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Engineering properties and performance of asphalt mixtures incorporating steel slag

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HIGHLIGHTS

- We characterize the engineering properties of asphalt mixtures mixed with BOF.
- We construct a test road to compare the field performance of BOF test sections.
- We discuss construction practices of BOF test sections.
- We evaluate performance of BOF test sections.

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ABSTRACT

Lack of natural stone and costly expense of purchasing high-quality aggregate promote the utilization of steel slag. Asphalt mixtures incorporating basic oxygen furnace (BOF) steel slag as coarse aggregate were prepared and subsequently subjected to laboratory tests to determine the engineering properties of asphalt concrete. Results showed that the addition of steel slag into asphalt mixtures had high resistance to permanent deformation and moisture-induced damage. Steel slag included angular and rough textured particles that would enhance the interlocking mechanism and provide good mechanical properties. According to the laboratory results, a test road was constructed in 2012 by using three different types of asphalt mixtures as follows: stone mastic asphalt with BOF (SMA-BOF), dense-graded asphalt concrete with BOF (DGAC-BOF), and dense-graded asphalt concrete with natural aggregate (DGAC-NA). The rut depth of the SMA-BOF section was lowest among the three sites even though it was subject to high stress induced by braking, accelerating and turning vehicles. Surveys for pavement performance were conducted at scheduled intervals. The ride quality and the friction characteristics of both BOF sections performed as well as or better than the section constructed using natural aggregate. Field data indicated that steel slag could be used as a surface course aggregate in locations where traffic is expected to perform heavy braking and cornering maneuvers. No rutting, cracking, or other failures have been observed to any significant extent on the BOF sections since they opened to traffic throughout the three-year period. Test results suggest that the use of steel slag as coarse aggregate substitute in surface courses be technically appropriate.

1. Introduction

The properties of the aggregates used in asphalt mixtures have a direct influence on pavement performance. Aggregates for asphalt mixtures should also be resistant enough to bear production, transportation and construction processes, as well as traffic loads and climate effects. When an asphalt mixture is designed, it is normally recommended that angular and rough-surfaced aggregates are selected, since they tend to improve resistance to permanent deformation of the mixture. Lack of good quality of natural crushed aggregate promotes the use of steel slag. The industrial by-products from the metallurgical industry have been applied to base and surface courses in the road structure since 1980's [1–4]. Steel slag is produced in a basic oxygen furnace (BOF) or an electric arc furnace. It is estimated that between 7.0 and 7.5 million metric tons of steel slag are produced each year in the U.S. [3]. BOF steel slag is the largest amount of secondary resources produced by integrated steel mills. Most of BOF steel slag has been recycled in developed countries. For instance, about 1.5 million metric tons of BOF steel slag produced in Germany are used as an aggregate material in construction applications

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annually [4]. Approximate 97% of BOF steel slag is recycled in the same ways in the U.K. [5].

BOF steel slag, a by-product of the conversion of pig iron to steel, has existed since the development of the oxygen converter in the 1950s. BOF steel slag is one the main by-products of an integrated steel plant with rates amounting to around 100 kg per metric ton of steel [4,5]. The slag primarily contains calcium silicates together with oxides and compounds of iron, manganese, alumina and other trace elements. It was first used in agriculture as a soil amendment to neutralize soil acidity, stabilize soil structure, and increase plant resistance, but its main valorization has concerned road works [6–12].

Nevertheless, two factors negatively affect the widespread use of BOF steel slag: its possible expansion and its relatively high specific gravity (often between 3.2 and 3.6), which is due to a certain amount of iron oxides it contains. This leads to some issues for the transport of the material and thus limits the geographical zone where it can economically be used. The second problem with BOF concerns the expansion of the material, which is attributed to the hydration of free lime in the form of calcium and magnesium oxides. The use of steel slag in asphalt mixtures could generally result in a binder film coating the steel slag and limiting potential expansion [2,6,7]. Furthermore, few studies of its use may have discouraged highway engineers from better understanding the engineering properties and performance of asphalt mixtures incorporating BOF steel slag.

This study was motivated by concerns that asphalt pavements mixed with BOF steel slag might not perform well under environmental and traffic conditions. It was concerned that the rut resistance, friction, and durability benefits of hot-mix asphalt mixtures with BOF would be lost due to demanding and heavily trafficked situation at high risk sites such as junction and crossing approaches. Prior to this study, little research has been performed on the performance of asphalt mixtures incorporating BOF steel slag as a surface course aggregate. The use of less traditional secondary materials in road construction requires the assessment of their physical and mechanical performance to ensure that the structures built using them are durable and sustainable. Long-term performance, however, especially the influence of steel slag under field conditions, is often difficult to predict. All aspects of using BOF steel slag in asphalt pavements will be evaluated, including:

- Evaluate the effect of steel slag on the engineering properties of hot-mix asphalt mixtures in the laboratory,
- Construct a test road to compare the field performance obtained from the use of steel slag and the use of traditional aggregate, and
- Compare the field performance of asphalt pavements constructed with steel slag with that of a test section constructed with conventional aggregate.

2. Materials

2.1. Aggregate and binder

Two types of aggregate were used as follows: limestone obtained from the Kao-Ping River, and BOF steel slag supplied by the CHC Resources Corporation. Steel slag was stockpiled outdoors for three months to expose the material to moisture from natural precipitation. The purpose of aging was to allow potential hydration and its associated expansion to take place prior to use of BOF steel slag in asphalt mixtures. The mechanical properties of BOF steel slag and natural aggregate are summarized in Table 1. Steel slag was employed in this study to replace the coarse faction of hot-mix asphalt mixtures (HMA). Coarse aggregate must be strong because it is primarily responsible for carrying traffic loads in an HMA mix. The Los Angeles abrasion value of coarse aggregate should be less than 30% to possess sufficient toughness. BOF steel slag possessed a better LA abrasion value than natural aggregate. Flat and elongated proportions must be limited to be a maximum value. Both BOF steel slag and limestone met the current criteria of no more than 15 percent 3–1 and no more than 5 percent 5–1 flat and elongated particles. Steel slag is highly angular in shape, and tends to be cube-like with very low percentages of flaky and elongated particles.

Table 1
Mechanical properties of BOF steel slag and limestone.

Type	Tests	BOF (%)	Limestone (%)	Spec. (%)
Coarse aggregate	LA Abrasion	11	25	<30
	Flat and elongated 3:1	4	14	<15
	Flat and elongated 5:1	1	4	<5
	Absorption	1.8	1.1	<2
	Soundness	4.2	5.6	<12
	One fracture face	100	100	100
	Two fracture faces	100	93	>90
	Dry bulk specific gravity	3.41	2.62	–
Fine aggregate	Soundness	na	7.9	<15
	Sand equivalent value	na	94	>50

Note: na = not applicable because BOF was only used as coarse aggregate in this study.

Coarse aggregate is required to provide fracture faces with high internal friction to carry the load. If the crushed content is significantly less than 100% for the coarse aggregate, an HMA mix is likely to be less resistant to shoving and rutting. Although BOF and natural aggregate were 100 percent crushed, steel slag had more fracture and rough surfaces that would be beneficial to provide microtexture and interlocking mechanism. The most significant difference between BOF and natural aggregate is its high specific gravity, which is a consequence of the presence of iron compounds in BOF. The dry bulk specific gravity of BOF and limestone used in this study was 3.41 and 2.62, respectively. The binder employed in this study was grade AC-20 according to ASTM D 3381. This material, supplied by the China Petroleum Cooperation, is the usual bitumen grade used for asphalt pavements in Taiwan. The selection of AC-20 cement is to emphasize the performance of steel slag used as coarse aggregate in asphalt mixtures.

2.2. Asphalt mixture design

A total of three mix designs were performed as follows: stone mastic asphalt with BOF (SMA-BOF), dense-graded asphalt concrete with BOF (DGAC-BOF), and dense-graded asphalt concrete with natural aggregate (DGAC-NA). The master aggregate gradation bands listed in Table 2 were based on the field test road selected. The 19-mm maximum aggregate size gradation is gapped on the 4.75-mm sieve for SMA mixtures. The percentage of mineral fillers used for SMA mixtures was 9.5 percent. The job mix formula was decided using the Marshall mix design method to determine the volumetric properties of the asphalt mixtures. The asphalt content of all mixtures was determined as that resulting in 4% air voids.

Both the control mix (i.e., DGAC-NA) and the slag mix (i.e., DGAC-BOF and SMA-BOF) were fabricated by the Marshall mix design procedure according to ASTM D1559. The Marshall compactor was used to compact the DGAC samples 75 times each side, but 50 times each side for the SMA samples. The optimum binder content was determined to be 5.1%, 4.3% and 5.2% for DGAC-NA, DGAC-BOF and SMA-BOF mixtures, respectively. The bulk specific