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Effect of hydration and silicone resin on Basic Oxygen Furnace slag and its asphalt mixture

Zongwu Chen, Shaopeng Wu*, Yue Xiao*, Wenbo Zeng, Mingwei Yi, Jiuming Wan

State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan 430070, China

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ABSTRACT

The primary purpose of this research was to evaluate the effect of hydration and silicone resin on material characteristics of Basic Oxygen Furnace (BOF) slag and performances of BOF slag asphalt mixture. BOF slags modified by different methods were prepared. Surface textures, elements distributions, pore characteristics and volume stability of various BOF slags were first studied. Then the performances of asphalt mixtures containing various BOF slags including volume stability, thermal property and moisture resistance were well evaluated. Results showed that the combined modification of hydration and silicone resin can lower the asphalt absorption of BOF slag, and improve the asphalt mixture's volume stability and thermal efficiency, which meant the applicability and economy of BOF slag asphalt mixture got enhanced when proper combined modification was applied on BOF slag.

1. Introduction

Nowadays, large numbers of infrastructure construction impose the pressure on the supply of natural raw materials. The use of some wastes is a promising way to relieve the pressure, and many research have been conducted (Gencel et al., 2012a, 2012b, 2013; Medina et al., 2014; Mo et al., 2015; Uygunoğlu et al., 2012). Traffic road is one of the main infrastructures. The new construction of traffic road is still dominant in developing countries, although maintenance has become the primary task in developed countries. For instance, in China the total mileage of state expressway has reached 111,900 km by the end of 2014 (MOT, 2015). More than 90% of expressway is constructed with Hot-mix Asphalt (HMA) mixture in China. Therefore large amount of non-renewable resource would be consumed every year. Recycling of solid wastes such as construction waste (Pasandín et al., 2015a; Wu et al., 2011; Zhu et al., 2012), industrial waste (Chen et al., 2014a, 2014c; Modarres et al., 2015; Pasandín et al., 2015b; Wu et al., 2007), recycled pavement materials (Jamshidi et al., 2012; Miliutenko et al., 2013; Xiao et al., 2009) in asphalt mixture is a promising way to reduce the demand of natural resource.

Steel slag is one of the industrial waste, and it makes up a portion of more than 10% of raw steel output (Reddy et al., 2006; Shen et al., 2009). Therefore it necessarily generates substantial amount of steel slag during steel manufacture. The mineral compositions of steel slag contain calcium silicates (C_2S, C_3S), calcium ferrites (C_4AF, C_2F), and calcium aluminates (C_3A, $C_{12}A_7$) (Wang et al., 2012). Steel slag has been applied in many fields such as the production of cement and concrete (Alanyali et al., 2009; Reddy et al., 2006), purification engineering (Xue et al., 2009a,b; Xue et al., 2013), road construction (Ahmedzade and Sengoz, 2009). According to the statistics of EUROSLAG, about 39–62 % of steel slag was used in road construction during 2000–2010, and the use ratio in road construction was significantly higher than in any other fields (EUROSLAG, 2000–2010). Many developed countries almost achieve a 100% recycling rate for steel slag, such as 98% of steel slag is used as aggregates in UK (ODPM, 2002). However a significant proportion of steel slag is either dumped or used for landfill with a low end use in developing countries (Reddy et al., 2006; Xue et al., 2006). Very few pavements are constructed with steel slag based asphalt mixture although it possesses excellent skid resistance (Shen et al., 2009; Xue et al., 2006), moisture resistance (Shen et al.,

Abbreviations: BOF, Basic Oxygen Furnace; HMA, Hot-mix Asphalt; SMA, Stone Mastic Asphalt; SEM, Scanning Electron Microscope; EPMA, Electron Probe Microanalysis; TSR, Tensile Strength Ratio; NCS, newly crushed slag; FHS, fully hydrated slag; HSS, slag with combined modification of hydration and silicone resin; SGC, Superpave Gyratory Compactor; ITS, Indirect Tensile Strength; XRD, X-ray Diffractometer; OAC, Optimum Asphalt Content.

* Corresponding authors. Tel./fax: +86 02787162595.
E-mail addresses: wusp@whut.edu.cn (S. Wu), xiaoy@whut.edu.cn (Y. Xiao).

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2009; Xie et al., 2012) and deformation resistance (Shen et al., 2009).

The main concerns which limit the wide use of steel slag in asphalt pavement are the volume expansion potential of furnace slag (Juckes, 2003; Wang et al., 2010) and high cost when constructing steel slag asphalt pavement. On the one hand, furnace slags contain certain proportion of free calcium oxide (f-CaO) and magnesium oxide (MgO). The f-CaO can get hydrated to $Ca(OH)_2$ and cause large volume expansion, while the hydration speed is much slower than that of burnt lime (Thomson, 2005). This is because the high temperature of approximately 1700 °C makes free lime in steel slag denser. The hydration speed of f-MgO is even much slower than that of f-CaO in steel slag and the high basicity condition is not benefit for the formation of free form of MgO. Therefore f-CaO is considered to be the major contribution to the volume expansion of steel slag (Wang et al., 2010). On the other hand, steel slag is a porous materials (Wu et al., 2007) and the porous structure will enhance the absorption of asphalt binder. About 0.2% increment of asphalt content for Stone Mastic Asphalt (SMA) (Wu et al., 2007), 0.05–0.25% increment for porous mixture (Shen et al., 2009) and 0.4% increment for dense asphalt concrete (Chen et al., 2014c) compared to conventional asphalt mixture. The increasing speed of temperature is slow when heating steel slag because of its pores. Heat could be released inside the steel slag (Huang et al., 2013). The poor thermal efficiency of steel slag consumes additional fuel when preparing asphalt mixture. Extra asphalt binder and fuel depress the application of steel slag asphalt mixture.

The main objective of this research is to observe the effect of hydration and silicone resin on steel slags and their asphalt mixtures. Surface textures and pore characteristics were observed by Scanning Electron Microscope (SEM), and elements distributions were detected by Electron Probe Micro-analysis (EPMA). The volume stability of steel slag was measured according to ASTM D4792 (ASTM, 2013). Thermal property and volume stability of HMA were determined by a thermal constants analyzer and a modified test method, respectively. Moisture resistance was quantified based on Tensile Strength Ratio (TSR) values when samples were subjected to different moisture freeze-thaw cycles.

2. Materials and methods

2.1. Raw materials

Two types of aggregates were used: steel slag (>2.36 mm) and basalt (<2.36 mm). Steel slag provided by Wuhan Iron and Steel Group, China is Basic Oxygen Furnace (BOF) slag. Some slags, with honeycomb shape, are easy to collapse during atmospheric weathering treatment because of the enrichment of retained f-CaO. The honeycomb slag's morphology also makes it unsuitable as asphalt mixture's aggregate. Hence, BOF slag used in this research is manufactured by crushing dense slag blocks.

The basic physical properties of basalt aggregate and newly crushed BOF slag aggregate were investigated. Apparent specific gravity and water absorption, flakiness content, Los Angeles abrasion were tested according to ASTM C127/128 (ASTM, 2015a,b), ASTM D4791 (ASTM, 2010), ASTM C131 (ASTM, 2014), respectively. Five batches of each aggregate were considered and results are listed in Table 1. It can be seen that BOF slag aggregates' physical properties fluctuate more obviously than that of basalt aggregate. This is because the components and structures of BOF slag are complex due to changeable types and origins of raw materials used in steelmaking.

A Chinese patented liquid silicone resin, provided by Hubei Huanyu Chemical Co. Ltd., was used in this research. It mainly consists of Si–O–Si structure, ethanol and a small proportion of some penetrating agent and thickening agent (Zhu et al., 2012). When this liquid silicone resin is used to treat porous materials, it will penetrate into pores on the material surface. Liquid silicone resin then will solidify with the evaporation of ethanol and multidimensional Si–O–Si structures generated by further polymerization during the solidification.

Base asphalt graded 70 (penetration grade), with penetration of 67 (0.1 mm at 25 °C, 100 g and 5 s), ductility of 157 cm (5 cm/min, 15 °C), and softening point of 46.4 °C was used as binder. Limestone powder with a hydrophilic factor of 0.79 was functioned as filler. The basic properties of asphalt binder and filler were obtained from factory inspection reports provided by manufacturers.

2.2. Experimental methods

2.2.1. Pretreatment of original BOF slag

Newly crushed BOF slag (NCS, namely original slag) with size of 19–9.5 mm, 9.5–4.75 mm, 4.75–2.36 mm first hydrated at 60 °C. The surface of BOF slag was kept wet but not immersed in water, in order to get hydration product accumulated on the surface of BOF slag (Chen et al., 2014b). The hydration process was finished when the mass of BOF slag was constant. Then fully hydrated BOF slag (FHS) was further treated by silicone resin. FHS was immersed in silicone resin for 1 h first. FHS coated with silicone resin was then cured in the oven at 60 °C for 24 h to solidify the silicone resin. The process of immersion and curing was repeated for three cycles. At the end, BOF slag suffered combined modification of hydration and silicone resin (HSS) was obtained. Therefore three types of slags (NCS, FHS and HSS) were used in this research.

2.2.2. Material characteristics of BOF slags

A JSM-5610 LV SEM was used to observe BOF slags' surface textures and pore changes, and the elements distributions of slags were detected by a JXA-8230 EPMA. The volume expansion test of NCS, FHS and HSS were conducted according to ASTM D4792 (ASTM, 2013). The proportions of particles with different sizes should be within the range stated in ASTM D2940 (ASTM, 2009). Each type of BOF slag mixture was mixed with optimum moisture content and compacted with standard heavy compaction test. As

Table 1
Basic physical properties of basalt and newly crushed BOF slag.

Aggregate types		Apparent specific gravity		Water absorption (%)		Flakiness content (%)		Los Angeles abrasion (%)	
		Avg.	Std. dev	Avg.	Std. dev	Avg.	Std. dev	Avg.	Std. dev
BOF slag	19–9.5 mm	3.342	0.091	1.7	0.381	6.8	1.084	16.8	2.056
	9.5–4.75 mm	3.381	0.089	1.6	0.314	9.6	1.387	14.8	1.462
	4.75–2.36 mm	3.319	0.098	2.0	0.451	NA	NA	17.6	2.442
Basalt	<2.36 mm	2.769	0.049	0.8	0.140	NA	NA	NA	NA
Criteria in China		≥2.5		≤3		≤18		≤28	