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REVIEW PAPER

The potential utilization of slag generated from iron- and steelmaking industries: a review

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Abstract Along with iron and steel production, large amount of slag is generated. Proper management on the iron- and steelmaking slag is highly demanded due to the high cost of direct disposal of the slag to landfill, which is the most adopted management approach. In this article, the potential application of iron- and steelmaking slag has been reviewed, which included the slag utilization in construction as cement and sand, in water, soil, and gas treatment, as well as in value material recovery. In addition, the challenge and required effort to be made in iron- and steelmaking slag management have been discussed.

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Introduction

Slag is the by-product of iron- and steelmaking processes. Normally, around half to one tonne of slag would be generated for yielding one tonne of rolled iron or steel (Lobato et al. 2015). It was reported that the world steel production was 1.9 billion tonnes in 2016, which suggested that at least around 1 billion tonnes of slag is produced during the year (Worldsteel Association 2016). The large amount production of slag requires appropriate management. Landfill is the simplest and most commonly adopted disposal strategy of slag management; however, the cost gradually increases as the land space and the environment regulations become tense and strict, respectively. Alternative management solutions are highly required. Currently, the idea of waste management is toward to converting waste to valuable products, but it should avoid the toxic elements or other potential contaminants to accumulate in the application chain. In fact, waste generated in one field could be useful materials in other areas. For instance, wastewater sludge is the waste generated in wastewater treatment, but it is considered as fertilizer in agriculture due to the presence of the essential element (nitrogen, phosphorus, potassium) for plant growth. Similarly, under

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circular economy concept slag as waste of iron- and steelmaking industries can be used as raw materials of other value product production (Velenturf et al. 2019; Wang et al. 2018).

Iron- and steelmaking slag has been widely studied for manufacturing construction materials, such as asphaltic concrete aggregate, road base, railroad ballasts, and roofing granules after grinding (Biskri et al. 2017; Ferreira et al. 2016; Pasetto et al. 2017; Vijayaraghavan et al. 2017); as fertilizer or soil conditioner after grinding (Ali and Shahram 2007; Li and Dai 2018; Wang and Cai 2006); as adsorbents for heavy metal and phosphorus removal from wastewater after activating process (Kim et al. 2008; Wu et al. 2014; Zhang and Itoh 2006); for neutralizing acid mine drainage (Goetz and Riefler 2014; Moodley et al. 2017); and for carbon dioxide fixation (Pan et al. 2016). In addition, the slag could be also used as iron source (also called iron recycle) due to the fact that the slag contains iron in abundance (around 20% iron content) (Lan et al. 2017). Generally, the slag with rich iron content could be directly returned to the furnace as feedstock. However, in order to increase the iron content in the slag, pre-treatment is usually performed prior to return the slag to the furnace as feedstock. The pretreatments mostly used are leaching and thermal treatment for removing the impurities (mainly toxic metals) and increasing the iron content (Baciocchi et al. 2015; Gomes and Pinto 2006; Peters and Colo 1978). The released toxic metals would be treated for recovery or removal through adsorption, extraction, or precipitation (Battsengel et al. 2018; Genç-Fuhrman et al. 2007). Iron- and steelmaking slag management can be fulfilled by processing or converting slag to the materials which can be used in construction or environmental treatments, or recovering value products.

Piatak et al. have reviewed the characteristic and environmental impact of ferrous and non-ferrous slag, and revealed that compared to non-ferrous slag, ferrous slag is more environmentally friendly and thus exhibited a greater potential for reuse or valuable material recovery (Piatak et al. 2015). Recently, Li and Dai have reviewed to converting the ferrous slag to glass–ceramics, mineral wool, and fertilizers (Li and Dai 2018). In fact, iron- and steel- making slag has been widely investigated for producing construction materials, and applying in environmental treatment; however, the related studies have not been discussed.

This article has reviewed the utilization of slag in construction and environmental treatment. In addition, recovery of valuable substances from the slag is also demonstrated. The problems that the application of iron- and steelmaking slag in construction and environmental treatment is facing have been discussed. The article was aimed to provide an insight of proper management on iron- and steelmaking slag.

Iron- and steelmaking slag

Slag is an inevitable by-product in metal making process. Iron slag (slag of blast furnace BF) and steel slag (slag of basic oxygen furnace BOF, and electric arc furnace, EAF) are two types of slag generated during iron and steel production processes. The composition of the slag varies with the production processes and the composition of the feed materials (ore). Detailed chemical composition and mineralogical characteristics have been discussed by Piatak et al. (2015) and Kambole et al. (2017). The major elements in the slag are iron (for BF), calcium, magnesium, silica, and aluminum, as well as trace amount of heavy metals, Cr, Ni, Pb, Zn, etc. These elements are mostly present in the forms of their oxides. The compositions of the slag are summarized in Table 1.

According to the difference of the methods used for cooling the molten slag, slag is divided into air-cooled blast furnace slag (ACBF), air, water, or steam cooled blast furnace slag (expanded or foamed blast furnace slag), air- and water-cooled blast furnace slag (pelletized blast furnace slag) and water-cooled blast furnace slag (granulated blast furnace slag). The slag is in bulk formation after formed, and thus, it will be grinded before any further utilization.

Application of iron- and steelmaking slag

Application in construction

The large volume production of slag from iron- and steelmaking process and the tightened regulation on the slag disposal urge engineers and researchers to explore the way which can massively use the slag. As the development of global economy, the need on buildings and roads extensively increases. Iron- and steelmaking slag contains large fraction of lime and

Table 1 Composition of iron slag and steel slag

Composition	Iron slag (BF) (% w/w)	Steel slag (BOF, EAF) (% w/w)	Refs.
Calcium (CaO)	30–50	30–60	Basu et al. (2008), Danilov (2003), Emery (1992), Kalyoncu (2000), Mihok et al. (2006), Piatak et al. (2015), Reddy et al. (2006)
Silica (SiO_2)	25–45	10–45	
Aluminum (Al_2O_3)	0–10	0–15	
Magnesium (MgO)	3.5–15	5–20	
Iron (FeO and Fe_2O_3)	10–30	0.1–3.6	
Others (P, S, toxic metals)	$< 5\%$	$< 5\%$	

silica, which are the main components in most of construction materials. Therefore, slag has been employed as construction resource for mitigating the pressure from expensive disposal and reducing the construction cost (Heribeert and Kuehn 2004; Hiroyuki et al. 2005). The slag has been investigated to be directly used as granular base, embankments or fill, highway shoulders, and asphalt pavement after crush and screen (Chen et al. 2017; Li et al. 2016; Wang 2016; Yildirim and Prezzi 2017). However, usually, the slag would be stored for a certain time for gaining the saturation of moisture prior to using in order to avoid the swelling of the slag in construction (caused by lime) (Jukes 2003). Apart from the applications in road constructing, slag has also been studied to produce cement and sand (Carvalho et al. 2017; Li et al. 2018; Ouda and Abdel-Gawwad 2017). The details information is presented below:

Cement

Cement produced from slag has been used for decades, and the most typical one is Portland clinker (35%)–Steelmaking Slag (30%)–Blast Furnace Slag (30%) Cement (PSSBFC) (Sun and Yuan 1983; Wang and Lin 1983). Iron- and steelmaking slag has been studied to be used for blended cement making or as a raw material in cement clinker. There are several parameters such as slag composition and the formation of the oxides, considered to affect the feasibility of slag to produce cement. Among all, the similarity of composition between slag and commercial cement [Portland Cement (PC)] determines if the slag could be used for manufacture cement. The fractions of free lime (CaO) and free magnesia (MgO) in slag are essential factors in cement production from slag as they significantly affect the hydraulic properties of cement which is associated with volume stability of the products. Free lime and free magnesia can react with water and hence induce large volume expansions of the slag. It would thus cause the premature failure when the slag is employed in roads. Usually, free lime is less than 20% w/w (based on slag weight) and free magnesia is less than 3% in the slag (Kambole et al. 2017). It suggests that the content of free lime and free magnesia should be lower than 7% and 4%, respectively, when the slag was used in unbound and bitumen bound layers, respectively (Geiseler 1996). Attention should be paid on the free lime content when utilizing the iron- and steelmaking slag in road construction as free magnesia is normally less than 3% in the slag.

Iron content including FeO, Fe^0, and Fe_2O_3 is another important factor to evaluate the possibility of slag as cement due to the concerns on the volume stability and appearance.

Generally, the production of cement from slag can be simply processed as grinding, treating, and blending. The order of the procedure is varied based on the treatment methods. Thermal and magnetic treatments are mostly applied technologies (Alanyali et al. 2009; Heikal et al. 2015; Reddy et al. 2006). Thermal treatment is to first melt the slag, and then, let it cool down in different cooling temperature for converting the free metallic oxides, especially CaO, into complex with other substances such as SiO_2 and Al_2O_3, and thus enhance the volume stability of the slag. The thermal treated slag will be grinded and screened for size selection after cooling. If necessary, PC clinker will be added to modify the property of the slag. Magnetic treatment is mainly used for cement production from the slag which has similar component with commercial cement but high content of iron. Magnetic separation of iron is performed after grinding and screen. The slag obtained from separation process could be used as cement with or without the addition of PC clinker based on the practical condition.

Recently, it was reported that slag after being activated with sodium carbonate could be used in autoclaved aerated concrete instead of cement (Ke et al. 2016; Yuan et al. 2017). The autoclaved aerated concrete produced from the alkali-activated slag showed comparable strength, raw density, thermal conductivity, porosity, and drying shrinkage as the one prepared from cement (Yuan et al. 2017). It suggests that the slag can replace the cement to produce autoclaved aerated concrete without effecting on the property of the product. In addition, it was observed that the method could greatly reduce the cost, energy consumption, and greenhouse gas emission. Similar results have been also achieved by others (Balczár et al. 2017; Burciaga-Díaz and Escalante-García 2017).

Sand

Sand is another mostly used material in construction. Over last decades, iron- and steelmaking slag has been used in concrete as sand (Dieter et al. 1988). Researchers have produced sand-like product from BF slag and achieved encourage results (Senani et al. 2016; Takahashi and Yabuta 2002). To produce sand from slag, rapidly cooling on the molten BF slag from blast furnace (temperature is around 1500 °C) with pressured water can be performed, and then crushed and screened the slag to obtain a similar particle size with commercial sand. Thereafter, inhibitors were normally added to prevent the consolidation of the slag. The sand-like product, commercially called granulated BF slag sand or Sandy-S, has widely used as fine concrete aggregate and showed compatible result (Ouda and Abdel-Gawwad 2017; Turhan 2006). Studies have revealed that utilization of sand produced from iron- and steelmaking slag performed similarly as the commercial sand in the cement mortar and foundry industries (Le et al. 2017; Li et al. 2018; Murthy and Rao 2016; Ouda and Abdel-Gawwad 2017).

Overall, the use of iron- and steelmaking slag in construction has significantly reduced the tension for the slag dumping and disposal due to the fact that construction is capable of consuming the slag in large amount. In addition, the performance of slag in construction is rather encouraging. However, there is still consideration on long-term volume stability of the slag in construction and the risk to environment and human health (Ferreira et al. 2016; Reis da Silva et al. 2007). Work on improving the volume stability of iron- and steelmaking slag is greatly required in order to promote the application of slag-obtained sand in construction.

Application in environmental treatments

The large amount production of iron- and steelmaking slag has proposed a great challenge to the environment as it has been considered as pollutant. In fact, the slag has showed impressive performance on removing contaminants from air, water, and soil (Barca et al. 2014, 2018; Jo et al. 2015; Yu et al. 2015; Zhou et al. 2016; Zuo et al. 2015). It indicates that the iron- and steelmaking slag has great potential in the application of environment treatment practice. The detailed information has been discussed below:

Water treatment

As adsorbent and filtration media Heavy metal removal from wastewater has grabbed a growing attention due to their toxicity to the living beings. Adsorption is the most applied method for heavy metal removal. Among all the commonly used adsorbents (various zeolite, fly ash, clay, and zero-valent irons, activated carbon), activated carbon is considered as the best performed one (Da'na and Awad 2017; Karnib et al. 2014; Pap et al. 2017). However, the high cost of heavy metal removal by activated carbon has hindered its application, and thus, seeking on cost-effective adsorbent is highly needed. Researchers have pointed out that iron- and steelmaking slag was a suitable alternative (Xue et al. 2009; Zahar et al. 2015). As shown in Table 1, iron- and steelmaking slag mainly contains calcium oxide, magnesium oxide, and aluminum silicates, which have great affinity to heavy metals (Curkovii et al. 2000).

The mechanism of heavy metal removal with slag is considered to be the adsorption, precipitation, and ion exchange (Dimitrova 1996, 2002; Kim et al. 2008). Slag hydrolysis converts the oxides into their relative hydroxides; for example, CaO could be turned into the form of $Ca(OH)_2$ which has higher solubility than most of heavy metal hydroxides, in the presence of water. Thus, when heavy metal exposes into the system, Ca in slag will be exchanged by heavy metal which results in precipitation of heavy metal onto slag or in the solution (Dimitrova 2002). In addition, the reaction occurring between soluble compounds in slag and heavy metals in solution to form hydro–oxo complexes would cause heavy metal removal as well (Beh et al. 2010; Dimitrova 1996; Kim et al. 2008). The study on the heavy metal removal with the slag before 2011 has been extensively reviewed by other researchers (Ahmaruzzaman 2011; Hashim et al. 2011); thus, in this article the related work after 2011 is summarized in Table 2. In fact, interests in evaluating the heave metal removal with iron- and steelmaking slag have reduced in recently years. As shown that there were toxic metals in the slag (Table 1), it suggests that the metals might be released during heavy metal removal from water and hence brings new contaminants to the water. It would be the cause of the less attention on the heave metal removal with iron- and steelmaking slag.

Filtration is a combination of physical (size exclusion and attachment) and chemical (sorption) processes in water treatment. Studies using iron- and steelmaking slag as filtration media have shown that the slag had good performance in various types of wastewater treatment and revealed that the slag was capable of removing contaminants such as suspended solids, chemical oxygen demand (COD), biochemical oxygen demand (BOD), phosphate (P), and ammonium ($N\text{-}NH_4^+$) (Barca et al. 2014, 2018; Kadirova et al. 2015; Zhou et al. 2016; Zuo et al. 2015). It was predicted that the porous structure of the slag would absorb the contaminants and free lime in the slag could react with the contaminants (Jha et al. 2004, 2008; Lu et al. 2008). In addition, inertial impaction, diffusion, interception, size exclusion, and electrostatic interaction could also be the reason for contaminant removal in slag filtration (Gao et al. 2017; Zhou et al. 2016). It was reported that ironmaking slag was capable of removal of hydrogen sulfide which was attributed to the oxidation and acid–base reaction (Xie et al. 2017). The hydrogen sulfide was converted to acid volatile sulfide (AVS), elemental sulfur, and thiosulfate after being reacted with the slag.

Among all the contaminants, phosphorus removal with iron- and steelmaking slag was studied the most (Table 3). It would be due to the high affinity of the slag component such as free lime to the phosphorus, as well as that phosphorus in the wastewater normally was difficult to eliminate with biological treatment process which was normally used to remove COD, BOD, and nitrogen.

Neutralizing agent Iron- and steelmaking slag contains abundant basic materials such as CaO and MgO (Table 1). Therefore, the slag would replace the commercial neutralizing agents such as lime, limestone, and calcined magnesia. Various slags have been demonstrated to neutralize pH of solutions (Gahan et al. 2009; Yilmaz et al. 2010). Composition of slag, formation of the oxides in slag, and physical characters of slag (particle size and shape) could significantly impact on neutralization. It was reported that the neutralizing capacity of the slag was affected by the form of oxides (CaO, MgO, SiO_2) and particle

Table 2 Heavy metal removal using iron- and steelmaking slag

Slag	Heavy metal	The highest removal efficiency (%)	Refs.
Steelmaking slag	As (III), As (V)	95–100	Oh et al. (2012)
Ironmaking slag	Zn(II)	85	Cantarino et al. (2012)
Ironmaking slag	Cu(II)	99.9	Santos et al. (2013)
Steelmaking slag	Cd(II)	99.1	Duan and Su (2014)
Steelmaking slag	Pb(II)	99.2	Wu et al. (2014)
Steelmaking slag	As(III), As(V)	93.7	Mercado-Borrayo et al. (2014)
Ironmaking slag	Cs(I), Sr(II)	57.4, 53.6	Tsutsumi et al. (2014)
Steelmaking slag (modified)	Ni (II)	–	Kadirova et al. (2015)
Steelmaking slag	Mn(II)	95	Zahar et al. (2015)
Steelmaking slag	Ni(II)	–	Sarkar et al. (2017)

Table 3 Contaminants removal with iron- and steelmaking slag

Slag type	Removed contaminants	Removal efficiency (%)	References
Steelmaking slag (modified)	Phosphorus	49.2	Jha et al. (2008)
	Ammonia	7.2	
Steelmaking slag (modified)	Phosphorus	85.2	Barca et al. (2012)
Steelmaking slag (modified)	Phosphorus	80.0	Li et al. (2013)
Steelmaking slag	Phosphorus	99.9	Claveau-Mallet et al. (2013)
	Fluoride	85.3	
	Mn(II)	98.0	
	Zn (II)	99.3	
Slag	Phosphorus	99.6	Barca et al. (2014)
Steelmaking slag	H_2S	93.5	Okada et al. (2014)
Steelmaking slag	COD	84.0–92.0	Jo et al. (2015)
Ironmaking slag	Phosphorus	96.3	Han et al. (2015)
Steelmaking slag (modified)	Phosphorus	99.9	Yu et al. (2015)
Ironmaking slag	Phosphorus	95.8	Han et al. (2016)
Ironmaking slag	Phosphorus	> 90	Zhou et al. (2016)
Steelmaking slag (modified)	Phosphorus	> 60	Park et al. (2017)
Steelmaking slag (modified)	Phosphorus	88	Claveau-Mallet et al. (2017)
Steelmaking slag	H_2S	94	Xie et al. (2017)
Steelmaking slag	Phosphorus	96	Barca et al. (2018)

size of the slag (Bodurtha and Brassard 2000). The results displayed that the slag with higher free oxides content and smaller particle size would more rapidly bring liquors from low pH to high pH in comparison with the slag with more bound oxides and lager particle size. The typical application of iron- and steelmaking slag in neutralization is the amendment of acid mine drainage (AMD) which is characterized with low pH (2.5–5.0) and high concentration of Fe^{2+} and Fe^{3+}(Goetz and Riefler 2014; Moodley et al. 2017). Raising pH and removing iron are the aim in AMD amendment. It was found that iron- and steelmaking slag could effectively generate alkalinity in AMD and precipitate iron (Goetz and Riefler 2014; Masindi et al. 2017, 2018). It suggests that iron- and steelmaking slag could be promising material to treat acid mine drainage.

Soil treatment

Similar as amendment of acidic liquors, iron- and steelmaking slag has also been used to amend acidic soil. Study has reported that the addition of converter slag (a type of steelmaking slag) could increase pH of acidic soils and the concentration of the available iron, P, and Mn in soil for plants (rice, maize, and tea) growth (Ali and Shahram 2007). It indicates that the addition of slag in soil also affects other properties of soil apart from acidity of soil. Negim et al. (2010) studied the effect of steelmaking slag on soil for bean growth (Negim et al. 2010). They found that the soil conditioned by slag enhanced bean growth with compared to plain soil. Moreover, as mentioned, iron- and steelmaking slag contains abundant Ca, Mg, and Fe, which are important elements in plant growth. It suggests that the slag could amend the soil which has elements Ca, Mg, and Fe in shortage. Researchers added steelmaking slag to Fe-deficient calcareous soils and planted corn with the modified soil and found that available Fe for plant growth was increased in soil (Wang and Cai 2006). The slag application in soil is a promising way to amend soil properties in the area where soil is not suitable for farming, which can be also considered slag as fertilizer (Li and Dai 2018; Qiu et al. 2012).

Gas treatment

CO_2 absorbents Global warming which is predicated to be caused due to the greenhouse gas

emission has become a serious environmental problem. The technology of carbon dioxide capture and storage, also called CO_2 sequestration, has been paid a great attention recently. Mineral sequestration which fixes carbon dioxide by forming carbonates is one of most potential methods in carbon sequestration (Huijgen and Comans 2003; Santos et al. 2013). Iron- and steelmaking slag richly containing CO_2 absorbents such as CaO and MgO would be a great candidate for CO_2 mineral sequestration. Direct (Eq. 1) and indirect (Eq. 2) carbonation have been reported using for carbon dioxide capture and storage. The direct route injects CO_2 into dry slag to accomplish carbonation, while the indirect route uses Ca and Mg ions leached out from the slag to precipitate CO_2 to complete carbonation (Bao et al. 2010; Sun et al. 2011).

$$CaO/MgO + CO_2 \rightarrow CaCO_3/MgCO_3 \quad (1)$$

$$Ca^{2+}/Mg^{2+} + CO_2 + H_2O \rightarrow CaCO_3/MgCO_3 + 2H^+ \quad (2)$$

According to the reports, steelmaking slag exhibited great potential in carbon sequestration (El-Naas et al. 2015; Gopinath and Mehra 2016; Pan et al. 2016). Study showed that the factors including the particle size of the grinded slag, surface area, and calcium leaching rate have significantly impacted on carbon dioxide sequestration (Ghouleh et al. 2017; Rawlins 2008). It was observed that small particle-sized slag was more efficient in sequestration process than the big-sized slag, and the slag with high calcium leaching rate was more cost-effective than the slag with low calcium leaching rate. It was due to that small-size slag provides larger surface area than big size ones when the equal amount slag was utilized. Calcium in the slag is the function material to capture CO_2; hence, high calcium leaching rate would promote CO_2 sequestration. It suggests that the process would be cost-effective than the slag with low calcium leaching rate.

The use of iron- and steelmaking slag in carbon sequestration might be another way to consume the slag in large quantity besides the use of slag in construction. In addition, as mentioned, the large content of free lime in the iron- and steelmaking slag was the barrier of slag utilization in construction; the volume stability of the slag would be highly improved after being employed in the carbon sequestration. Hence, the slag gone through carbon storage would be great material using in construction. However, there is still need for evaluating the cost balance using for grinding slag and storing carbon dioxide due to the slow reaction kinetics of the carbonation. It reveals that the reaction kinetics could be enhanced by adjusting CO_2 pressure, temperature, and water-to-solid ratio (Ukwattage et al. 2017). However, the improvement was limited. Further study is essentially required.

Catalysts CH_4 is another contributor in greenhouse effect. Dry reforming of CH_4 is effective method to reduce greenhouse gas emission and produce green fuel (H_2). Generally, metal catalysts such as Ni/La/Al_2O_3 and Ni/γ-Al_2O_3 were applied to catalyze the reforming process (Aramouni et al. 2018); however, the high cost has hampered the technology of CH_4 reforming with CO_2. Iron- and steelmaking slag with iron in abundance has been used as catalyst in reforming of methane to generate syngas (Eq. 3) (Fidalgo et al. 2009). The result revealed that the conversion using slag mixing with activated carbon had higher stability than using solo activated carbon. It implies that the slag is capable of catalyzing CH_4 reforming.

$$CH_4 + CO_2 \xrightarrow{\text{Temperature/catalyst}} 2CO + 2H_2 \quad (3)$$

In short, iron- and steelmaking slag has shown great potential in environmental treatment. It is a cheap and relatively effective resource in water treatment, soil amendment, and greenhouse emission control; however, the application of the slag in environment field is still in its enfant stage; further efforts are needed to be made.

Recovery of valuable substance from iron- and steelmaking slag

Iron and lime

The slag generated from iron- and steelmaking industry is characterized with high content of lime, magnesia, silicates, and iron (Table 1). Iron and lime are two essential substances in iron- and steelmaking process as iron is the raw material of iron- and steelmaking and lime is added for slag formation

(Kalyoncu 2000). High cost required in transporting the slag from iron- and steelmaking industries to the sites of construction and environmental treatment has hindered the application. Recycling iron and lime from the slag and adding them back to iron- and steelmaking process would reduce the cost for making iron and steel, and the cost for transporting slag for disposal or other utilization. Among all the slag, blast furnace (BF) slag and steel slag have more value in iron recycle due to their attractive iron content (Shen and Forssberg 2003). A German company called STEIN Injection Technology developed a method to achieve iron and lime recycling (Danilov 2003). The process included slag cooling, primary screening, iron separating, and secondary screening. The cooling was accomplished in hoppers. Primary screening was a preparation of scalp metal separation. Magnetic separators were employed to recovery iron from the slag, and the iron obtained from separation was sent back to production line as iron raw material. The nonmagnetic portion of the slag (mainly containing lime) was further grinded to relative size according to requirements. The recycled lime was used in iron- and steelmaking process after mixing with a certain amount of fresh lime. (The addition of fresh lime was determined by the steelmaking regime.)

Chemical leaching is another effective approach using for iron recycling from iron- and steelmaking slag (Gomes and Pinto 2006). Usually, control on pH in the leaching process can manipulate the sequence of elements leaching out from the slag due to the difference of the solubility of each component in slag under different pH (Bao et al. 2010; Xiang et al. 2018). It was reported that Ca, Mg, and toxic metals in slag such as Cr, Ni, Pb, and Zn, could be leached out by adjusting pH, and the residue was highly concentrated iron complex (Apul et al. 2005). It reveals that leaching could be used for iron recycling.

Valuable metals

Apart from iron, calcium, and magnesium, heavy metals such as chromium, lead, manganese, and zinc are also present in large amounts in certain slags such as electric arc furnace slag (Coppola et al. 2016; Santamaría et al. 2017). These heavy metals are mainly from the addition of these heavy metals during iron and steel production for improving the property of the products and the presence of these metals in ore (He et al. 2017; Hocheng et al. 2014). The metals are required to be separated from the slag before the slag disposal due to their toxicity. Moreover, the high value of these metals in industry also encourages researchers to study the separation of these metals from the slag. Therefore, recovery of these metals becomes rather promising. Various technologies such as flotation, leaching, precipitation, and heating have been developed for metal recovery from different types of slag (Lenz and Martins 2007; Shen and Forssberg 2003; Spooren et al. 2016). Generally, the process using for recovering metals from the slag is combination of these technologies.

Among all the methods employed for metal recovery, leaching is the most widely used one as it can be a standalone process as well as a pre-treatment of slag application in construction and environmental treatment. Decades ago, a method for zinc recovery from steelmaking slag through ammonia and carbon dioxide leaching has been reported (McIntosh and Baglin 1992; Peters and Colo 1978). It was found that 85% zinc and 90% lead could be recovered by NaOH leaching within 2 h (Orhan 2005). Lenz and Martins (2007) successfully recovered Zn and Pb from steelmaking slag through precipitation after leaching (Lenz and Martins 2007).

Thermal (heating) treatment was reported to be an effective method for recovery Zn, Pb, and Cr due to the volatile property of these metals (Jalkanen et al. 2005). Rotary hearth furnace (RHF) is one of the most favorable technologies used in volatile metal recovery. The main principle of RHF is that the metal oxides such as zinc oxide and lead oxide will be reduced to corresponding elemental metals such as Zn and Pb under radiation heating in the presence of carbon (Ichikawa and Morishige 2002). The process could be simply described as Eq. (4). The volatile metals gasified will be separated from the slag and will go into exhausted gas. The vapor of the metals will turn to solid phase after cooling, and thus, the recovery is completed.

$$\begin{aligned} &\mathrm{Me}_m\mathrm{O}_m + n\mathrm{C/CO} \longrightarrow m\mathrm{Me} + n\mathrm{CO/CO_2} \\ &\mathrm{C} + \mathrm{O_2} \longrightarrow \mathrm{CO_2} \\ &\mathrm{C} + \mathrm{CO_2} \longrightarrow \mathrm{CO} \end{aligned} \tag{4}$$

where Me is metals.

In fact, the recovery of valuable metals from slag is also a way for iron and lime recycling since the residue will mainly contain iron and lime after metal recovery process. In addition, leaching could be an alternative of safe disposal of iron- and steelmaking slag besides thermal solidification which uses binders such as clay, fly ash, cullet and sand, cements, and anhydrite to stabilize the hazardous metals in the slag through high-temperature treatment (Tang et al. 2008; Wang et al. 2017).

Outlook

In fact, the slag application is mainly decided by its composition. As described in above sections, iron- and steelmaking slag has been widespreadly studied in construction and environmental treatment, and used to recovery valuable substances such as iron, lime, and heavy metals, as well. Application of the slag in these fields could extensively mitigate the increasing pressure for slag management. Among all, in present, use of the slag in road construction and building construction is the most effective and popular slag management strategy all over the world due to the mature technology and large quantity requirement in slag. However, high transportation cost, the risks on volume stability of the construction, and release of hazardous substances (heavy metals) have impacted the slag application. The use of the slag in environmental treatment including water treatment as adsorbent, filtration media, and neutralizing agent, in soil as soil conditioner and fertilizer, and in greenhouse capture and storage, are alternatives of slag management. However, different iron- and steelmaking processes make the property of generated slag varied, and thus, the application of the slag in environmental treatment is complicated. The recovery of useful substances from the slag is economical and promising method in slag management as iron and lime in large fractions in slag after recovery can be reused in iron- and steelmaking industry and the slag after heavy metals extraction can be safely disposed or used as soil conditioner or fertilizer.

Overall, to some extend the current management on iron- and steelmaking slag could solve the large amount slag disposal problem; however, there are still challenges. The following work is required for cost-effective use and safe disposal of the slag:

1. Study on proper treatments for enhance volume stability of the slag in construction is highly demanded;
2. Long-term behavior of the toxic substances in slag using in construction should be evaluated, and proper measures should be taken to avoid the negative impacts of the slag on environment and human beings;
3. The cost balance should be evaluated on slag application in environmental treatment as well as on substance recovery from slag;
4. Slag application in environmental treatment has great potential as it simultaneously reduces slag burden to environment and benefits to environmental treatment;
5. Most of the applications of slag in environmental treatment are still in study stage (lab-scale); therefore, practical application of the slag should be investigated.

The production of slag is inevitable as by-product of iron- and steelmaking industry. As the increase of iron- and steel production, slag management becomes difficult due to the large amount generation. The promising management methods including utilization of iron- and steelmaking slag in construction and environmental treatment have been extensively reported; however, the concern on volume stability and the release of toxic metals have to be given special attention before application. Recovery of valuable substances from slag is another suitable way of the management. In fact, the current usage of the slag is still in the initial stage. Its application in environmental treatment has great potential, and great efforts are demanded in the field.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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