in comparison to other modifiers [7].

4. Specimen preparation

Commonly, the Marshall method is used for determining the optimum bitumen content in SMA mix design. Samples having 6 different bitumen ratios (5%–7.5%) were prepared at 0.5% increments. Three identical samples were produced for all alternatives. Since 75 compaction blows tend to break down the aggregate and do not cause a significant increase in density
Table 1: Properties of coarse and fine aggregates.

| Properties                  | Test method | Value       |
|-----------------------------|-------------|-------------|
|                             |             | Limestone   | Esfahan's steel slag | Mobarake's steel slag |
| Coarse aggregate            |             |             |                      |
| Bulk sp. gr. (gr/cm³)       | ASTM-C127  | 2.65        | 3.44                 | 3.51                 |
| Apparent sp. gr. (gr/cm³)   | ASTM-C127  | 2.69        | 3.63                 | 3.74                 |
| Water absorption (%)        | ASTM-C127  | 0.7         | 1.7                  | 1.6                  |
| L.A. abrasion (%)           | ASTM-C131  | 25.4        | 20.7                 | 19.5                 |
| Soundness, Na₂SO₄ (%)       | ASTM-C88    | 4.5         | 3.2                  | 2.4                  |
| Fine Aggregates             |             |             |                      |
| Bulk sp. gr. (gr/cm³)       | ASTM-C128  | 2.43        | 2.91                 | 2.98                 |
| Apparent sp. gr. (gr/cm³)   | ASTM-C128  | 2.77        | 3.68                 | 3.86                 |
| Plasticity index            | Non-plastic | Non-plastic | Non-plastic         |

Table 2: The results of tests performed on asphalt cement (AC 60–70).

| Test                        | Method | Unit     | Value |
|-----------------------------|--------|----------|-------|
| Specific gravity (25 °C)    | ASTM-D-70 | gr/cm³  | 1.016 |
| Flash point (Cleveland)     | ASTM-D-92 | °C      | 305   |
| Penetration (25 °C)         | ASTM-D-5 | 0.1 mm  | 64    |
| Ductility (25 °C)           | ASTM-D-113 | cm   | 100+  |
| Heating loss (163 °C)       | ASTM-D-1754 | %     | 0.03  |
| Heating loss pen/original pen | ASTM-D-5 | %       | 51.3  |
| Ductility after heating loss | ASTM-D-113 | cm   | 46+   |
| Softening point             | ASTM-D-36 | °C      | 50    |

Table 3: Summary of Marshall test results.

| Type of mixture | Optimum bitumen content (%) | Marshall stability (kN) | Marshall flow (mm) | Flow | Bulk density (gr/cm³) | VMA (%) | Void content (%) | MQ (kN/mm) |
|----------------|-----------------------------|------------------------|--------------------|------|-----------------------|---------|-----------------|------------|
| LL             | 5.9                         | 8.84                   | 3.34               | 2.341| 17.9                  | 3.72    | 2.65            |
| LE             | 6.6                         | 10.86                  | 2.95               | 2.520| 18.5                  | 3.51    | 3.68            |
| LM             | 6.7                         | 11.08                  | 2.89               | 2.486| 18.7                  | 3.48    | 3.83            |
| EL             | 6.1                         | 9.46                   | 3.17               | 2.421| 18.1                  | 3.64    | 2.98            |
| ML             | 6.1                         | 9.61                   | 3.16               | 2.437| 18.1                  | 3.65    | 3.04            |

5. Testing program

5.1. Marshall stability, flow and Marshall quotient

The Marshall properties of SMA mixtures were evaluated in this test, according to ASTM D1559. The Marshall Quotient (MQ), which is an indicator of resistance against deformation of the bituminous mixture, is also calculated. MQ values can be used as a measure of the material’s resistance to shear stresses, permanent deformation and rutting in service. Higher MQ values indicate stiffer and more resistant mixtures [22].

5.2. Indirect Tensile Strength (ITS) test

To evaluate the tensile properties of the asphalt concrete, a tensile strength test was performed. Outcomes of indirect tensile tests are often used to evaluate the relative quality of materials. This test involves loading a cylindrical specimen between...
two loading strips, which allows us to generate a relatively uniform tensile stress along the vertical diametrical plane. Failure usually occurs by splitting along this loaded plain [23]. The tensile strength of the specimens was determined by the following equation:

\[ ITS = \frac{2P_{ul}}{\pi D t} \]

where \( ITS \) is the tensile strength of specimens in kPa; \( P_{ul} \) is the ultimate applied load required to fail specimens in kN; \( D \) is the diameter of the specimen in mm; \( t \) is the thickness of the specimen in mm. To perform the ITS test, five specimens with optimum bitumen content were prepared for each SMA mixture mentioned in Section 3.

5.3. Moisture susceptibility and loss of Marshall stability

The moisture susceptibility of asphalt mixtures was evaluated by performing the AASTHO T283 Test. This test was carried out in order to find the water susceptibility (stripping resistance) of mixtures utilizing Indirect Tensile Strength (ITS). To follow the test, the six samples from each mixture were prepared. Three of them were selected to be conditioned by vacuum saturation (at 55%–80% saturation level), followed by a freeze cycle (for 16 h at a temperature of \(-18^\circ\)C), and subsequently having a warm-water soaking cycle (60 °C water bath for 24 h). The other three samples from each mixture were selected as unconditioned samples and tested without moisture conditioning. The samples were then tested for indirect tensile strength.

The indirect Tensile Strength Ratio (TSR) was then calculated using the following equation:

\[ TSR = \frac{S_{con}}{S_{dry}} \times 100 \]

where \( S_{con} \) is the average indirect tensile stress of conditioned samples, and \( S_{dry} \) is the average indirect tensile stress of unconditioned (dry) samples. There is no universally accepted minimum TSR value for SMA mixtures. Alabama Department of Transportation specifies a minimum TSR of 0.8 for SMA, but there are some other agencies which allow 0.7 [24,25].

In order to study the loss of Marshall stability, six samples from each mix were immersed in the water bath at a temperature of 60 °C. The Marshall stability values for three samples from each mixture were recorded after 40 min of water immersion. These samples were named as unconditioned samples. The other three samples of each mixture were tested after 24 h immersion in a water bath. These samples were named as conditioned samples. The Marshall Stability Ratio (MSR) was then found using the following equation:

\[ MSR = \frac{MS_{con}}{MS_{mean}} \times 100 \]

where \( MS_{con} \) is the average Marshall stability for conditioned samples, and \( MS_{mean} \) is the average Marshall stability for unconditioned samples.

5.4. Resilient modulus

Resilient modulus (\( M_R \)) is the most important parameter used in the mechanistic design of pavement structures. It is the measure of pavement response in terms of dynamic stresses and corresponding strains. Methods based on elastic theory require elastic properties of pavements as input. The resilient modulus of bituminous mixes, determined in accordance with ASTM D4123 method, is the most popular form of stress–strain measurement used to evaluate the elastic properties of asphaltic mixtures [7]. Five specimens with optimum bitumen content were prepared for each SMA mixture mentioned in Section 3. The tests were conducted at 25 °C.

5.5. Dynamic creep test

There are various methods for determining asphalt mixture rutting; Marshall test, static creep test, dynamic creep test and the wheel tracking test. In this study, the dynamic creep test was performed to determine the rutting potential of SMA mixtures. The Dynamic Creep Test applies a repeated pulsed uniaxial stress on an asphalt specimen and measures the resulting deformations in the same direction using Linear Variable Differential Transducers (LVDTs).

Different types of mixture at the dosage of optimal bitumen content were tested for dynamic creep test by the Universal Testing Machine (UTM) at 40 °C. 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 s. Then, the conditioning stress was removed, a stress of 100 kPa was applied for 10,000 cycles with 500 ms loading and 500 ms rest period, and the axial deformation was measured using LVDT.

6. Results and discussion

6.1. Marshall stability, flow and Marshall quotient

The results of the Marshall test are shown in Table 3. The presented results are the average of three specimens which are prepared in optimum bitumen content. The results indicate that the use of steel slag in SMA mixtures can enhance the Marshall properties of mixtures. The maximum average stability value of the mixture prepared with limestone was 8.84 kN. However, the use of steel slag in preparation of Marshall specimens resulted in increased values of Marshall stability. Also, MQ values increased in mixtures that contained steel slag. The use of steel slag as coarse portion of SMA mixtures resulted in an increase in MQ values of 39% and 45% as compared to samples that contained limestone in their coarse portion. The reason could be due to the hardness of slag aggregates. MQ is an indicator of the resistance against the deformation of the asphalt concrete. High MQ value indicates a high stiffness mixture with a great ability to resist creep deformation. Therefore, the use of steel slag in SMA mixtures provides a positive contribution to the overall performance of asphalt pavements.

6.2. Indirect Tensile Strength (ITS) test

The typical values of the indirect tensile strength of five mixtures obtained from this study are shown in Figure 2. Table 5 shows the VMA and air void content of mixtures prepared for indirect tensile strength tests. It can be seen that all of the mixtures containing steel slag aggregates have higher values of tensile strength at failure, and indirect tensile strength under static loading. In addition, there is a substantial improvement in the resistance to permanent deformation of mixtures containing steel slag in their coarse portion. The indirect tensile strength of mixtures containing limestone is approximately 690 kPa, whereas the mixtures containing steel slag in their coarse portion have an indirect tensile strength up to 833 kPa. This is probably because of the high air void content of limestone mixtures. It is believed that a high air void content causes the mixtures to have higher deformation and lower strength. In addition, this would further imply that these mixtures appear to be capable of withstanding larger tensile stresses prior to cracking.
Table 5: VMA and void contents of mixtures prepared for indirect tensile strength test.

| Type of mixture | VMA (%) | Void content (%) |
|-----------------|---------|------------------|
| LL              | 17.1    | 3.52             |
| LE              | 18.6    | 3.33             |
| LM              | 17.9    | 3.24             |
| EL              | 18.1    | 3.27             |
| ML              | 18.3    | 3.44             |

Figure 2: Results of tensile strength tests.

6.3. Moisture susceptibility and loss of Marshall stability

Marshall stability and indirect tensile values for both conditioned and unconditioned samples are given in Table 6. MSR and TSR values are also indicated in Table 6. It is clearly evident that the retained stability (MSR) increases in the mixtures containing steel slag as their coarse portion of aggregate. Obtained TSR values for all mixes were well above the limit value (0.7). The highest TSR value was achieved for LM and LE mixes. These mixtures have the highest bitumen content, having utilized steel slag as their coarse portion. Both MSR and TSR values confirm the strong affinity between steel slag and binder in LM and LE mixtures. Also, they indicate that the use of steel slag in the coarse portion of SMA mixtures can improve resistance to moisture damage of SMA mixtures.

Table 6: MSR and TSR values of the mixtures.

| Type of mixture | Marshall stability (kN) | Tensile strength (kN) | MSR | TSR |
|-----------------|-------------------------|-----------------------|-----|-----|
|                 | Unconditioned           | Conditioned           | Unconditioned | Conditioned | Unconditioned | Conditioned |
| LL              | 8.5                      | 7.0                   | 693.3 | 513.0 | 0.83         | 0.74         |
| LE              | 10.4                     | 9.2                   | 834.5 | 700.0 | 0.88         | 0.84         |
| LM              | 10.7                     | 9.5                   | 815.2 | 676.6 | 0.89         | 0.83         |
| EL              | 9.1                      | 7.6                   | 712.8 | 563.1 | 0.84         | 0.79         |
| ML              | 9.2                      | 7.7                   | 723.3 | 549.7 | 0.84         | 0.76         |

Figure 3: Results of resilient modulus tests.

6.5. Dynamic creep test

The VMA and air void content of mixtures prepared for dynamic creep tests are shown in Table 7. Figure 4 presents the dynamic creep test results for different types of mixture. This figure indicates the relationship between permanent deformation and the number of load cycles for five types of mixture. It is seen that SMA mixtures prepared with limestone aggregate experienced higher creep value than those prepared using steel slag. The results of dynamic creep tests show that the application of steel slag as the coarse portion of aggregates in SMA mixtures leads to lower rut depth. This could be attributed to the hardness and high bearing strength of steel slag aggregates. Since the steel slag aggregate is rougher than limestone aggregate, the mechanical interlock between asphalt and steel slag aggregate will be higher, leading to higher resistance to creep.

Figure 4: Dynamic creep test results.
7. Conclusion

In this paper, the feasibility of utilizing steel slag as aggregate in Stone Mastic Asphalt (SMA) mixtures is researched. On the basis of the data obtained in this study, the following conclusions are made:

1. According to the results obtained from Marshall stability, indirect tensile strength, and resilient modulus tests, it should be noted that mixtures with steel slag have shown encouraging results in comparison with those containing limestone. Also, replacing the coarse portion of limestone aggregate with steel slag leads to better results in comparison with mixtures that contain steel slag as the fine portion. Steel slag used as the coarse portion in SMA mixtures increased Marshall stability and decreased flow values. Hence, mixtures with steel slag coarse aggregate have higher MQ values, which is an indicator of high stiffness and resistance to permanent deformation.

2. MSR and TSR values obtained from the loss of Marshall and moisture susceptibility tests, respectively, indicated that utilizing steel slag as the coarse portion of aggregates can enhance the resistance of mixtures to moisture damage.

3. Dynamic creep test results indicated that mixtures containing steel slag as the coarse portion are more resistant to permanent deformation and have lower rut depth.

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