Portland slag cement using ground granulated blast furnace slag (GGBFS) - A review

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Abstract

Cement replacement materials such as ground granulated blast furnace slag (GGBFS), which is a by-product of iron manufacturing, are commonly used with Portland cement in concrete construction. GGBFS is the most valuable due to its cementitious properties and it is often mixed with Portland cement to produce slag cement The use of ground granulated blast furnace slag cement in concrete gives many technical benefits, such as improving workability, durability and the long-term strength of the concrete. Furthermore, since the slag is an industrial by-product, use of slag has many environmental advantages, such as low energy cost, use of secondary raw material and low pollutant gas emission. These advantages make it preferable to the conventional binders in practice.
Keywords: Concrete, Durability, Ground granulated blast furnace slag (GGBFS), Portland slag cement, Workability

Introduction

Blast furnace slag is produced when iron ore is reduced by coke at about 1,350–1,550 °C in a blast furnace. The molten iron, main product of a blast furnace, is formed from the ore, while the other components form a liquid slag. When flowing to the bottom of the furnace, the liquid slag forms a layer above the molten iron due to the smaller density of slag. After being separated from the molten iron, the liquid slag is cooled down in the air or with water and is prepared for further use. Typically, about 220 to 370 kilograms of blast furnace slag are produced per metric ton of pig iron. Lower grade ore results in more slag—sometimes as much as 1.0 to 1.2 tons of slag per ton of pig iron [1]. There are three main types of blast furnace slag, categorized by the way of cooling it. The granulated slag is produced by quenching the liquid slag with large amount of water to produce sand-like granulates. Granulates normally contain more than 95 percent of glass. Normally, they are ground to fine powder, called ground granulated blast furnace slag (GGBFS). The pelletized slag is produced by partially cooling the slag with water, and then flinging it in to air. The pellets contain much less glass content if compared to granulates, as low as 50 percent. Part of the pelletized slag is used as concrete aggregate and much is used in cement production as raw material as well. The air-cooled slag is formed by allowing the slag to solidify slowly in air, and sometimes followed by accelerated cooling with a water spray. The air-cooled slag is hard and dense, being normally used for road bases, railway ballast, and asphalt paving and concrete aggregate.

Among the three types of blast furnace slag, GGBFS is the most valuable due to its cementitious properties and it is often mixed with Portland cement to produce slag (blended) cement. According to the standard in the India [2] the slag content in the Portland slag cement can be up to 65 percent in mass. Portland slag cement is obtained by mixing Portland cement clinker, gypsum and granulated slag, in suitable proportions and grinding the mixture to get a thorough and intimate mix between the constituents. It may also be manufactured by separately grinding Portland cement clinker, gypsum and granulated slag and then mixing them intimately. The resultant product is cement which has physical properties similar to those of ordinary Portland cement. In addition, it has low heat of hydration and is relatively better resistant to soils and water containing excessive amounts of sulphates of alkali metals, alumina and iron, as well as to acidic waters, and can, therefore, be 'used for marine works with advantage. The use of slag cement in construction practice has attracted much attention because slag as a by-product is often cheaper than Portland cement. Furthermore, since the slag is an industrial by-product, use of slag has many environmental advantages, such as low energy cost, use of secondary raw material and low pollutant gas emission. These advantages make it preferable to the conventional binders in practice. The present paper reviewed the different properties of concrete using GGBFS blended cement.

History of GGBFS in cement

The use of GGBFS as a cementitious material dates back to 1774 when Loriot made a mortar using GGBFS in combination with slaked lime [3]. In 1862, Emil Langen proposed a granulation process to facilitate removal and handling of iron blast-furnace slag leaving the blast furnace. Glassy iron blast-furnace slags were later investigated by Michaelis, Prussing, Tetmayer, Prost, Feret, and Green. Their investigation, along with that of Pasow, who introduced the process of air granulation, played an important part in the development of iron blast furnace slag as a hydraulic binder [4]. This development resulted in the first commercial use of slag-lime cements in Germany in 1865. In France, these slag cements were used as early as 1889 to build the Paris underground metro system [4]. The use of GGBFS in the production of blended cements accounted for nearly 20 percent of the total hydraulic cement produced in Europe [5]. The first recorded production of Portland blast-furnace slag cement was in Germany in 1892; the first United States production was in 1896. Until the 1950s, GGBFS was used in production of cement or as a cementitious material in two basic ways: as a raw material for the manufacture of Portland cement, and as a cementitious material combined with Portland cement, hydrated lime, gypsum, or anhydrite [6]. Since the late 1950s, use of GGBFS as a separate cementitious material added at the concrete mixer with Portland cement has gained acceptance in South Africa, Australia, the United Kingdom, Japan, Canada, and the United States.

Effect of GGBFS on fresh concrete properties

The effects of partial cement replacements by GGBFS on the water demand and requirement for a given slump have been investigated by several researchers. In non-super plasticized concrete, Meusel *et al* [7] reported that when the GGBFS content is increased there is an accompanying increase in slump. In plasticized concretes having 0.43-0.46 w/b ratios, Nishibayashi *et al* [8] found that the water demand needed to obtain a given slump decreases with increasing GGBFS content, and is typically reduced by I1 kg/m^3 at the 85% replacement level. They concluded that GGBFS in concrete appears to act as a super plasticizing agent replacement of the cement by GGBFS reduces the super plasticizer dosage by about 10-12% compared to concrete without GGBFS at 0.45-0.35 w/b ratios. In High Strength Concrete (HSC), Soutsos *et al* [9] found that the higher the cement replacement by GGBFS, and the lower the w/b ratio, the larger is the reduction in the super plasticizer dosage needed to obtain a target slump of 150 mm. Wimpenny *et al* [10] investigated the effects of two sources of GGBFS, three cementitious contents, at three GGBFS levels (40, 70 and 100%) and a fixed water content of 165 $1/m^3$. From their results they merely concluded that the GGBFS level, type (or source), and cementitious content all have significant effects on the workability of fresh concrete. More recently, Domone *et al* [11] reported that the incorporation of GGBFS at 0.40 w/b ratio gives lower slumps, and higher plastic viscosities.

GGBFS as a replacement for part of the Portland cement usually increases the time of setting of concrete mixtures. The degree to which the time of setting is affected is dependent on the initial temperature of the concrete, the proportion of t he blend used, the water-cementitious materials ratio, and the characteristics of the Portland cement [12]. Typically, the time of initial setting is extended one-half to one hour at temperatures of 23^0C; little if any change is found at temperatures above 29^0C. Although significant retardation has been observed at low temperatures, the additions of conventional accelerators, such as calcium chloride or other accelerating admixtures, can greatly reduce or eliminate this effect. Since the amount of Portland cement in a mixture usually determines setting characteristics, changing the GGBFS proportions may be considered in cold weather. At higher temperatures, the slower rate of setting is desirable in most cases, but care may need to be taken to minimize plastic shrinkage cracking.

Bleeding capacity and bleeding rate of concrete are mostly affected by the ratio of the surface area of solids to the unit volume of water. Therefore, when GGBFS is used, these effects can be estimated depending on the fineness of the GGBFS as compared to that of the cement and the combined effect of the two cementitious materials. When the GGBFS is finer than the Portland cement and is substituted on an equal-mass basis, bleeding is reduced; conversely, when the GGBFS is coarser, the rate and amount of bleeding may increase. Cesareni and Frigione [13] found that in all GGBFS tested, both total amount and rate of bleeding increased with the addition of slag. No explanation was given for the phenomenon, but since the cement and GGBFS were ground of the same fineness, the results contradict what is normally found with finely divided materials. Time of setting of the concrete and nonabsorptive qualities of the dense GGBFS is likely to have contributed to the increased bleeding.

Effect of GGBFS on hardened concrete properties

Compressive strength-gain characteristics of concrete containing GGBFS can vary over a wide range. Hogan and Meusel [5] reported that the compressive strength of concrete containing 40-60% GGBFS was slower than that of Portland cement concrete of the same water-binder ratio for the first three days. However, they further reported that the strength development of GGBFS concrete after three days was higher than that of concrete with Portland cement only, especially for concrete with 40% GGBFS. Roy and Idorn [14] also reported similar results. They reported, however, that the advantage in strength of concrete comprises 20–60% GGBFS has not been obtained yet until 28-days of curing, where similar or higher long-term strength was gained as compared with that of concrete with Portland cement only. In 2006, Barnett et al [15] reported that the strength development of mixtures containing GGBFS is greatly dependent on temperature. They found that under standard curing conditions, GGBFS mortars gain strength much slower than that of mortars with Portland cement only. However, at higher temperatures, strength development of GGBFS mortars is much more rapid.

The improvement in early age strength is more significant for mortars with higher levels of GGBFS, even when the curing temperature increases by 100^0C only above the standard curing temperature. Similar with a research, which was conducted by Cakir and Akin [16], they observed the influence of curing conditions on the compressive strength of mortar with and without GGBFS. They found that the temperature and humidity curing significantly influenced the strength of concrete, particularly for GGBFS mortar, which takes a longer time for hydration. Klieger and Isberner [17] found essentially the same modulus of elasticity in concretes containing Portland blast-furnace slag cement as compared with Type I cement concrete.

Normally, GGBFS is used as cement replacement at levels from 20 to 80 percent, which is varied depending on the application. Cement replacement levels are generally much lower in cold weather applications. Conversely, in hot weather concreting, the levels of GGBFS used in concrete might be higher in order to delay the setting time of the concrete [18]. Table 1 presented the levels of GGBFS suggested for different applications and environmental conditions.

Table 1: Suggested slag cement replacement levels [18]

Concrete application	**Percentage of** GGBFS
Concrete paving	25-50%
Exterior flatwork not	25-50%
Exposed to deicer salts	
Exterior flatwork exposed to deicer salts with w/c < 0.45	25-50%
Interior flatwork	25-50%
Basement floors	25-50%
Footings	30-65%
Walls & columns	25-50%
Tilt-up panels	25-50%
Pre-stressed concrete	20-50%
Pre-cast concrete	20-50%
Concrete blocks	20-50%
Concrete pavers	20-50%
High strength	25-50%
ASR mitigation	25-70%
Sulfate resistance	
Type II equivalence	25-50%
Type V equivalence	50-65%
Lower permeability	25-65%
Mass concrete	50-80%

Effect of GGBFS on durability of concrete

The durability of concrete in a certain condition is one of its most important properties when exploring the application of a certain type of concrete. In this section, some durability aspects of concrete containing slag are discussed, including the alkali-silica reactivity, sulfate resistance, salt scaling, carbonation and ion diffusion. The partial replacement of Portland cement by GGBFS reduces the reaction between some siliceous components of concrete aggregates and the alkalis. Several factors contribute. First, normal GGBFS contains less alkali compared to Portland cement. Thus, a dilution effect takes place, reducing the total amount of alkali in concrete. Second, the slag in cement reacts at a remarkably lower rate, further reducing the total amount of alkalis released by the cement hydration. Third, the reaction products of slag with Portland cement clinker have higher potentials for binding alkalis. Thus, a large part of the alkali is immobilized in the solid products and the pH value of the pore solution is lower. High glass content in the slag reduces the expansion caused by alkali-silica reaction [19].

The addition of slag into concrete reduces the risk of sulfate attack. 15 and 25 percent slag cement replacement can already achieve moderate sulfate resistance, and 35 and 50 percent can achieve high sulfate resistance. Possible explanations for this effect include that slag cement concrete has low permeability, making it harder for sulfates to penetrate into concrete and slag reacts with calcium hydroxide to form calcium silicate hydrate gel. Thus decreasing the total amount of calcium hydroxide in the system is necessary in the case of sodium sulfate attack.

The carbonation resistance of concrete made from slag cement is affected by the environment and the slag content. Investigations of some field structures showed that concretes with 50 percent slag as replacement achieved resistance to carbonation similar to that of normal Portland cement concretes of equivalent mixture proportions. However, carbonation is greater in the high slag content (70%) cements, especially if the concrete is exposed to a dry environment [20].

Normal concrete made from slag cement shows denser microstructure as compared to Portland cement concrete if the same water/cement ratios are used. The ion diffusion rates in slag cement concrete are thus much lower than those in Portland cement concrete (Table 2). The low diffusion rates partially explain the good performance of slag cement concrete against alkali-silica reaction expansion and chloride ingression. Another important feature of slag cement concrete is the low heat release of slag cement hydration. Since the heat release of slag reaction is slow and low compared to that of Portland cement, the risk of cracking due to the thermal gradient generated in massive concrete is minimized, which in turn improves the durability of concrete.

Table 2: Diffusion coefficients of Na^+ and K^+ ions in hardened mortars made with Portland cement and slag cement [21]

Diffused ion	Time (days)	W/c	Diffusion coefficient($\times 10^{-8}$ cm^2/s)		Slag content of cement (%)
			Portland cement	Blended cement	
Na^+	3	0.5	7.02	1.44	75
	14	0.5	2.38	0.1	75
	28	0.55	1.47	0.05	60
	28	0.6	3.18	0.05	60
	28	0.65	4.73	0.06	60
K^+	3	0.5	11.38	2.1	75
	14	0.5	3.58	0.21	75
	28	0.55	3.57	0.12	60
	28	0.6	6.21	0.23	60
	28	0.65	8.53	0.41	60

Conclusion

From the above review, it was found that the use of ground granulated blast furnace slag cement in concrete gives many technical benefits, such as improving workability, durability and the long-term strength of the concrete. Furthermore, since the slag is an industrial by-product, use of slag has many environmental advantages, such as low energy cost, use of secondary raw material and low pollutant gas emission.

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