Construction and Building Materials 64 (2014) 60–66

Contents lists available at ScienceDirect

Construction and Building Materials

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

# Characteristics of bonding behavior between basic oxygen furnace slag and asphalt binder

Zongwu Chen, Jun Xie, Yue Xiao, Juyong Chen, Shaopeng Wu *

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

## HIGHLIGHTS

- Basic oxygen furnace slag was used as aggregates in asphalt mixture.
- Chemical components on BOF slag surface have vital influence on bonding strength.
- BOF is covered with hydration layer to provide better asphalt stripping resistance.
- BOF slag shows higher adhesive strength to asphalt binder than basalt and granite.

## ARTICLE INFO

*Article history:*
Received 26 December 2013
Received in revised form 30 March 2014
Accepted 4 April 2014
Available online 24 April 2014

*Keywords:*
BOF slag
Bonding behavior
Hydration product
Modified boiling water test
Tensile test

## ABSTRACT

Basic Oxygen Furnace (BOF) slag is one of the steel slags, which are by-products in steel industry. Currently there is lack of effective ways to reuse it. It has caused various environmental issues such as water pollution, soil pollution and shortage of storage spaces. Therefore, research on using BOF slag as a novel aggregate in asphalt pavement has benefits both in environment and economics. The bonding behavior between slags and asphalt binder is one of the most important properties to ensure a durable BOF slag based asphalt pavement.

In this research, the bonding behavior between BOF slag and asphalt binder was studied. X-ray diffraction (XRD) was first conducted to understand the physical and hydration characteristics of BOF slag. Modified boiling water test and self-designed tensile test were than used to quantify the bonding behavior. Moisture resistance of bonding behavior can be also investigated with modified boiling water test. The results of boiling water test indicated that the BOF slag, firmly coved with hydration products, has the potential to protect the asphalt binder from being stripped by boiling water. Self-designed tensile test result illustrated that BOF slag had better bonding strength than the values of basalt and granite aggregates.



## 1. Introduction

Basic oxygen furnace slag, electric furnace slag and open hearth furnace slag are the most common by-products in steelmaking industry. Among these three by-products, basic oxygen furnace slag is more attractive to investors due to its large output and less payout. As a result, BOF slag [1] is produced in horrendous numbers. According to EUROSLAG 2010 [2], BOF slag represents 48% in the total production of steel slag (see Fig. 1a). WISCO groups (Wuhan, China) states that its annual production of BOF slag already reaches 2 million tons. Among these 2 million tons of BOF slag, only small amount of metal components can be recycled. The rest huge amount is mainly stacked up over somewhere. The enormous storage has caused many issues. It consumes large amounts of land for storage yard, and leach liquor of BOF slag results in water pollution and land destruction during the rainy season. Reuse steel slag in an environmental way will solve these problems.

Steel slag has applied in many aspects (see Fig. 1b). It is involved in sewage treatment as an adsorbent [3,4], and gets used as raw material in the preparation of construction material, such as glass, glass–ceramic [5] and cement production [6–9]. But the utilization rate in these fields is rather lower and limited. As a result, the steel slag dumping rate is rather high. Therefore newly effective way to use steel slag should be established. Many researchers have been contributed to promote its effective utilization, especially its application in road construction as a novel aggregate.

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

http://dx.doi.org/10.1016/j.conbuildmat.2014.04.074

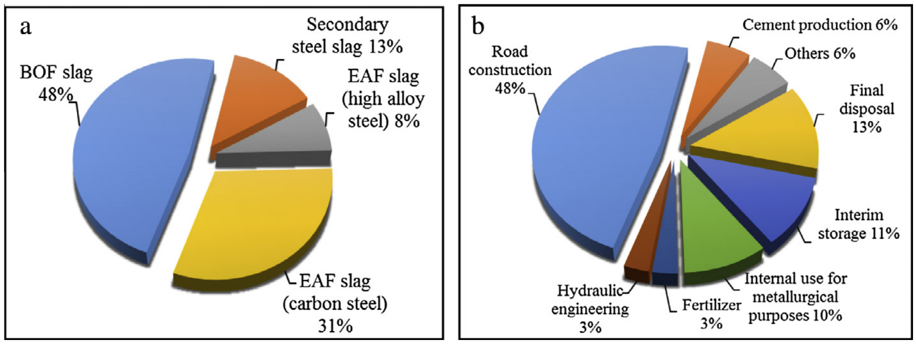


**Fig. 1.** Production and application of steel slag in European. (a) Different steel slag production in 2010. (b) Use of Steel slag in 2010 [2].

Road construction is considered as a promising way to solve the urgent issue caused by the storage of steel slag. Fig. 1b shows that road construction is the main reuse method, reaches to 48% of the total reuse in Europe. For one reason, the development of road construction has made remarkable achievements over the past decades in the world. The rapid increase of road construction has resulted in a burden on the supply of high-quality natural aggregates. The effective reuse of steel slag as a novel aggregate can alleviate this problem. For the other reason, a large scale of road construction and maintenance provides huge market demand of steel slag.

Many research on the application of steel slag in cement concrete and asphalt concrete have been carried out. Maslehuddin M's research indicated that the durability characteristics of steel slag cement concretes were better than crushed limestone aggregate concrete [10]. Rockliff D stated that BOF slag was a competent aggregate which could be used without compromising the integrity of asphalts [11]. Ahmedzade P proved that steel slag used as a coarse aggregate improved the mechanical properties and moisture resistance of asphalt mixture [12]. Xue YJ also conducted the research on the application of BOF slag as coarse aggregate in asphalt mixture. His research result indicated that some performance of BOF slag based asphalt mixture even better than traditional mixture which used natural stone such as basalt and limestone [13]. Shen DH researched the application of BOF slag in porous asphalt mixture. Results indicated that the crush stone completely replaced by BOF slag coarse aggregate was recommended to obtain the optimum performance of asphalt mixture [14]. While some technical problems still limit the widely application of steel slag, such as higher asphalt absorption compared to traditional aggregates due to microscopic and macroscopic pore structure of slag. Lack of systematic and comprehensive method to evaluate the behavior of steel slag based asphalt mixture is also a big barrier.

Moisture-induced damage is a primary form of distress in hot mix asphalt (HMA) pavements. Xie J evaluated the moisture resistance of BOF slag based asphalt mixture based on dissipated creep strain energy limits ($DCSE_f$). He found that the BOF slag based mixture is superior to basalt based mixture after several freeze–thaw cycles, with respect to moisture sensitivity [15]. It's well known that bonding strength between aggregates and asphalt binder has direct effect on moisture resistance of asphalt mixture [16–18]. Moisture damage growth in asphalt mixtures can occur either within the asphalt binder as cohesive cracking or at the interface between asphalt binder or asphalt mortar and the aggregate as adhesive cracking [19]. Therefore moisture results in two forms of damage, namely adhesive failure and cohesive failure. Adhesive failure normally associate with thin film coatings of an asphalt binder on aggregate surface and cohesive normally failure associated with a thicker one. Both adhesive failure and cohesive failure will finally propagate to loss aggregate in pavements. In Chinese specifications, many experiment methods to evaluate moisture resistance of asphalt mixture are promoted. While research methods focus on bonding behavior between aggregates and asphalt binder are not well developed.

New self-designed tensile method and modified boiling water method were proposed to evaluate the bonding strength between asphalt and aggregates in this research. BOF slag contains substances that can hydrate [20–23], such as tricalcium silicate ($C_3S$), dicalcium silicate ($C_2S$) and free calcium oxide (f-CaO). Wang Q and Yan P stated that the hydration process of steel slag, which can be divided into five stages, was very similar with that of cement [20]. Therefore the surface of BOF slag will be modified by hydration product during the storage of slag in natural damp outside environment. A modified boiling water test was introduced to investigate the effect of various surface characteristics of BOF slag caused by hydration on its bonding behavior with asphalt binder. The difference of BOF slag (without hydration), basalt and granite in bonding with asphalt binder was also studied and compared in this research. A self-designed tensile test was explained and used. Samples with flat surfaces were adopted in the tensile test under Universal Test Machine 25 (UTM-25).

## 2. Materials and experiments

### 2.1. Raw materials

BOF slag, basalt, granite, and asphalt binder were involved in this research. BOF slag was supplied by Metallurgical Slag Corp., Wuhan Iron and Steel. Basalt and granite were provided by Agoura Stone Processing Factory, Inner Mongolia. The 60/80 penetration graded asphalt binder (AH-70) was supplied by Guochuang Co., Ltd., Hubei, and China. Basically characteristics of aggregates and asphalt binder were measured according to ASTM standards, EN standards and AASHTO standards. The results were listed in Tables 1 and 2 respectively. All values of raw materials satisfied the requirements defined in the specification.

### 2.2. Experiments

#### 2.2.1. Hydration analysis and boiling water test

BOF slag with various surfaces were prepared, including BOF slag without hydration (WOH), with hydration for 15 days (WH1) and hydration for 60 days (WH2). The hydration temperature was kept at 60 °C. BOF slags with various surfaces for boiling water test are shown in Fig. 2. It is obvious that white hydration product gets accumulated with the increase of hydration time. When the BOF slag was subjected to the water, white product will be formed at the surface and got stripped off. Such with product can be collected as pure hydration material for further XRD test. However, the slag cannot be kept in the water to preparing hydration slag for boiling water test. This is because such hydration product cannot be kept on the surface when the slag is flooded in the water. Keeping the surface of BOF slag always wet is enough.

The mineral composition of hydration product and BOF slag was analyzed by X-ray diffraction (XRD), using a D/MAX-RB X-ray diffractometer from RIGAKU Corporation, Japan. The effect of hydration product on bonding behavior between asphalt binder and BOF slag was carried out by means of a modified boiling water test. According to ASTM D3625, bonding behavior between aggregate and asphalt