Construction and Building Materials 38 (2013) 796–803

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Performance characteristics of asphalt mixture with basic oxygen furnace slag

Jun Xie [a], Juyong Chen [a], Shaopeng Wu [a,*], Juntao Lin [a], Wei Wei [b]

[a] State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan 430070, PR China
[b] Hubei Construction Science Research and Design Institute, Wuhan 430071, PR China

HIGHLIGHTS

- We characterized the elements distribution on surface of BOF.
- CaO–FeO–MnO–MgO solid solution and inert CaO are the major compositions on surface of BOF.
- BOF based asphalt mixture is superior to basalt based asphalt mixture with respect to moisture sensitivity.
- The permanent deformation behavior of BOF based asphalt mixture can be perfectly modeled by Zhou's model.

ARTICLE INFO

Article history:
Received 5 July 2012
Received in revised form 16 August 2012
Accepted 20 September 2012
Available online 27 October 2012

Keywords:
Basic oxygen furnace slag (BOF)
Asphalt mixture
Contact angle
Fatigue life
Electron probe micro-analysis (EPMA)
Moisture sensitivity
Permanent deformation behavior

ABSTRACT

Lack of superior natural crushed stone and negative dumping effects on environment promote the recycling of basic oxygen furnace slag (BOF). Since BOF based asphalt pavements have been utilized for a certain history, their in-service performances necessitate comprehensive investigation imperatively, with respect to moisture sensitivity and permanent deformation behavior in particular. In this study the surface of BOF was firstly characterized by electron probe micro-analysis (EPMA) coupled with X-ray wavelength Energy Disperse Spectroscopy (EDS). Then the surface energies of asphalt and BOF were measured by determination of contact angles and they are further used to determine the work of adhesion. The asphalt mixtures incorporating BOF as coarse aggregate were prepared and subsequently subjected to modified Lottman test, immersion rutting test and fatigue life test to determine the moisture resistance. Also dynamic creep test was carried out to characterize the permanent deformation behavior at different high temperatures and various stress levels. Results show that the CaO–FeO–MnO–MgO solid solution and inert CaO are the major compositions on the surface of BOF. Large contents of Al and Ca elements may be beneficial for the bond energy between BOF and asphalt. The results of contact angle demonstrate that BOF possesses superior wettability with asphalt to basalt. The results combined with modified Lottman test show the superior moisture sensitivity of BOF based asphalt mixture to basalt based mixtures. And at higher temperature (above 45 °C), mastic performs a prominent role in the resistance of BOF based mixture to permanent deformation. Additionally the permanent deformation behavior of BOF based asphalt mixture can be perfectly modeled and the results provide possibility to the establishment of predicting model for the permanent deformation of asphalt pavement with BOF.

1. Introduction

Basic oxygen furnace slag (BOF) is a byproduct from the conversion of mineral ore into iron. It is the largest volume byproduct from metallurgical mills and has been used as aggregate in asphalt pavement for a long history all over the world. Lack of superior natural crushed stone and negative dumping effects on environment promote the recycling of BOF. Statistics show that the reserve of limestone in China cannot sustain the consumption nationally more than 15 years at current level [1]. Almost 100% of BOF have been recycled in major developed countries. For instance, UK transport research laboratory reported that some 1 Mt of BOF is produced annually in the UK, with about 4 Mt in stockpiles. By 2002 about 98% of BOF are used as aggregates, mainly in concrete and asphalt [2]. Almost 97% of BOF are recycled in the same ways in Germany [3].

In contrast, there is great potential for the reutilization of BOF in China. Nearly 5 Mt of BOF are produced each year. Most of them are disposed and waiting for value added applications. Literature shows that BOF is of rough texture, high angularity and superior mechanical properties [4]. For this reason, crushed BOF is suitable to be applied as the substitution of natural aggregate in asphalt mixture. The reuse of BOF is continuously progressing in Wuhan (in Hubei province, China) due to the increasing pressure cast by large amount of BOF generated each year from local steel mills.

* Corresponding author. Tel./fax: +86 27 87162595.
E-mail addresses: xiejun3970@whut.edu.cn (J. Xie), wusp@whut.edu.cn (S. Wu).

0950-0618/$ - see front matter Crown Copyright © 2012 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2012.09.056

Since there are several section trails of BOF based asphalt pavement, several issues including moisture damage and permanent deformation still necessitate comprehensive investigation because these failures are the typical destructive modes observed in the section trails. The annual rainfall is approximately 1300 mm in Wuhan. In summer, the rainfall is concentrated and the surface temperatures of pavements are always beyond 70 °C. The local climatic environment is a severe challenge for the in-service performance of asphalt pavement with BOF. Therefore the researches referred to moisture sensitivity and permanent deformation behavior particularly are of great significance for the further positive reutilization of BOF in asphalt pavement.

The moisture sensitivity of steel slag including furnace slag, BOF and EAF (electric arc furnace slag) based asphalt mixtures were investigated by several researchers according to the literature. Airey conducted a research on stone mastic asphalt mixture (SMA-13) and dense graded asphalt mixture with furnace slag and BOF. He points out that the involvement of steel slag provides benefits on the moisture sensitivity of asphalt mixture, as well as the stiffness and fatigue life. All the improvement of performance attributes to the vesicular and pitted structure of steel slag [5]. Noureldin's researches show that after freeze–thaw treatment, steel slag based asphalt mixtures exhibit larger indirect tensile strengths, compared to the limestone based asphalt mixtures. Also their volume expansions were lower than 1% [6]. Xue carried out an investigation of BOF as coarse aggregate in SMA asphalt mixture. He states that the BOF based mixtures show superior moisture sensitivity to the controlled mixtures composed by basalt or limestone [7]. Marco analyzed the performances of asphalt concretes with EAF. His results show that the mixtures with EAF slag have been characterized by a low water damage so demonstrating a good durability [8]. Shen prepared mixtures with different percentages of BOF by volume as a coarse aggregate substitution. Results show that the tensile strength ratios for all of the mixtures exceed the minimum values of 70% requirement. It is indicated that the mixtures may have sufficient resistance against moisture induced damage [9]. In conclusion, researches have demonstrated the feasibility of BOF in asphalt mixture. The BOF based asphalt mixture exceeds the minimum requirement of specifications with respect to moisture sensitivity. Indirect tensile strength in modified Lottman test was commonly used as an important indication. However there is limit research on the interface characteristics of BOF and asphalt on microscopic level. More advanced techniques should be involved.

Besides the mechanical parameters referred to the evaluation of moisture resistance, such as indirect tensile strength (ITS) and Marshall stability, the surface energy theory is also extensively applied to analyze the interface characteristics between aggregate and asphalt, as well as predict the moisture damage in asphalt mixtures. But unlike ITS, the theory is based on microscopic structure and inner properties of materials. The surface energy is defined as the sum of all the excess energies of the surface atoms which possess higher energies since they are less tightly bound. It is of the essence of "energy" and can be defines in term of Gibbs free energy. Arabani successfully evaluated moisture resistance of polymeric aggregate treated asphalt mixtures. It is thought that the surface free energy is intimately related with the work of adhesion between the aggregates, asphalt, and the cohesive bond strength in the asphalt binder [10]. Universal sorption device and Wihelmy plate method are widely accepted to determine the surface energies of different aggregates and binder types [11]. Jahromi also tried to explain the theoretical and experimental concepts of predicting moisture destruction in HMA by using surface energy concept [12]. The technique for calculating surface energy from measurement of contact angle is widely used for its simplicity and good practicability. There are several models for the determination of the surface energy of aggregate or asphalt based on contact angle , such as Zisman plot, Fowkes, Owens–Wendt–Rabel–Kaelble (OWRK), etc. Probably up to 25% differences between the results can be obtained by using these models. However, they are still available on evaluating the surface energies of various aggregates. For example, the OWRK model was successfully applied to assess the surface energy of material in several researches [13–15].

As a serious problem encountered in the pavement industry, the permanent deformation behavior of asphalt mixture is always characterized by wheel-tracking analyzer or repeated load creep test. Monismith firstly employed the repeated load permanent deformation test to determine permanent deformation characteristics of paving materials and it has been widely used [16]. When asphalt mixture is subjected to repetitive loading, the asphalt binder in it exhibits viscoelastic behavior. As a result the cumulative permanent strain is normally composed of three stages: primary, secondary, and tertiary [17]. The tertiary stage is supposed to have a crucial importance as it is an indication of the start of shear deformations [18]. The other two stages of creep curve can also present valuable information about specimen deformation potential prior to failure. Since the three-stage permanent deformation behavior is the typical expression of viscoelastic properties of asphalt mastic, Zhou developed a mathematical model that accurately characterized it [19].

The major objectives of this study are to: (1) evaluate the moisture sensitivity of asphalt mixture with BOF by multi-approach including modified Lottman test, measurement of contact angle and fatigue life test; (2) evaluate the permanent deformation behavior and establish its related formulae as a function of loading cycles by using Zhou's model. The study is thought to provide insight to a deep interpretation of moisture destruction and permanent deformation behavior of asphalt pavement with BOF.

2. Materials

Basic oxygen furnace slag with maximum size 31.5 mm was procured from Metallurgical Slag Corp., Wuhan Iron and Steel. It was stored and weathered at least 6 months outdoors. In BOF based hybrid asphalt mixture, BOF filled the coarse parts and the rest was substituted by limestone. Crushed basalt was chosen as reference aggregate. Their basic physical properties were list in Table 1. Each value expressed

Table 1
Properties of BOF, limestone, and basalt.

Aggregate types	Hybrid mixture with BOF and Limestone		Reference mixture
	BOF slag (coarse)	Limestone (fine)	Basalt
Bulk.S.G	3.203	2.641	2.740
Apparent.S.G	3.409	2.728	2.751
Water absorption (%)	1.9	0.9	0.3
Abrasion loss (log angeles) (%)	12.9	N/A	17.100
Frost action with Na_2SO_4 (%)	3.9	N/A	4.4
Volume expansion (%)	1.1	Not detected	Not detected
F–CaO content (%)	1.9	N/A	N/A
Polishing value (%)	46.8	N/A	41.0

Table 2
Basic properties of AH70 base asphalt.

Properties	Measured values	Requirements
Specific gravity (g cm^{-3})	1.032	N/A
Penetration at 25 °C (0.1 mm)	68	60–80
Ductility, 5 cm/min, 15 °C (cm)	⩾150	>40
Softening point (°C)	48	>46
Flash point (°C)	320	>260
Viscosity at 60 °C (Pa s)	198	>180
Loss on heating (%)	+0.02	⩽±0.8