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REVIEW

A review of steel slag usage in construction industry for sustainable development

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Abstract Use of by-products from the steelmaking process can play an important role in achieving sustainable development. The available literature suggests that the use of iron and steel industry slags as mineral admixture or partial replacement of cement improves the microstructure of the concrete as well as its mechanical and durability characteristics. This paper reviews utilization of steel slag (SS) in the construction industry by considering current and possible future utilization fields, advantages of SS usage, and problems associated with its use. Strength and durability evolution of concretes or mortars containing SS in different ratios as aggregate or cement replacement material, combined use of ground granulated blast furnace slag with SS, and some relatively new fields of utilization of SS are also addressed. Improvements in and results of SS utilization in cement and concrete are discussed by addressing its beneficial effects. This article could help researchers to understand the recent developments in evaluation of SS in the construction industry.

Keywords Cement · Concrete · Slag · Steel · Sustainability

1 Introduction

Environmental regulations require minimization of industrial waste disposal and force the reuse of those waste materials in many countries worldwide. For this reason, industrial wastes and/or some by-products cause significant problems for these countries. Sustainable development can be described as enhancing quality of life, thus allowing people to live in a healthy environment, and improving social, economic, and environmental conditions for present and future generations. An overall life cycle assessment should be performed in

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order to consider the sustainability of any material. In this assessment, the extraction, transportation, transformation, and processing of the raw materials, the use and the maintenance of the product, and finally the elimination or recycling of the product must be analyzed. One of the goals of sustainable steelmaking is to reduce materials sent to landfills and to reduce the amount of hazardous waste. The cement and concrete industries can make substantial contributions to sustainable development by using slags. Utilization of steel slag (SS) as a raw material in another industry has a great environmental aspect, since the reuse or recovery of this slag provides environmentally related benefits.

The reduction of the use of Portland cement by replacing it with supplementary materials, especially if these are by-products of industrial processes or recycled materials, is one of the basic steps toward the achievement of concrete sustainability (Meyer 2009). It is generally assumed that an improvement in compressive strength will improve its mechanical and durability properties. Durability of concrete, which plays a critical role in controlling its serviceability, is mainly dependent on the capacity of a fluid to penetrate the concrete's microstructure, which is called permeability (Zhang and Zong 2014). The construction industry consumes significant amounts of natural minerals. On the other hand, 50 million tons of SS per year are produced worldwide, while nearly 12 million tons of SS are produced annually in Europe (Altun and Yılmaz 2002). Production of SS depends on the composition of the steel and on the steel production process. The slag produced in the basic oxygen furnace (BOF) and electric arc furnace (EAF) processes amounts to approximately 120–150 kg per ton of steel produced (ASA 2002). These slags contain recoverable and reusable materials. In order to build sustainable development, the concrete industry should decrease use of natural resources in one sense and utilize steel slag (SS). While some portions of SS are recycled in some developed countries such as Germany, Japan, and USA, high percentages of SS are directly discarded in many countries (Motz and Geiseler 2001). The detrimental effects of the industry on the environment can be reduced by developing environmental-friendly technologies.

This paper reviews utilization of SS in the construction industry. Current and potential utilization fields, some problems associated with its use, and strength and durability properties of cement, aggregate, mortar, concrete or bricks incorporating SS in different ratios are discussed. Combined usage of ground granulated blast furnace slag (GGBFS) and SS, and some relatively new fields of usage are also addressed in addition to the environmental impacts of SS utilization in different fields.

2 Steel slag output and reclamation

World crude steel production reached 1607 megatons (Mt) for the year 2013, up by 3.5 % compared to 2012 (see https://www.worldsteel.org/media-centre/press-releases/2014/World-crude-steel-output-increases-by-3-5–in-2013.html). China, the biggest producer, produced 48.5 % of this total production. The other important producers are Japan, European Union (EU), United States (US), India, Russia, and South Africa. Annual SS output in 2014 was about 170–250 million tons worldwide, based on typical ratios of slag to steel output. The amount of SS produced by European Slag Association (EUROSLAG) members in 2012 was about 24.7 million tons. 46 % of this production was BOF slag, 38 % was EAF slag, and 17 % was secondary steel slag. EUROSLAG members reused 24.7 million tons of SS in 2012. 43 % of this utilization was in road construction (EUROSLAG 2015). The amount of slag in the iron and steel industry in Turkey is approximately 5 million tons per year at the end of the year 2009. 87 % of the iron and steel industry slag is being stored in the plants. In Turkey, only 1 % of slag was recycled and used in cement production (see http://www.recyclingdergisi.com/HaberlerDetay.aspx?ID=34). There is no comprehensive industry statistics on slag produced versus slag utilized in the US. Data on actual US slag production are unavailable, but it is estimated to have been in the range of 18–25 million tons in 2013 (see http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel_slag/mcs-2014-fesla.pdf). The current utilization rate of SS in China is only 22 % (Yi et al. 2012). The amount of SS (EAF + BOF) produced in Japan in 2012 was about 14,397 tons. In Japan, the reuse rate was very high and is about 100 % in different sectors in the same year (see http://www.slg.jp/e/statistics/index.html). While rate of reuse is very high in developed countries such as Japan or Germany, it is still very low in other less-developed countries. This is a source of environmental problems for these countries and also for the world.

3 Steel slag (SS)

SS is produced as the nonmetallic co-product of steel production. Solid SS exhibits block honeycomb shape and high porosity. It consists primarily of oxides of calcium, iron, silicon, aluminum, magnesium, and manganese in complexes of calcium silicates, aluminosilicates, and aluminoferrite. These compounds are generally similar to those found in the natural environment. SS is generated in the process of refining hot metal produced by a blast furnace into steel (Takahashi and Yabuta 2002). Historically, slag has been used for the construction of roads and as filler material. However, more recently, slag uses have been expanded to include use as a cement additive, landfill cover material, and for a number of agricultural and construction applications (Proctor et al. 2000).

SS is a byproduct from either the conversion of iron to steel in a BOF, or the melting of scrap to make steel in an electric arc furnace (EAF) (Shi 2004). BOF slag (LD-converter slag) is formed in a BOF during the conversion of hot metal from the blast furnace into steel. It is generated by the addition of lime and/or dolomite that combines with silicates and oxides to form liquid slag. The molten slag is poured into pits or ground bays where it air-cools under controlled conditions, forming crystalline slag. EAF slag is produced during the manufacture of steel by EAF process. In order to adjust the required technical properties for a specific use, different measures like weathering, crushing, and/or sieving are performed on the crystalline slag. SS consists primarily of CaO, MgO, SiO_2, and FeO. Mineralogical composition of SS is highly variable from source to source. The reason for this variability is the variation of chemical composition from source to source. It has poor cementing properties due to low reactive calcium silicate content. SS contains high concentrations of CaO and MgO in the form of silicates, ferrites, aluminates, oxides and some free CaO and MgO that can cause immediate and long-term expansions. Free CaO content of steel slag aggregates (SSA) can be determined with standardized methods such as described in the European Standard EN 1744-1:2009+A1 (2013). The potential expansion of oxidizing slag can be evaluated according to the ASTM D-4792, which contains a test method for determining the compliance of SS-containing components subjected to hydration. The expansion of cement-based materials containing free CaO or MgO is due to the delayed hydration of these two oxides. Volume stability is a key criterion for using SS as a construction material. Volume stability of SS is evaluated by immersion expansion ratio in USA and Japan (Yi et al. 2012). In Germany, steam test is used for road construction and boiling test is used for hydraulic construction. 4 % free CaO content is generally the upper bound value for asphaltic layers in Germany (Motz and Geiseler 2001). After 2009, a national standard was developed for immersion expansion test in China. Practical methods should be developed in order to decrease the free CaO content of SSA. Aging or weathering of slag, and steam and autoclave curing of slag are generally performed to reduce expansive oxide content. In order to use SS in concrete, treatment is generally recommended to reduce the free oxides. A general method usually used to overcome the expansion problem is to store the SS for aging in stockpiles for about 6 months before using it. During this weathering process, the SS is required to be in contact with water so that the hydration process between lime and water takes place. Untreated SS may be suitable for unbound aggregate applications (Wang et al. 2010). Some aging processes such as outdoor aging, Sumitomo–Kawasaki aging, or steam aging can improve volume stability of SS (Han et al. 2002; Altun and Yılmaz 2002). Autoclave treatment methods can lower the content of free lime. Lun et al. (2008) suggested the autoclave treatment process instead of steam treatment due to the difference of hydraulic activity of periclase and over-burn free lime under steam and autoclave conditions. Moreover, cementitious performance of SS could be improved by applying mechanical, thermal (Ducman and Mladenovič 2011; Qian and Suna 2002) or chemical (Li et al. 1997; Zhang et al. 2008) activation approaches. These techniques need additional energy and complicated processing. The SS whose cementitious performance was improved is called modified steel slag (MSS), and the modification effect varies with the chemical and mineral compositions of SS. Li et al. (2011) mixed BOF slag with EAF slag in appropriate ratios and heated again at high temperature, thus producing a kind of MSS with improved cementitious activity. They stated that the improvement of cementitious activity of MSS results from increased alite content, smaller alite crystals, and formation of cementitious C_6AF_2. The hydration rate of SS was investigated by Wang and Yan (2010). It can be seen from their results that the hydration process of SS is very similar to that of cement. The activity of the main components, which are C_2S and C_3S, is very low. The hydration rate of SS could be accelerated by increasing its fineness. Belhadj et al. (2014) presented a hydration study of BOF slag pastes. According to their experimental results, BOF slags containing 40 % C_2S have attractive mechanical properties. Hydration tests showed pastes swelling due to the hydration of CaO contained in BOF slags. Therefore, they proposed a lime extinction procedure as an alternative to the standard EN 13282-2. They concluded that their approach is more effective for these materials. The volume expansion of pastes cured in water is avoided.

High water absorption capacity is a distinct property of SS; that property of SS has effects on the water content of the concrete mixture. Since water–cement ratio (w/c) is a major factor that influences most engineering properties of fresh and hardened concrete, it is expected that the inclusion of SS would have effects on the concrete workability produced from it. Olonade et al. (2015) used crushed and sieved SS, which has 19.13 % water absorption capacity, as a partial replacement material for sand in structural concrete. They found that as the replacement ratio increased, the w/c ratio decreased for a constant slump value. Subatra Devi and Gnanavel (2014) and Yang et al. (2013) studied workability of concrete including SS as aggregate or sand. They stated that the slump decreases as the percentage level increases. Concrete containing SS can get good workability by adding the proper superplasticizer amount. On the other hand, the 48-h water absorption of SS aggregate concretes was less than that of the limestone aggregate concrete (Maslehuddin et al. 2003).

A detailed examination of the effect of SS usage in cement and concrete is reported in the following sections.

3.1 Environmental impacts

SS consists of several different types of heavy metals in various concentrations. However, heavy metal leaching is mostly related to stainless slag because it contains a higher amount of Cr and Ni than ordinary slag. In spite of this, SS requires a detailed study of its potential toxicity. Because SS contains trace amounts of potential toxic elements such as chromium and vanadium, its impacts on the environment and human health must be taken into account (Chaurand et al. 2007). Chromium is a redox active metal that persists as either Cr (III) or Cr (VI) in the environment. These two oxidation states have opposing toxicity and mobility. Proctor et al. (2000) showed differences in TCLP concentrations (mg/L) for these three types of slag (Table 1). TCLP leachate concentrations were very low; the only metals detected at greater than 1 mg/L were barium and manganese. The mean value of hexavalent chromium that was shown in the reference by Proctor et al. (2000) as a steel industry slag characterization result was 1.2 mg/kg for EAF slag samples. Since total chromium concentrations are highest in EAF slag, EAF slag is more likely to contain hexavalent chromium than BOF and BF slags. The hexavalent chromium level shown in Table 1 for EAF slag is not considered to be a health concern. It is far below the limit values of soil screening levels and inhalation exposures (270 mg/kg) at residential sites given by the United States EPA. The chromium (VI) Directive issued by the European Commission stated similar limits. It states "cement and cement-containing preparations may not be used or placed on the market if they contain, when hydrated, more than 0.0002 % (2 ppm) soluble chromium (VI) of the total dry weight of the cement".

About 100–150 kg SS is co-produced for 1000 kg steel, and a huge amount of slag storage is generated annually worldwide. Despite the problems associated with SS, this storage should be evaluated for sustainable development, and it has many possibilities for use in the cement and concrete industry (Lizarazo-Marriaga et al. 2011). Millions of tons of SS are produced in iron and steel factories worldwide every year. Although an important amount of SS is used, millions of tons of these slags are still dumped. The ratio of the

Table 1 Mean TCLP concentrations values for BF, BOF, and EAF Slag [adopted from Proctor et al. (2000)]

Metal	Mean values of TCLP concentration (mg/L)			Metal	Mean values of TCLP concentration (mg/L)		
	BF	BOF	EAF		BF	BOF	EAF
Antimony	0.005	ND	0.003	Manganese	26	30.15	21
Arsenic	0.003	0.002	0.002	Mercury	ND	0.0003	0.0002
Barium	1.0	0.41	1.4	Nickel	ND	0.012	0.07
Beryllium	0.03	ND	ND	Selenium	ND	ND	0.003
Cadmium	0.002	0.001	0.002	Silver	ND	0.0064	0.005
Chromium (total)	0.06	0.01	0.04	Thallium	ND	ND	ND
Chromium (VI)	0.01	ND	0.006	Zinc	0.11	0.07	0.11
Lead	ND	0.004	0.004				

utilized portion to total quantity is high in industrialized countries. For example, the dumping rate of SS in Germany is only 7 % (Motz and Geiseler (2001). In fact, SS was used in the construction industry as asphalt and concrete aggregate in granular bases, as cement replacement, or in embankments or fill applications in some countries for decades. New utilization fields should be sought out, and the rate of utilization should be increased in the current fields of application. The cement industry could use SS as raw material for clinker production or blended in the cement as a mineral admixture (Monshi and Asgarani 1999; Tsakiridis et al. 2008; Xuequan et al. 1999; Rai et al. 2002; Altun and Yilmaz 2002; Kourounis et al. 2007). According to Motz and Geiseler (2001), the targets of the European Community hold us responsible for saving natural resources by using industrial co-products and increasing their utilization rate. In the case of cement manufacture, the use of GGBFS instead of clinker reduces the overall process CO_2-emissions as a result of fuel savings and avoidance of sintering limestone or other calcareous materials.

SS slag has some advantageous properties for use as an ideal aggregate for road construction. It has high impact and crushing strength compared to natural rocks (e.g. basalt). It has increased skid resistance, excellent affinity to bitumen, and good resistance to polishing. Based on high frictional and abrasion resistance, steel slag is used widely in industrial roads, intersections, and parking areas where high wear resistance is required (Hainin et al. 2012). The first studies on SS in asphalt mixtures reported in the literature date back to the beginning of the 1970s (Emery 1984). While the studies from the 1970s to 2000s usually covered physical and chemical properties, Motz and Geiseler (2001) studied the possibility of reusing SS in road paving, focusing on leaching tests to evaluate environmental behavior and on expansion tests to determine volume stability. The physical properties of SS aggregates were superior to those of crushed limestone aggregates. SS has high bulk density and is suitable for hydraulic engineering purposes. Other technical properties are comparable or even better than those of natural aggregates. Its impact and crushing value is high, and it has rough surface texture. These properties make it a good aggregate for unbound and bituminous bound mixtures. The volume stability of SS is important for unbound and bound layers of roads. SS has been used successfully in different European countries as a road construction material because of its advantageous technical properties (Motz and Geiseler 2001). There are free lime limits in the literature for SS use as a granular material; that limit is given as 4 % in road construction. Wang et al. 2010 developed an equation that could be used as a criterion for the use of SS as a granular material. Overall expansion will not occur if this criterion is satisfied.

Other researchers (Ahmedzade and Sengöz 2009; Xue et al. 2006; Wu et al. 2007; Asi et al. 2007) also studied usability of SS as coarse aggregate in asphalt mixtures. Their results showed similar characteristics between the mixtures containing natural aggregates and SS. The successful utilization of SS as an aggregate in pavement construction can provide a new and more cost-effective approach for aggregate resources and decrease the threats of solid waste to the environment (Wu et al. 2007).

Sorlini et al. (2012) performed several tests to characterize physical, geometrical, mechanical, and chemical properties of EAF slag, and they studied the environmental suitability of this slag in bituminous paving mixtures. They examined bituminous mixtures of aggregates for flexible road pavement containing up to 40 % EAF slag. They found wear resistance and water absorption values comparable with values obtained with natural materials. Mechanical characteristics were similar or even more satisfactory than the mixtures obtained using natural aggregates. The concentrations of all pollutant elements were below the limits.

SS can be used to produce energy-saving cement. In SS cement preparations, clinker is about 15–30 %, SS around 30–40 %, and blast furnace slag is around 40–50 %. Given that about 5 GJ of energy are needed to produce 1 t of clinker, manufacturing 1 t of SS cement consumes only about 0.75–1.5 GJ of energy. This represents an energy savings of 70–85 %. Meanwhile, it only consumes about 0.2–0.5 t of virgin raw materials against about 1.4 t for 1 t of ordinary Portland cement. This saves 70–85 % of virgin natural resources and cuts greenhouse gas emissions by 70–85 % (see http://www.globalcement.com/magazine/articles/419-steel-slag-a-supplementary-cementious-material-and-basis-for-energy-saving-cement).

3.2 Steel slag aggregate (SSA)

Replacing some portion of natural aggregates with SSA would lead to considerable environmental benefits. The aggregates typically account for about 75 % of the concrete volume and play a substantial role in different concrete properties such as workability, strength, dimensional stability, and durability (Saravanan and Suganya 2015). When some portion of this huge volume is replaced by SSA, then a huge amount of natural aggregate could be saved. For example, according to ERMCO (2014) statistics, a total of 217.7 million cubic meters of ready-mixed concrete (RMC) was produced in 16 European Union (EU) countries in 2013. This means that they used about a 100 million cubic meters of coarse aggregate for RMC production. 5 million cubic meters of natural coarse aggregate could be saved if SS replaces 50 % of natural coarse aggregate for only 10 % of this total RMC production. As a result, 10–12 million tons of SS, which is about 40 % of annual SS produced by European Slag Association (EUROSLAG) members, are used in the concrete industry. Although there are many obstacles in using SS as a concrete aggregate or cement raw feed, studies should be continued.

The improved properties of concrete prepared with SSA indicate that this material can be beneficially utilized in Portland cement concrete. The SSA concretes may be proportioned to have 50 % coarse aggregates and 50 % fine aggregates to reduce its weight (Maslehuddin et al. 2003). Performance of EAF slag concretes is similar to that of a more traditional concrete in terms of its strength and slightly less so in terms of its durability (Manso et al. 2006). Wang et al. (2008) used SS as sand in ordinary concrete and showed that the compressive strength of concrete with the mixture of SS is very close to that of ordinary concrete on the 7th and 28th days. Vasanthi (2014) tested flexural behavior of slabs containing SS as partial replacement of natural coarse aggregate of size 20 mm as opposed to that of normal concrete. M30 and M40 grade concrete was used, and tests were conducted by casting slabs for various proportions of SS replacement of coarse aggregate with 0, 30, 60 and 100 %. The use of SS as replacement of coarse aggregate in concrete was beneficial for better workability and strength imparted up to a 60 % replacement level. Gokul et al. (2012) used mild steel slag as an effective replacement for aggregate. They concluded that the compressive strength and other tests show that mild steel slag is superior to natural aggregates. Addition of mild steel slag as a fine aggregate improves good interlocking and eventually improved the mechanical properties of the mixes. The use of fine-crushed mild steel slag also improves the stiffness of the concrete model. The SSA concretes achieved indirect tensile strengths and elasticity moduli that were similar to the reference specimen, but with a slightly higher compressive strength (San-Jose et al. 2014). Not only strength development but also durability of the SSA concretes improved. For example, Arribas et al. (2014) found that SSA concrete undergoing freeze–thaw cycles showed better behavior than limestone concrete. The SSA concrete was more stable than the normal concrete with regard to linear expansion and contraction. The expansion of the slag aggregate mortars did not exceed the limit given for alkali–silica reaction (ASR). Moreover, the SSA concrete showed greater susceptibility to corrosion than the normal limestone concrete. Tarawneh et al. (2014) studied the effect of using SS combined with limestone aggregates in different ratios on improving the mechanical properties of hardened concrete. They used SS in three main phases, which are as a replacement of sand, as a replacement of fine aggregate, and as a replacement of coarse aggregate. The percentages of replacement in the concrete mix ranged from 0 to 100 %. They found that in all replacement ratios, the flexural strength increased with the increase in slag ratio. Tarawneh et al. (2014) found that SSA has better abrasion factor and impact value than natural aggregate. Also, Vardaka et al. (2014) observed that the incorporation of SS leads to a significant reduction in abrasion, which must be attributed to the better bonding and packing between the aggregates and the cement mortar in pervious concrete samples. Polanco et al. (2011) tested mixtures containing BOF slag. They observed loss of strength in almost all tests in comparison with the control mixture. However, they recorded that the durability test was only positive in the case of concrete prepared with EAF slag in the form of coarse and fine aggregates. On the other hand, Kuo et al. (2014) recommended 30 % replacement as a threshold for electric arc furnace oxidizing slag (EOS), a type of EAF slag. They reported that if this critical range is exceeded, there might be earlier expansion aging. Maslehuddin et al. (2003) conducted mechanical and some durability tests to ascertain the mechanical properties and durability characteristics of Portland cement concrete prepared with SSA. The compressive strength of SSA concrete was marginally better than that of crushed limestone aggregate concrete. However, they did not report significant improvement in the flexural and split tensile strength in the SSA concrete.

Manso et al. (2004) conducted an experimental study to produce concrete with good properties using oxidizing electric arc furnace (EAF) slag as fine and coarse aggregate. They deduced that the concretes obtained with oxidizing slag as aggregate have good properties in both the fresh and the hardened state and have a wide range of possible uses. Tests were performed on the durability of these concretes showing an acceptable behavior against aggressive environments. Manso et al. (2006) also performed durability tests of concrete containing EAF slag as fine and coarse aggregate. Accelerated aging tests (autoclave, aging), chemical reactivity test (alkali–aggregate), and environmental tests (freezing–thawing, wetting–drying, leaching) were applied. Their results showed that the performance of EAF slag concretes was similar to that of a more traditional concrete in terms of its strength and slightly less so in terms of its durability (Manso et al. 2006). The high porosity of EAF slag is reported as an obstacle in producing a freezing-resistant concrete. Pellegrino and Gaddo (2009) found similar results in terms of mechanical strength and durability. They also suggested use of a small amount of air-entraining agent in order to improve resistance to wetting and drying cycles.

Some researchers used SS as binder or aggregate with other industrial by-products to manufacture high strength concretes in last decades. They found noticeable advantageous use of EAF and LF slag. For example, according to Papayianni and Anastasiou (2010), it is possible to produce high strength concrete by using high calcium fly ash (HCFA) as 50 % of the total binder and EAF slag as aggregates. The use of EAF slag aggregates in concrete can increase compressive strength up to 20 % compared to conventional concrete. The use of LF slag as 30 % of the total binder and EAF slag as coarse aggregates seems to give a concrete with 28-day strength levels equal to those of conventional concrete. Not only the strength but also durability of the concrete can be improved by using these slags. Papayianni and Anastasiou (2010) reported significant improvements on abrasion resistance and impermeability of the concrete. Moreover, EAF slag aggregate concrete shows increased fracture toughness. Peng et al. (2010) used SS powder as cement replacement material at different proportions to prepare reactive powder concrete. According to their test results, the reactive powder concrete containing high volume binary (silica fume + SS) or ternary (silica fume + ultra-fine fly ash + SS) blends had no significant mechanical performance losses.

3.3 Cement replacement

At least 1.5–1.75 tons of raw material are required to produce 1 ton of Portland cement (Post and Alsop 1995). Steelmaking by-products could be used as a partial replacement of cement without decreasing the compressive strength significantly (Tüfekçi et al. 1997; Monshi and Asgarani 1999). Steel slag cement (SSC) had been developed as a new kind of cement in China. It is a product of a ground mixture of SS, BFS, Portland cement clinker, gypsum, and admixture. Cement-containing SS has much better corrosion resistance than conventional Portland cement. Shi (2002) explored potential applications for ladle slag fines in cement and concrete production. Their experimental results have indicated that ladle slag fines show significant cementitious property in the presence of an alkaline activator. As the fineness of the slag increases, the cementitious property of the slag increases. However, Wang et al. (2013) concluded that the activity of super-fine SS is obviously lower than that of cement, and replacing part of the cement with super-fine SS weakens the cementitious properties of the binder. Portland cement was commonly replaced partly by mineral supplementary materials such as fly ash, silica fume, and BFS to produce blended cement. The main compositional differences between SS and Portland cement are the high iron oxide content and the presence of substantial free lime in the SS. The contents of free CaO (lime) and free MgO (periclase) are the most important components. The presence of free calcium oxide, accounting for more than 1 % of cement by mass, causes the appearance of white powder in the form of sediment. Free calcium oxide causes calcium carbonate, and this carbonate settles down in the form of a white powder that may cause obstructions in the pore system of the concrete mass. These obstructions are particularly dangerous in the case of freezing, which renders great damage to pavement structures (Barišić et al. 2010). Presence of free calcium oxide can also cause loss of strength in concrete. Depending on the content of free lime and/or free MgO, this reaction causes a volume increase in the slag, mostly combined with a disintegration of the slag pieces and a loss of strength (Alanyali et al. 2009). There is no global standard available that specifies the usage of SS in cement production, except for the GB/T 12957-05 and GB 13590-92 Chinese National Standards (Chinese National Standard 1992). GB/T 12957-05 Chinese National Standard specifies the method for the testing of steelmaking slags' hydraulic reactivity in determining the steel-making slag to be used as a cement mixture additive (Chinese National Standard 2005). Furthermore, the GB 13590-92 Chinese National Standard specifies the composition, properties, testing, storage, and applications for steel and iron slag cement. Kourounis et al. (2007) investigated the properties and hydration of blended cements with steelmaking slag. They measured physical and mechanical properties of mortar incorporating 0–5 mm SS. The microstructure of the hardened cement pastes was also examined. As a result, cements containing 15 or 30 % slag satisfied the requirements of the strength class 42.5 of EN 197-1. The addition of SS slows down the hydration of the blended cements due to the morphology of the contained C_2S and its low calcium silicate content. Alanyali et al. (2009) studied BOF slag as a clinker additive in cement. Their study confirmed that the compressive strength of concretes produced by addition of BOF slags up to 30 % by mass were within the values of Grade-325 and Grade-425 steelmaking slag cement. Barišic et al. (2014) showed that curing age is important for cement-stabilized base courses. Barišic et al. (2014) used SS as aggregate and concluded that compressive and indirect tensile strength increase with curing age.

3.4 Mortar and bricks

Shrinkage of SS–cement mortar specimens was similar to that of sand–cement mortar. The initiation time of rebar corrosion and time to cracking of concrete specimens was longer in SS aggregate concrete compared to crushed limestone aggregate concrete. The improved properties of concrete prepared with SS aggregates indicate that SS can be beneficially utilized in Portland cement concrete (Maslehuddin et al. 2003). Some attempts have been made to use SS in the production of clay bricks. According to experimental results of Korany and El-Haggar (2001), water absorption values of masonry brick groups containing SS are below the limit value (13 %) given in related ASTM standard. They found higher bulk density values than in the control. Also, higher compressive strength results were reached for all masonry groups at 28-day age compared to the control and commercial bricks. Shih et al. (2004) investigated the characteristics of bricks made from SS. They manufactured bricks in which the slag content in the clay-slag mixture varied from 5 % to 10, 20 or 30 % by weight. Water absorption, loss on ignition, firing shrinkage, and compressive strength tests were conducted. They proposed a maximum 10 % SS addition. Rodriguez et al. (2009) manufactured masonry mortars including ladle furnace slag instead of sand and cement in different percentages. Workability and mechanical strength of the mortar samples were investigated. They showed that appropriate additions of ladle furnace slag in masonry mortars improve workability and mechanical strength. Moreover, the incorporation of ladle furnace slag to complement sand and in partial replacement of cement reduces the need to use admixtures in masonry mortars. Faraone et al. (2009) also used SS as coarse aggregate in concrete, and they found similar results to those of Rodriguez et al. (2009).

The ladle furnace reducing slag is suitable for use in masonry mortars, providing mixtures with good properties such as binding, workability, shrinkage, and durability (Manso et al. 2005). It is suitable for paving roads with low levels of traffic, such as country roads, as a soil–cement mixture. Low cost and time dependent properties of ladle furnace reducing slag, i.e., resistance to load and durability, also contribute to its potential use.

3.5 SS in self-compacting concrete

Self-compacting concrete (SCC), defined as a composite material that can be placed and compacted with little or no vibration effort, needs a higher content of fine material in order to improve workability. The effects of fine powder of BOF slag on the rheological characteristics of cement pastes derived from SCC mixtures were studied by Calmon et al. (2013). They used BOF slag, BF slag, fly ash, and limestone filler blended in different proportions, and the workability-related properties of these were evaluated. Test results showed that BOF slag could be an alternative material to be incorporated in SCC mixtures as fine filler. Moreover, the blend of BOF slag with other cementitious materials showed similar rheological behavior compared to the use of BOF slag only. Anastasiou et al. (2014) studied the use of ladle furnace slag (LFS) as filler in SCC. Different contents of

LFS filler, ranging from 60 to 120 kg/m^3, and steel fibers, ranging from 0 % to 0.7 %, were used. LFS seemed to have a positive effect on strength development concerning 28-day and 120-day compressive strength. Freeze–thaw resistance test results showed that by increasing LFS filler content, the durability of the slag-incorporated concrete increased. Also, they showed that LFS could also be combined with steel fibers in order to produce a high-performance SCC.

3.6 Durability and other

The influence of ground BOF slag whose specific surface area was 453 m^2/kg on the compressive strength and durability characteristics such as drying shrinkage, permeability to chloride, and carbonation resistance of concrete was investigated by Wang et al. (2013) with constant water–binder ratio. According to their experimental results, the concrete with BOF slag had a lower early compressive strength as compared with the Portland cement concrete. However, the late compressive strength of the concrete with SS exceeded that of the Portland cement concrete. As the content of SS increased, the concrete tended to have a higher late compressive strength. A very similar development trend of drying shrinkage to the pure cement concrete was observed in the case of 15 % SS replacement. Also, the ultimate drying shrinkage of the reference, 15 % replaced, and 30 % replaced concretes are found to be very close to each other. SS tends to increase the permeability of concrete with high water–binder ratio, especially when the SS replacement is high. At low water–binder ratio, the SS replacement has little influence on the permeability of concrete at 360 days. It is clear that SS has less negative effect on the permeability of concrete at lower water–binder ratio. They concluded that SS has little influence on the carbonation of concrete with constant 28 days' compressive strength if no less than 3 days' initial standard curing is ensured.

Onoue et al. (2014) experimentally investigated the fatigue characteristics of steel-making slag concrete (SSC) under compression in submerged conditions for applications in marine and harbor structures. When they used hot metal pretreatment slag or converter slag as fine and coarse aggregates in concrete, the fatigue strength of SSC was slightly less than that of ordinary cement concrete. However, when they used ground hot metal pretreatment slag as fine and coarse aggregates, then the fatigue strength of SSC was improved.

High-temperature treatment could be used to improve the stability of SS. Ducman and Mladenovič (2011) investigated the potential use of EAF slag in refractory concrete for industrial applications. They prepared refractory concrete using EAF slag and bauxite aggregate and 25 wt% of high alumina cement. They used EAF slag aggregate that was heated from room temperature up to 1000 °C and then cooled down to room temperature again. Since an irreversible transformation occurred between 700 and 800 °C by the transition of wustite into magnetite, the slag gains thermal stability. This thermal MSS could remain stable up to 1000 °C and could be used in refractory concrete instead of conventional refractory aggregate such as bauxite.

A relatively new and different usage form of SS was developed by Pati and Satapathy (2015); that usage is wear-resistant coatings using LD slag premixed with Al_2O_3. They developed surface coatings by plasma spraying technique. Premixing of Al_2O_3 powder with LDS was found to substantially improve the interfacial adhesion. The mixture of 30 % Al_2O_3 + LDS gave maximum adhesion strength with respect to torch input power.

4 SS and GBFS combinations

Use of granulated blast furnace slag (GBFS) as cement replacement in concrete is a common practice due to technological, economic, and environmental benefits (Kumar et al. 2008). On the other hand, the utilization ratio of SS is not very high as it is with GBFS. Both of these materials are used in cement replacement materials. The combination of ground granulated blast furnace slag (GGBFS) and ground steel slag (GSS) could be used in cement. A special kind of Portland-steel slag-blast furnace slag cement (PSS−BFC) has been commercially marketed in China. It is composed of approximately 30 % SS, 30 % GGBFS, 35 % cement clinker, and 5 % gypsum. In order to increase SS utilization, some researchers such as Yüksel and Özkan (2009), Yüksel et al. (2009), and Guo and Huisheng (2013) investigated the feasibility of SS powder and GGBFS combination in cement-based materials. Figure 1 shows the effect of fineness-replaced material in composite cement and replacement ratio of 30 % SS + 70 % GBFS combination on mortar normalized compressive strength (Yüksel and Özkan 2009). Although as the replacement ratio increases, the normalized strength decreases, the fineness has a positive effect on the strength. It can be concluded that if 60 % Portland cement clinker has been replaced by 30 % SS + 70 % GBFS combination, a higher strength was obtained compared to the reference sample whose normalized strength value was 100. The combination of 80 % clinker + 12 % GGBFS + 8 % GSS was used instead of normal Portland cement by Özkan (2006) and Özkan et al. (2013), and he reported positive effects on compressive strength at normal and elevated temperatures, modulus of elasticity, decomposition of $Ca(OH)_2$, and sulfate resistance of concrete.

Effects of SS powder on workability and durability of C30-grade concrete was investigated by Guo et al. (2014). The combined admixture of GGBFS–SS powder had a lower reactivity and needed longer reaction and setting time. The setting times were slightly retarded. The dry shrinkages were lower, and the abrasion resistance was better. The chemically activated SS powder could improve compressive strengths, resistance to chloride permeation and water permeation, as well as carbonization resistance. Compared

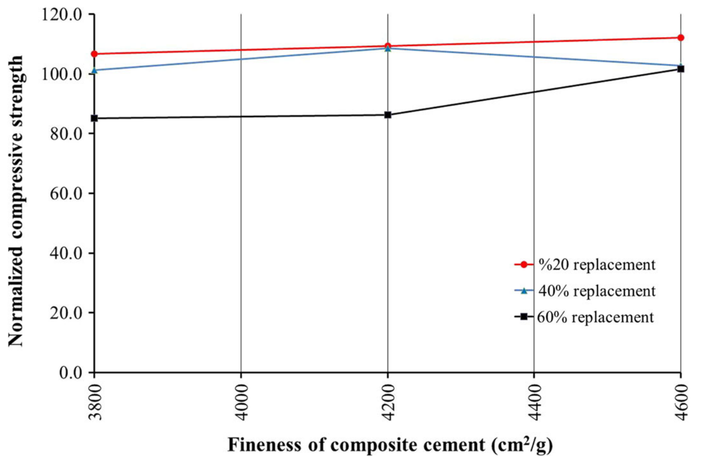

Fig. 1 Alteration of mortar strength with respect to fineness and replacement ratio (Yüksel and Özkan, 2009)

to the concrete with GGBFS, the concrete with combined admixture enhanced the abrasion resistance. The reason for this is that the hardness of SS powder was much stronger than that of GGBFS. The SS powder made an important contribution to concrete hardness.

The workability and durability of a type of sustainable concrete made with steel slag powder were investigated by Guo et al. (2014). Their results showed that when SS powder was added to concrete, workability properties of the concrete were similar to or better than normal concrete. Also, the chemically activated SS powder could improve compressive strengths, impermeability, and carbonization resistance. However, Shuguang et al. (2006) stated that fine SS powder retards the hydration of Portland cement at early age. The major reason for this phenomenon is the relative high content of MgO, MnO_2, and P_2O_5 in SS.

5 Conclusions

This paper presents a review of SS usage in the construction industry for sustainable development. Improvements and results of SS usage in cement and concrete production are discussed by addressing its beneficial effects. In order to achieve sustainable development, large-scale utilization of SS is essential because of environmental problems. In this context, the construction industry can play an important role. Using SS in cement and concrete production as aggregate or as supplementary cementing materials has an important environmental impact associated with higher long-term strength and improved long-term durability. SS has not yet reached a high level of utilization worldwide because of some difficulties, and more studies should be done in the future to overcome the difficulties encountered. However, high levels of utilization in some developed countries give hope for the future. Volume instability due to free CaO and MgO and contaminants such as chromium, lead, and mercury are two basic formidable obstacles in increasing the level of usage. Another difficulty is the high water absorption capacity of SSA as compared with natural aggregate. As a result, SS needs to be pre-processed to resolve these difficulties before use in the construction industry. Certainly, these pre-processes yield extra costs. Therefore, more investigations should be done in the future in order to develop feasible pre-processes and to decrease the rate of potential toxic elements in SS. Additionally, more studies should be done to diversify the usage fields.

References

Ahmedzade, P., & Sengöz, B. (2009). Evaluation of steel slag coarse aggregate in hot mix asphalt concrete. *Journal of Hazardous Materials, 165*(1–3), 300–305.

Alanyali, H., Çöl, M., Yılmaz, M., & Karagöz, Ş. (2009). Concrete produced by steel-making slag (basic oxygen furnace) addition in Portland cement. *International Journal of Applied Ceramic Technology, 6*(6), 736–748.

Altun, I. A., & Yılmaz, I. (2002). Study on steel furnace slags with high MgO as additive in Portland cement. *Cement and Concrete Research, 32*(8), 1247–1249.

Anastasiou, E. K., Papayianni, I., & Papachristoforou, M. (2014). Behavior of self compacting concrete containing ladle furnace slag and steel fiber reinforcement. *Materials and Design, 59*, 454–460.

Arribas, I., Vegas, I., San-Jose, J. T., & Manso, J. M. (2014). Durability studies on steelmaking slag concretes. *Materials and Design, 63*, 168–176.

ASA-Australasian Slag Association. (2002). *A guide to the use of iron and steel slag in roads.* http://www.asa-inc.org.au/uploads/default/files/asa_guide_to_the_use_of_iron_and_steel_slag_in_roads.pdf.

Asi, I. M., Qasrawi, H. Y., & Shalabi, F. I. (2007). Use of steel slag aggregate in asphalt concrete mixes. *Canadian Journal of Civil Engineering, 34*(8), 902–911.

Barišić, I., Dimter, S., & Netinger, I. (2010). Possibilities of application of slag in road construction. *Technical Gazette, 17*(4), 523–528.

Barišic, I., Dimter, S., & Rukavina, T. (2014). Strength properties of steel slag stabilized mixes. *Composites: Part B, 58*, 386–391.

Belhadj, E., Diliberto, C., & Lecomte, A. (2014). Properties of hydraulic paste of basic oxygen furnace slag. *Cement & Concrete Composites, 45*, 15–21.

Calmon, J. L., Tristão, F. A., Giacometti, M., Meneguelli, M., Moratti, M., & Teixeira, J. E. S. L. (2013). Effects of BOF steel slag and other cementitious materials on the rheological properties of self-compacting cement pastes. *Construction and Building Materials, 40*, 1046–1053.

Chaurand, P., Rose, J., Briois, V., Olivi, L., Hazemann, J. L., Proux, O., et al. (2007). Environmental impacts of steel slag reused in road construction, a crystallographic and molecular (XANES) approach. *Journal of Hazardous Materials, 139*(3), 537–542.

Chinese National Standard GB/T 12957–05. (2005). *The Method for the testing of steel-making slags' hydraulic reactivity in determining the steel-making slag to be used as cement mixture additive*. Beijing: Standardization Administration of the People's Republic of China.

Chinese National Standard GB13590-92. (1992). *Steel and iron slag cement*. Beijing: Standardization Administration of the People's Republic of China.

Devi, V. S., & Gnanavel, B. K. (2014). Properties of concrete manufactured using steel slag. *Procedia Engineering, 97*, 95–104.

Ducman, V., & Mladenovič, A. (2011). The potential use of steel slag in refractory concrete. *Materials Characterization, 62*(7), 716–723.

Emery, J. (1984). Steel slag utilization in asphalt mixes. *National Slag Association MF186-1*. http://www.nationalslag.org/sites/nationalslag/files/documents/nsa_186-1_steel_slag_utilization_in_asphalt_mixes.pdf. Accessed 05 May 2015.

ERMCO-European Ready Mixed Concrete Organization. (2014). *Ready-mixed concrete industry statistics*. http://www.ermco.eu/document/ermco-statistics-2013-pdf/. Accessed 18 Oct 2015.

EUROSLAG (The European Association Representing Metallurgical Slag Producers and Processors) (2015). http://www.euroslag.com/status-of-slag/legislation/. Accessed 05 May 2015.

Faraone, N., Tonello, G., Furlani, E., & Maschio, S. (2009). Steelmaking slag as aggregate for mortars: Effects of particle dimension on compression strength. *Chemosphere, 77*(8), 1152–1156.

Gokul, J., Suganthan, S., Venkatram, R., & Karthikeyan, K. (2012). Mild steel slag as a potential replacement for concrete. *International Journal of Current Research, 4*(11), 106–109.

Guo, X., & Huisheng, S. (2013). Utilization of steel slag powder as a combined admixture with ground granulated blast-furnace slag in cement based materials. *Journal of Materials in Civil Engineering, 25*(12), 1990–1993.

Guo, X., Shi, H., & Wu, K. (2014). Effects of steel slag powder on workability and durability of concrete. *Journal of Wuhan University of Technology-Materials Science Edition, 29*(4), 733–739.

Hainin, M. R., Yusoff, N. I. M., Sabri, M. F. M., Aziz, M. A. A., Hameed, M. A. S., & Reshi, W. F. (2012). Steel slag as an aggregate replacement in Malaysian hot mix asphalt. *ISRN Civil Engineering, 2012, Article ID* 459016.

Han, Y. M., Jung, H. Y., & Seong, S. K. (2002). A fundamental study on the steel slag aggregate for concrete. *Geosystem Engineering, 5*(2), 38–45.

Korany, Y., & El-Haggar, S. (2001). Using slag in manufacturing masonry bricks and paving units. *TMS Journal, 19*(1), 97–106.

Kourounis, S., Tsivilis, S., Tsakiridis, P. E., Papadimitriou, G. D., & Tsibouki, Z. (2007). Properties and hydration of blended cements with steelmaking slag. *Cement and Concrete Research, 37*(6), 815–822.

Kumar, S., Kumar, R., Bandopadhyay, A., Alex, T. C., Ravi, Kumar B., Das, S. K., & Mehrotra, S. P. (2008). Mechanical activation of granulated blast furnace slag and its effect on the properties and structure of Portland slag cement. *Cement and Concrete Composites, 30*(8), 679–685.

Kuo, W. T., Shu, C. Y., & Han, Y. W. (2014). Electric arc furnace oxidizing slag mortar with volume stability for rapid detection. *Construction and Building Materials, 53*, 635–641.

Li, D. X., Fu, X. H., Wu, X. Q., & Tang, M. S. (1997). Durability study of steel slag cement. *Cement and Concrete Research, 27*(7), 983–987.

Li, J., Yu, Q., Wei, J., & Zhang, T. (2011). Structural characteristics and hydration kinetics of modified steel slag. *Cement and Concrete Research, 41*(3), 324–329.

Lizarazo-Marriaga, J., Claisse, P., & Ganjian, E. (2011). Effect of steel slag and Portland cement in the rate of hydration and strength of blast furnace slag pastes. *Journal of Materials in Civil Engineering, 23*(2), 153–160.

Lun, Y., Zhou, M., Cai, X., & Xu, F. (2008). Methods for improving volume stability of steel slag as fine aggregate. *Journal of Wuhan University of Technology-Materials Science Edition, 23*(5), 737–742.

Manso, J. M., Gonzalez, J. J., & Polanco, J. A. (2004). Electric arc furnace slag in concrete. *Journal of Materials in Civil Engineering, 16*(6), 639–645.

Manso, J. M., Losañez, M., Polanco, J. A., & Gonzalez, J. J. (2005). Ladle furnace slag in construction. *Journal of Materials in Civil Engineering, 17*(5), 513–518.

Manso, J. M., Polanco, J. A., Losañezc, M., & Gonzalez, J. J. (2006). Durability of concrete made with EAF slag as aggregate. *Cement and Concrete Composites, 28*(6), 528–534.

Maslehuddin, M., Sharif, A. M., Shameem, M., Ibrahim, M., & Barry, M. S. (2003). Comparison of properties of steel slag and crushed limestone aggregate concretes. *Construction and Building Materials, 17*(2), 105–112.

Meyer, C. (2009). The greening of the concrete industry. *Cement & Concrete Composites, 31*(8), 601–605.

Monshi, A., & Asgarani, M. K. (1999). Producing Portland cement from iron and steel slags and limestone. *Cement and Concrete Research, 29*(9), 1373–1377.

Motz, H., & Geiseler, J. (2001). Products of steel slags an opportunity to save natural resources. *Waste Management, 21*(3), 285–293.

Olonade, K. A., Kadiri, M. B., & Aderemi, P. O. (2015). Performance of steel slag as fine aggregate in structural performance of steel slag as fine aggregate in structural concrete. *Nigerian Journal of Technology, 34*(3), 452–458.

Onoue, K., Tokitsu, M., Ohtsu, M., & Bier, T. A. (2014). Fatigue characteristics of steel-making slag concrete under compression in submerged condition. *Construction and Building Materials, 70*, 231–242.

Özkan, Ö. (2006). Heat effects on cements produced with GBSF and SS additives. *Journal of materials science, 41*(21), 7130–7140.

Özkan, Ö., Yılmaz, C., & Koubaa, A. (2013). Prediction of sulfate resistance of cements produced with GBFS and SS additives using artificial neural network. *International Journal of Materials and Product Technology, 46*(4), 215–231.

Papayianni, I., & Anastasiou, E. (2010). Production of high-strength concrete using high volume of industrial by-products. *Construction and Building Materials, 24*(8), 1412–1417.

Pati, P. R., & Satapathy, A. (2015). Development of wear resistant coatings using LD slag premixed with Al_2O_3. *Journal of Material Cycles and Waste Management, 17*(1), 135–143.

Pellegrino, C., & Gaddo, V. (2009). Mechanical and durability characteristics of concrete containing EAF slag as aggregate. *Cement & Concrete Composites, 31*(9), 663–671.

Peng, Y., Hu, S., & Ding, Q. (2010). Preparation of reactive powder concrete using fly ash and steel slag powder. *Journal of Wuhan University of Technology-Materials Science Edition, 25*(2), 349–354.

Polanco, J. A., Manso, J. M., Setién, J., & González, J. J. (2011). Strength and durability of concrete made with electric steelmaking slag. *ACI Materials Journal, 108*(2), 196–203.

Post, P. A., & Alsop, J. W. (1995). *The cement plant operations handbook* (1st ed.). Dorking: Tradeship Publications Ltd.

Proctor, D. M., Fehling, K. A., Shay, E. C., Wittenborn, J. L., Green, J. J., et al. (2000). Physical and chemical characteristics of blast furnace, and electric arc furnace steel industry slags. *Environmental Science and Technology, 34*(8), 1576–1582.

Qian, G. R., & Suna, D. D. (2002). Autoclave properties of kirschsteinite-based steel slag. *Cement and Concrete Research, 32*(9), 1377–1382.

Rai, A., Prabakar, J., Raju, C. B., & Morchalle, R. K. (2002). Metallurgical slag as a component in blended cement. *Construction and Building Materials, 16*(8), 489–494.

Rodriguez, A., Manso, J. M., Aragón, A., & Gonzalez, J. J. (2009). Strength and workability of masonry mortars manufactured with ladle furnace slag. *Resources, Conservation and Recycling, 53*(11), 645–651.

San-Jose, J. T., Vegas, I., Arribas, I., & Marcos, I. (2014). The performance of steel-making slag concretes in the hardened state. *Materials and Design, 60*, 612–619.

Saravanan, J., & Suganya, N. (2015). Mechanical properties of concrete using steel slag aggregate. *International Journal of Engineering Inventions, 4*(9), 07–16.

Shi, C. (2002). Characteristics and cementitious properties of ladle slag fines from steel production. *Cement and Concrete Research, 32*(3), 459–462.

Shi, C. (2004). Steel slag—Its production, processing, characteristics, and cementitious properties. *Journal of Materials in Civil Engineering, 16*(3), 230–236.

Shih, P. H., Wu, Z. Z., & Chiang, H. L. (2004). Characteristics of bricks made from waste steel slag. *Waste Management, 24*(10), 1043–1047.

Shuguang, H., Yongjia, H., Linnu, L., & Qingjun, D. (2006). Effect of fine steel slag powder on the early hydration process of Portland cement. *Journal of Wuhan University of Technology-Materials Science Edition, 21*(1), 147–149.

Sorlini, S., Sanzeni, A., & Rondi, L. (2012). Reuse of steel slag in bituminous paving mixtures. *Journal of Hazardous Materials, 209–210*, 84–91.
Takahashi, T., & Yabuta, K. (2002). New applications for iron and steelmaking slag. *NKK Technical Review, 87*, 38–44.
Tarawneh, S. A., Gharaibeh, E.S., Saraireh, F.M. (2014). Effect of using steel slag aggregate on mechanical properties of concrete. *American Journal of Applied Sciences, 11*(5), 700–706.
Tsakiridis, P. E., Papadimitriou, G. D., Tsivilis, S., & Koroneos, C. (2008). Utilization of steel slag for Portland cement clinker production. *Journal of Hazardous Materials, 152*(2), 805–811.
Tüfekçi, M., Demirbaş, A., & Genç, H. (1997). Evaluation of steel furnace slags as cement additives. *Cement and Concrete Research, 27*(11), 1713–1717.
Vardaka, G., Kiriakos, T., Christos, L., & Stamatis, T. (2014). Use of steel slag as coarse aggregate for the production of pervious concrete. *Journal of Sustainable Development of Energy, Water and Environment Systems, 2*(1), 30–40.
Vasanthi, P. (2014). Flexural behavior of reinforced concrete slabs using steel slag as coarse aggregate replacement. *IJRET: International Journal of Research in Engineering and Technology, 03*(9), 141–146.
Wang, C. L., Qi, Y. M., & He, J. Y. (2008). Experimental study on steel slag and slag replacing sand in concrete. In *Proceedings of a* 2008 *International Workshop on Modelling, Simulation and Optimization. IEEE computer Society*, Hong Kong, China.
Wang, G., Wang, Y., & Gao, Z. (2010). Use of steel slag as a granular material: Volume expansion prediction and usability criteria. *Journal of Hazardous Materials, 184*(1–3), 555–560.
Wang, Q., & Yan, P. (2010). Hydration properties of basic oxygen furnace steel slag. *Construction and Building Materials, 24*(7), 1134–1140.
Wang, Q., Yang, J., & Yan, P. (2013). Cementitious properties of super-fine steel slag. *Powder Technology, 245*, 35–39.
Wang, Q., Yan, P., Yang, J., Zhang, B. (2013). Influence of steel slag on mechanical properties and durability of concrete. *Construction and Building Materials, 47*(1), 1414–1420.
Wu, S., Xue, Y., Ye, Q., & Chen, Y. (2007). Utilization of steel slag as aggregates for stone mastic asphalt (SMA) mixtures. *Building and Environment, 42*(7), 2580–2585.
Xue, Y., Wu, S., Hou, H., & Zha, J. (2006). Experimental investigation of basic oxygen furnace slag used as aggregate in asphalt mixture. *Journal of Hazardous Materials, 138*(2), 261–268.
Xuequan, W., Hong, Z., Xinkai, H., & Husen, L. (1999). Study on steel slag and fly ash composite Portland cement. *Cement and Concrete Research, 29*(7), 1103–1106.
Yang, J. W., Wang, Q., Yan, P. Y., & Zhang, B. (2013). Influence of steel slag on the workability of concrete. *Key Engineering Materials, 539*, 235–238.
Yi, H., Xu, G., Cheng, H., Wang, J., Wan, Y., & Chen, H. (2012). An overview of utilization of steel slag. *Procedia Environmental Sciences, 16*, 791–801.
Yüksel, İ., & Özkan, Ö. (2009). Physical and mechanical properties of composite cements. *ZKG International, 62*(12), 54–63.
Yüksel, İ., Siddique, R., Özkan, Ö., & Khatib, J. M. (2009). Effect of GGBFS and GSS on the properties of mortar. In M. C. Limbachiya & H. Y. Kew (Eds.), *Proceedings of international conference on excellence in concrete construction through innovation* (pp. 445–451). London: CRC Press.
Zhang, T. S., Liu, F. T., Liu, S. Q., Zhou, Z. H., & Cheng, X. (2008). Factors influencing the properties of steel slag composite cement. *Advances in Cement Research, 20*(4), 145–150.
Zhang, S. P., & Zong, L. (2014). Evaluation of relationship between water absorption and durability of concrete materials. *Advances in Materials Science and Engineering, 2014*, 1–8.