Waste Management 78 (2018) 318–330

Contents lists available at ScienceDirect

Waste Management

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

Steel slag in China: Treatment, recycling, and management

Jianlong Guo, Yanping Bao *, Min Wang

State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, No. 30 Xueyuan Road, Haidian District, Beijing, China

ARTICLE INFO

Article history:
Received 6 December 2017
Revised 26 April 2018
Accepted 27 April 2018

Keywords:
Steel slag
Treatment
Recycling
Management
China
Policy

ABSTRACT

Steel slag is the main waste product in the steelmaking process. Because of its chemical composition and technical properties, it can be reused as raw material in steel plants and can serve as a substitute for aggregates in civil engineering. In this paper, we reviewed steel slag treatment, recycling, and management in China. Although China's annual slag production reached more than 100 million tons, its utilization rate is only 29.5%. As of 2016, more than 300 million tons of steel slag have not been used effectively. Large steel slag emissions are causing environmental problems for China. China's steel slag utilization rate is low compared with that of industrial countries: the utilization rate is 98.4% in Japan, 87.0% in Europe, and 84.4% in the United States. Compared with other nations, China also has a gap in its usage of slag in road construction and agriculture. Although the Chinese government has been active in creating a legislative and institutional framework to realize effective steel slag treatment and recycling, these efforts are limited. Outdated treatment approaches is one of the reason for low utilization rate in China, most Chinese steel plants carry out the preliminary treatment (like family workshops) of steel slag, no one system can be used for all ferrous waste recovery, and 47% enterprises' steel slag stability after treatment do not meet requirements of follow-up product. Road construction issues caused by high costs and policy limited, legal restrictions and lack of standard on agricultural applications are other two reasons for low utilization rate of steel slag. New policies are needed to improve utilization rates. We propose the concept of gradual utilization to promote the effective utilization of steel slag.

1. Introduction

Steel slag is the oxidized material that is generated when lime, dolomite, and other auxiliary materials are added, and oxygen is blown onto the pig iron produced by a blast furnace to remove carbon (C), phosphorus (P), sulfur (S), and other components to produce crude steel in a basic oxygen furnace (BOF). Steel slag is the main by-product of steel production. China's crude steel output was 808.1 million tons in 2016 according to the National Bureau of Statistics of China (2016), and steel slag production exceeded 100 million tons. In China, after steelmaking, the steel slag is poured from the converter, transported to the slag stacking place, and treated by aging. Then the steel slag is magnetically separated to recover the metal iron (Fe). After magnetic separation, the steel slag is irregularly piled on the open ground. Powder formation of the steel slag that is solidified and stored on the ground begins immediately after its discharge, and it is a continuous process. During the bulk powder formation from steel slag, a large amount of the dust produced during the transport and treatment process can pollute the air. Harmful components like chromium (Cr) and arsenic (As) can dissolve in water. In addition, simple processing facilities will lead to steel slag after treatment cannot be used effetely, their disposal will pollute the farmland. Therefore, steel slag is a serious problem in China, both in terms of quantity and discharge, as China's steel slag reserves continue to increase. In 2012, the haze in central and eastern China began to attract the attention of citizens, the international media, and the Chinese government. Not surprisingly, 75% of China's steel enterprises and 66% of the country's steel output are in these regions. When steel slag cannot be used in a timely and effective way, its disposal becomes a serious problem for society and industry (Dippenaar, 2005).

To solve the problem of steel slag, two different efforts have been made. The first effort is to reduce the amount of steel slag. A hot metal pretreatment can be used to remove silicon (Si), P, and S before the decarburization of pig iron. In Japan, slag production resulting from BOF steelmaking decreased from 138 to 121 kgt-steel^{-1} by simply using this approach (Kitagawa, 2000). Using a duplex process also can reduce the amount of steel slag (Ogawa et al., 2001). In this process, the decarburization and dephosphorization are divided into two converters. Using this approach, the amount of steel slag decreased from 130 kgt-steel^{-1} in the conven-

* Corresponding author.
E-mail address: baoyp@ustb.edu.cn (Y. Bao).

https://doi.org/10.1016/j.wasman.2018.04.045
0956-053X/

tional BOF process to 60 kgt-steel^{-1} (Tanaka et al., 2000). This process is widely used in Japan and a few advanced steel plants in China. The majority of Chinese enterprises have adopted traditional steelmaking methods, and the steel slag generated using these approaches is about 100–150 kgt^{-1} (Semykina et al., 2010; Gao et al., 2015).

The second effort to reduce the amount of steel slag is to promote the utilization of steel slag. The utilization of steel slag has a long history. Europe began using steel slag for phosphate fertilizer as early as 1880 (Geiseler, 1996). Because of its chemical composition, including calcium oxide (CaO), Fe, iron oxide (FeO), silicon dioxide (SiO_2), magnesium oxide (MgO), and manganese oxide (MnO), steel slag can be reused as a raw material in steel plants (including the sinter and converter); (Topkaya et al., 2004; Diao et al., 2016; Sarfo et al., 2017a,b). Because of its porous structure and alkaline properties, steel slag can be used for wastewater treatment (Ortiz et al., 2001; Yildirim and Prezzi 2011; Ponsot and Bernardo, 2013). Sarfo have studied the carbothermal reduction method that the value metal can be recycled from slag for steelmaking, and the residual slag can be used for glass and ceramic industries (Sarfo et al., 2016; Sarfo et al., 2017a,b). Some researchers have affirmed that steel slag can be used successfully as aggregates for road and hydraulic construction due to its favorable physical and mechanical properties, including hardness, wear-resistance, adhesiveness, roughness, and toughness (Pasetto et al., 2017; Ferreira et al., 2016; Shen et al., 2009; Emery, 1984; Mahieux et al., 2009). The presence of Calcium silicate (C_2S), Tricalcium silicate (C_3S), Tetracalcium aluminoferrite (C_4AF) and other mineral components confers steel slag with cementation properties, and steel slag is regarded as a potential material for cement production (Tsakiridis et al., 2008; Kourounis et al., 2007; Amuchi and Piatak, 2015; Gonçalves et al., 2016). In addition, because it contains CaO and MgO, steel slag can be reused to capture and storage carbon dioxide (CO_2) (Ma et al., 2011; Pan et al., 2016; Zhang et al., 2017; Tong et al., 2018), and as a result of its beneficial elements for the promotion of plant growth, such as Si, Ca, Mg, P, and Fe, steel slag also can be reused as a fertilizer and for soil improvement (Fujisawa et al., 2012; Gómez-Nubla et al., 2017). Table 1 shows the relationship between the characteristics of steel slag and its potential areas of application (Faeghinia, 2015; Yi et al., 2012).

Many restrictions exist, however, on the utilization of steel slag. When steel slag is used internally, in steel plants, the most obvious problem is that of the enrichment of P and S (Drissen et al., 2009). The Bhilai Steel Plant in India was shut down because of its high S and P content (Das et al., 2007). The amounts of free lime and free MgO are important for the utilization of steel slag in construction because of their volume stability. Total Fe (T. Fe) content and the possibility of the leaching of heavy elements, such as As, Cr, and vanadium (V) (Nakase et al., 2013), are key factors that affect the use of steel slag in cement production and fertilizers. Because of a range of economic and social factors, these problems with steel slag have not been completely solved in China.

Table 1
Relationship among the characteristics and potential applications of steel slag.

Characteristics	Applications
Hard, wear-resistant, adhesive, rough	Aggregates for road and hydraulic construction
Porous, alkaline	Wastewater treatment; glass-ceramic composites
FeOx, Fe components	Iron reclamation
CaO, MgO, FeO, MgO, MnO components	Fluxing agent
Cementitious components (C_3S, C_2S, and C_4AF)	Cement and concrete production
CaO, MgO components	CO_2 capture and flue gas desulfurization
FeO, CaO, SiO_2 components	Raw material for cement clinker
Fertilizer components (CaO, SiO_2, MgO, and FeO)	Fertilizer and soil improvement

A large difference exists amount the various steel slag utilization rates across nations. Some industrial countries, like Japan, the United States, and some European nations, have high utilization rates. The utilization rate in China, however, is only about 29.5%, and more than 70 million tons of steel slag are disposed of every year (Yi et al., 2012). As of 2016, nearly 300 million tons of steel slag have not been used effectively in China. The Chinese government is working to make policies and to develop technologies to recycle and manage steel slag. As will be discussed in greater depth in this article, such efforts are limited because of legal limitations, policy restrictions, treatment and utilization costs, and environmental protections.

The purpose of this paper is to examine the factors that contribute to the current state of steel slag treatment, recycling, and management in China. Beginning with the general overview of steel slag, we describe the chemical composition and utilization of steel slag in different countries. We then introduce the overview of steel slag management in China, including its utilization history; and the laws, regulations, policies, and standards related to steel slag. We analyze why the utilization rate in China is low and introduce the challenges facing China's steel slag utilization. Finally, we analyze how slag utilization and management are expected to change from an environmental point of view. We propose a new concept of gradual steel slag utilization to improve the management of this waste product.

2. General overview of steel slag

2.1. Chemical composition of steel slag

The generation of steel slag usually depends on the smelting process, Si content, and use of dolomite (Gao et al., 2015). The CaO/SiO_2 ratio often is used as the basis for determining the amount of lime required; lime plays the primary role in controlling the amount, chemical composition, and mineral composition of the slag (Kitamura et al., 2009).

Table 2 shows typical examples of the chemical composition of steel slag in different countries. The main components of steel slag are CaO, Fe, SiO_2, MgO, and MnO. Steel slag is calciumsilicatic, with a CaO range of 38–48%, and it has a SiO_2 range of 11–20%. The Fe in steel slag is in the form of steel, FeO, and iron-bearing minerals. These components can be separated from the steel slag by magnetic separation for the sinter and blast furnace or may be used in steelmaking. In addition, the high content of CaO, MgO, and MnO in steel slag means that it can be used as a substitute for limestone, dolomite, and manganese ore to reduce the cost of iron and steelmaking (Shen et al., 2003).

2.2. Steel slag utilization in different countries

According to the data from the World Steel Association (2016), world crude steel production reached 1620 million tons in 2015. As shown in Fig. 1, China, Europe, Japan, and the United States were the top four regions in the world's crude steel production, accounting for 71.7% of the total. To understand the main applications of steel slag in the major regions in the world, the production and utilization approach of steel slag in these four regions is described in this section (see also Fig. 2).

Steel slag is largely used in road construction, cement production, internal recycling, civil engineering, and agriculture in Japan,