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Recycling of RAP and steel slag aggregates into the warm mix asphalt: A performance evaluation

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HIGHLIGHTS

- RAP improves moisture sensitivity and resilient modulus of WMA mixes.
- No specific trend is detected for influence of steel slag on moisture sensitivity.
- Steel slag improves resilient modulus especially at high temperatures.
- RAP- and/or slag-incorporated mixes have a lower rutting potential.
- Incorporating RAP and/or steel slag into the WMA enhances fatigue resistance.

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ABSTRACT

Incorporation of electric arc furnace (EAF) steel slag aggregates in asphalt mixes boosts their performance, but the high bitumen consumption is the primary obstacle that hinder their widespread application. To remove this barrier this research investigates the effects of concurrent recycling of reclaimed asphalt pavement (RAP) and steel slag aggregates into the warm mix asphalt (WMA) mixes. To this end, six types of WMA asphalt mixes with two coarse steel slag contents (0% and 40%) and three fine RAP contents (0%, 20% and 40%) were prepared and their moisture resistance, resilient modulus, dynamic creep and fatigue behavior were evaluated and statistically were compared to each other. Results showed that contrary to the steel slag, RAP clearly improves resistance to moisture damage of mixes. The addition of RAP to the WMA also increases the resilient modulus at all the temperatures; however, addition of steel slag only at intermediate and high temperatures leads to improvement in the resilient modulus. Nonetheless, sensitivity of resilient modulus to the temperature decreases with incorporation of both marginal materials. Moreover, it is found that adding RAP and/or steel slag significantly improves the number of cycles that the asphalt mix can tolerate in both dynamic creep and indirect tensile fatigue tests (ITFT). In addition, it is demonstrated that the fatigue behavior of RAP- and/or slag-incorporated mixes has a lower sensitivity to stress level, with the exception of mixes containing 40% coarse steel slag along with 40% fine RAP materials. Overall, simultaneous incorporation of steel slag and RAP materials into the WMA is proven to be an economic and environment-friendly option with a comparable or even better performance with respect to conventional WMA.

1. Introduction

Nowadays, many countries try to fulfil the principles of sustainable development, which aims to recycle waste materials and reduce energy consumption. In this context, various marginal materials such as: recycled concrete, crumb rubber, plastic bottles, copper slag, waste glass, steel slag, and reclaimed asphalt pavement (RAP) have been successfully recycled in asphalt mixes and in some cases, improved the behavior of conventional asphalt mixes [1–7].

Electric arc furnace (EAF) steel slag, is the co-product of steel-making factories whose global production rate is about 50 million tons per year [8]. The application of steel slag in road construction is profitable as it reduces the consumption of non-renewable aggregates. Moreover, this application releases huge spaces occupied by the disposal of this material in landfills [9]. The peculiar properties of steel slag aggregates such as rough texture, broken faces, and angular shape have encouraged pavement engineers to

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use this material in order that asphalt mixes can attain higher stability and skid resistance [6,10]. In addition, steel slag aggregates have shown excellent results in polish resistance tests, which means that surface courses made with them keep their friction over time [9]. This result also confirmed in field studies reporting that sections made with steel slag have equal or better skid resistance and macro texture than sections made with conventional asphalt mix [10–12]. However, steel slag aggregates have irregular shape and porous texture, which slightly degrade the workability of asphalt mix [13] and absorb high amount of binder in their porosities and hence, the consumption of binder increases [6]. Concurrently, a reduction in rutting resistance and a remarkable increase in binder consumption have been reported in the literature with the use of fine steel slag aggregates in HMA mixes [6,14]. Therefore, studies have preferred to only deal with the coarse part of steel slag aggregates to tackle costs [15]. Another concern about steel slag aggregates is the presence of free CaO and MgO in their chemical composition [16]. If these components are hydrated, they result in volume increase and pavement cracking [17]. To overcome this problem, steel slag aggregates should be exposed to weather for at least six months before recycling them into the asphalt mixes [18]. Another obstacle that may bridle the wide application of steel slag aggregates in asphalt mixes is the costs of delivering this material to asphalt producers [15]. Recently, results of a life cycle assessment (LCA) performed to compare conventional and slag-incorporated mixes with regard to all the environmental impacts have revealed that the latter option is economic, even with 160 km of delivery distance [9].

RAP is produced during the rehabilitation and reconstruction of asphalt surfacing [19]. For years, using RAP in unbound granular layers of pavements was a common practice [20]. However, in addition to aggregates, RAP also contains binder; therefore, recycling RAP into the bituminous layers is more beneficial, at least in terms of economy. Nonetheless, incorporating high percentages of RAP materials into hot mix asphalt (HMA) leads to problems with durability, workability, and stiffness [21]. Asphalt mixes with low workability are difficult to compact and to achieve desired density. Bahia et al. proposed to use the energy needed to compact the asphalt mixture by Superpave gyratory compactor between N**ini** and 92% of maximum theoretical specific gravity as an index for assessing the workability of asphalt mix [22]. In a laboratory study Kusam et al. used this criteriation and showed that the workability of HMA significantly decreases as RAP content increases. They suggest to use a softer virgin RAP or WMA foam technology to overcome this problem [21]. Considering these problems, the application of RAP in HMA mixes has been limited to 15% without any changes in the grade and content of virgin binder [23]. Conversely, warm mix asphalt (WMA) has the potential of using higher amounts of RAP content without compromising the performance [24] because WMA technologies help maintaining the workability of the mixtures when RAP is added [25]; furthermore, the energy needed and emissions generated during production are significantly reduced [26]. Moreover, while the high stiffness of combined binder in RAP-incorporated WMA results in a higher rutting resistance [27], it may lead to lower fatigue and thermal cracking resistance [7,28].

High RAP mixes also showed satisfactory performance in field. Timm et al. statistically compared the result of strain responses obtained from instruments embedded below the asphalt mix layers in NCAT test track and revealed that RAP-WMA sections outperform control and even RAP-HMA sections particularly at high temperatures (e.g., 40 °C) [29]. Another study on the data obtained from the same test track showed that sections made with up to 45% RAP demonstrate very good result, with respect to rutting resistance, raveling and international roughness index; nevertheless, the section made with 45% RAP and Sasobit® had moderate reflect cracking, while control section had no cracking [30].

To the best of our knowledge, previous works have only focused on the effects of steel slag or RAP materials on the performance of asphalt mixes, and the influences of using both these materials in WMA have received little, if any, attention in the literature. Furthermore, by considering the characteristics of these materials, it can be hypothesized that their simultaneous incorporation in WMA can lead to a mix that is economic and environment-friendly, and whose performance is expected to be equal to or better than that of conventional WMA. To this end, six types of WMA with different proportions of coarse steel slag aggregates and fine RAP materials were prepared, their moisture susceptibility, resilient modulus, dynamic creep, and fatigue behavior were tested, and the effect of each factor as well as the correlation between them analyzed, as discussed in the following sections.

2. Materials and methods

Neat bitumen, limestone aggregates, EAF steel slag aggregates, RAP, and Sasobit® were used to produce asphalt mixes in this research. The neat bitumen had a penetration and ductility of 64 dmm and 103 cm at 25 °C, respectively, and the softening point of 48 °C. These values were 35 dmm, 22 cm and 56 °C for the extracted bitumen of RAP, and the binder content of fine RAP particles was 6.1%. Table 1 lists the basic properties of aggregates considering sieve No. 4 as a cutoff between fine and coarse aggregates. Table 2 presents the chemical components of steel slag and limestone aggregates, which were analyzed by the X-ray Fluorescence Spectrometer (XRF) test. Notably, the amount of free Cao in steel slag was 0.2%, far less than 5%, which was reported for newly produced steel slag [31], implying the fact that the weathering process was conducted adequately for this material and concerns regarding expansion potential that is commonly considered for steel slag aggregates would not be an issue.

Sasobit® is a well-known commercial additive that has extensively been used for the production of WMA in recent years. It contains long-chain aliphatic hydrocarbon manufactured during the gasification of coal through the Fischer–Tropsch (FT) process, which thoroughly melts in binder at 115 °C and significantly reduces its viscosity, thereby providing the potential for reduction in the mixing and compacting temperatures of the asphalt mix up to 20–30 °C [32].

2.1. Mix design and specimen preparation

Fig. 1 presents the target aggregate size distribution that was chosen within the upper and lower limits specified by Iran Highway Asphalt Paving Code for nominal maximum aggregate size of 19 mm [33] along with the particle size range of the aggregates recovered from RAP materials. As illustrated in Fig. 1, the ratio of coarse to fine aggregates is exactly 4:6, and RAP materials are No.4 sieve screened. Table 3 presents the volume proportion of aggregates in six types of mixes with different combinations of limestone, steel slag, and RAP. As coarse steel slag aggregates (size above 4.75 mm) have significantly different specific gravity from limestone aggregates (Table 3), they were sieved into individual portions and were replaced with exactly the same volume gradation of limestone aggregates. In contrast, sieving RAP materials into individual sizes would lead to inaccurate gradation due to the presence of aged bitumen around aggregates along with the existence of agglomerated particles in RAP materials. In addition, as shown in Fig. 1, the gradation of extracted RAP aggregates was slightly different from the target aggregate distribution. Hence, in mixes containing RAP, the limestone served to fill the gaps in order to achieve a single aggregate distribution.

The mixing and compaction temperatures were selected 135 and 125 °C, and Sasobit® was introduced directly into the mix with the dosage rate of 1.5% of bitumen weight based on its manufacture's recommendations [32].

Limestone and steel slag were placed in an oven at 135 °C for at least four hours prior to the mixing; however, based on NCHRP recommendation, RAP materials were placed in the oven for only two hours at 110 °C to avoid further ageing [34]. Meanwhile, the bitumen was separately heated to the mixing temperature. The desired proportions of these materials with the required amount of Sasobit® were mixed and then the loose mix was compacted with a Marshall hammer.

The optimum bitumen contents (OBC) of control and slag-incorporated (C and S**4**) mixes were determined using the standard Marshall design method, following ASTM D-6927 [35]. The loose mixes were poured into a 102-mm cylindrical mold and each side of them was subjected to 75 blows of standard Marshall hammer. Three specimens were fabricated in each bitumen content to enhance reproducibility then Marshall stability, flow, bulk specific gravity, and volumetric characteristics of specimens were determined. The OBC was determined to be 5.1 and 5.8% for control and S**4** mixes, respectively, to achieve 4% air void content in the mix. The virgin binder that has to be added to other mixes was determined using Eq. (1) [27].