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Evaluation of electric arc furnace steel slag coarse aggregate in warm mix asphalt subjected to long-term aging

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HIGHLIGHTS

- Aging indices were defined for evaluation of specimens aging.
- The use of EAF steel slag improved tensile strength and resilient modulus.
- Moisture resistance of WMAs containing steel slag were similar to HMAs with limestone.
- Mixtures containing EAF steel slag showed higher aging.

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ABSTRACT

Considering the sustainable development principle, it seems necessary to reduce the temperature demands in producing asphalt mixtures and to replace mineral aggregates with secondary materials. In this study, the long-term performance of warm mix asphalt containing electric arc furnace steel slag was investigated. For this, Marshall Stability, resilient modulus at 25 °C and 40 °C, indirect tensile strength and moisture susceptibility tests were conducted. In the last stage, the ratio between the results of long-term and short-term aging of these tests was presented as an aging index. Using warm mix asphalt and replacing mineral aggregates with steel slag aggregate cause Marshall Stability, stiffness, resilient modulus and indirect tensile strength to increase. Although the tests conducted in this study indicate that using steel slag results in increased aging of the asphalt mixtures, warm asphalt mixtures containing steel slag experience less aging compared to control specimens (hot mix asphalt with limestone). Therefore, warm asphalt mixtures containing steel slag exhibit enhanced short-term and long-term performance as well as less aging. Hence, utilizing warm mix asphalt containing steel slag is generally recommended.

1. Introduction

Transportation significantly contributes to the environmental pollution. Roads and their pavements as indivisible parts of transportation possess the same importance. Strategies to reduce pollution and protect the environment during the production of asphalt mixtures can be classified into the following categories:

a) Reducing the temperature of mixing and compacting of asphalt mixtures.
b) Replacement of mineral aggregates with by-products.
c) Improving the bearing capacity of asphalt mixtures and thereby reducing road asphalt volumes due to decreases in pavement thickness.
d) Use of special additives to improve durability and to extend the life of asphalt pavements.
e) Use of recycled products.
f) Development of inexhaustible and non-polluting new energy sources.
g) Use of renewable natural resources and synthetic adhesive binders as replacements for asphalt binders [1].

Reduced mixing temperature has led to considerable energy conservation in the construction of asphalt pavements as less than 50% of the total energy consumption occurs during mixing and drying aggregates [2]. Warm Mix Asphalt (WMA) technologies can help reduce the temperature of mixing and compacting of asphalt

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mixes. This objective is accomplished by either lowering the viscosity of the asphalt binder or improving the workability of the asphalt mix at temperatures lower than those used to produce traditional Hot Mix Asphalt (HMA) [3]. The sustainability of WMA technology is highlighted by the fact that each 10 °C reduction in asphalt mix production temperature decreases fuel oil consumption by 1 L and CO_2 emission by 1 kg per ton, according to world bank estimates [4]. Also, lowering the production temperature allows reducing the energy consumption up to 35% or more depending on the WMA process applied [5] and on how much the temperature is reduced [6]. Hurley and Prowell explained that the aggregate type and its interaction with binder grading as well as the type of warm mix additive are important parameters which influence the performance of WMA [7]. Moreover, the physical properties of coarse and fine aggregates have a significant effect on the performance of pavement [8].

Due to the limited natural resources and decreasing mineral aggregates on the one hand and the large-scale production of steel slag on the other hand (approximately fifty million tons of steel slag is produced per year as a by–product in the world) [9], the use of steel slag as an alternative to mineral aggregate seems reasonable, provided that its use does not have significant negative effect on the performance of asphalt mixtures. Depending on the type of metal and the implementation of manufacturing operation, steel slag is a by-product of steel making process that can be categorized as Electric Arc Furnace (EAF), Basic Oxygen Furnace (BOF) and Blast Furnace (BF). Of these categories, EAF steel slag is the common type used in road construction.

Numerous research have been undertaken to investigate the possibility of replacing mineral aggregates by steel slag as well as assessing the effects of this slag on the performance of HMA and WMA mixtures, the results of some of which will be cited in following parts.

Kara et al. stated that physical properties of steel slag satisfied the requirements in order to be used in asphaltic mixtures [10], but aggregates should not be completely replaced by steel slag as the asphalt mix with 100% steel slag is highly susceptible to bulking and air voids problems due to its angular shape [11].

The influence of utilization of steel slag as a coarse aggregate on the properties of HMA was investigated by Ahmedzadeh and Sengoz. Their observations indicated that the use of steel slag as a coarse aggregate improved the mechanical properties of asphalt mixtures, but increased the optimum binder percentage [12].

Ameri et al. used steel slag as both a fine and coarse portion of aggregate gradation in HMA mixtures and as coarse portion of aggregate gradation in WMA mixture. Among these mixes, HMA mixtures in which fine aggregate was replaced by steel slag had the lowest resilient modulus and indirect tensile strength. In their study, laboratory tests results indicated that the use of coarse steel slag aggregate in WMA mixture enhanced Marshall Stability, Resilient Modulus (MR), Indirect Tensile Strength (ITS), resistance to moisture damage and resistance to permanent deformation of the mixture and thus they recommended the use of coarse electric arc furnace steel slag aggregate for the production of WMA mixture [13].

Kavussi and Qazizadeh investigated the fatigue behavior of asphalt mixes with different percentages of EAF steel slag (25%, 50%, 75%, 100%, purely steel slag and also limestone as the control sample) as coarse aggregate in both aged and unaged conditions. For this purpose, they used a four-point bending beam fatigue test. Their studies showed that although the inclusion of EAF in mixes improved fatigue life of samples, this parameter did not change appreciably in aged specimens [14].

The long-term performance of asphalt mixes is a very important indicator of their economic and environmental assessments. As the WMA is a relatively new technology, few studies have been conducted on long-term aging of warm mix asphalt mixtures containing EAF steel slag. Therefore, it is important to study their long-term performance in the laboratory to predict the behavior of these mixtures in the field.

This research primarily attempts to examine the long-term performance of WMA mixes containing EAF steel slag. Therefore, in this research, limestone and EAF steel slag were used for construction of HMA and WMA specimens, considering the short and long term aging. In the last stage, Marshall, ITS, MR and moisture susceptibility tests were conducted on all specimens and aging indices were reported.

2. Materials and experimental procedures

One aggregate gradation with two different aggregates has been used in this research. In the first type, the aggregate gradation is comprised of limestone while in second type, steel slag is used as a coarse aggregate ($\geqslant$ 4.75 mm) and limestone as both fine aggregate and filler. Depending on the aggregate and the mixing temperature, four types of asphalt mixtures used in this study are listed in Table 1. The asphalt binder utilized to prepare both HMA and WMA mixtures was a PG 64-22 (60/70 penetration grade) from the refinery of Isfahan. The major properties of this binder are reported in Table 2.

Limestone used in this study was obtained from a quarry located in eastern Isfahan while EAF steel slag was produced in Mobarakeh steel complex in Isfahan. Table 3 gives the engineering properties of the aggregates used.

Chemical and mineralogical composition of the aggregate plays an important role in the way mixtures behave. For this, the chemical properties of limestone and steel slag were determined via applying XRF (X ray fluorescence) testing method, the results of which are presented in Table 4.

As is shown in Fig. 1 the aggregate gradations used in this study was fitted in the median limits of ASTM D3515 [15] specifications for dense asphalt mixtures.

2.1. Sample preparation

To construct warm asphalt mixtures, 1.5% sasobit by weight of asphalt binder has been added to the mixtures. To mix the binder

Table 1
Properties of asphalt mixtures.

Type of mixture	Abbreviation	Mixing temp. (°C)	Compaction temp. (°C)
HMA with limestone as a fine and coarse aggregate	HL	155	135
HMA with steel slag as a coarse aggregate and limestone as a fine aggregate	HS	155	135
WMA with limestone as a fine and coarse aggregate	WL	135	115
WMA with steel slag as a coarse aggregate and limestone as a fine aggregate	WS	135	115

Table 2
Properties of asphalt binder.

Test	Standard	Result
Specific gravity @ 25 °C (g/cm^3)	ASTM D70	1.019
Penetration @ 25 °C (0.1 mm)	ASTM D5	64
Softening point (°C)	ASTM D36	49.7
Ductility @ 25 °C (cm)	ASTM D113	100<
Flash point (°C)	ASTM D92	311
Dynamic viscosity @ 60 °C (P)	ASTM D2171	1840
Kinematic viscosity @ 135 °C (cSt)	ASTM D2170	342