

Review

Studies on the corrosion resistance of reinforced steel in concrete with ground granulated blast-furnace slag—An overview

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Abstract

The partial replacement of clinker, the main constituent of ordinary Portland cement by pozzolanic or latent hydraulic industrial by-products such as ground granulated blast furnace slag (GGBFS), effectively lowers the cost of cement by saving energy in the production process. It also reduces CO₂ emissions from the cement plant and offers a low priced solution to the environmental problem of depositing industrial wastes. The utilization of GGBFS as partial replacement of Portland cement takes advantage of economic, technical and environmental benefits of this material. Recently offshore, coastal and marine concrete structures were constructed using GGBFS concrete because high volume of GGBFS can contribute to the reduction of chloride ingress. In this paper, the influence of using GGBFS in reinforced concrete structures from the durability aspects such as chloride ingress and corrosion resistance, long term durability, microstructure and porosity of GGBFS concrete has been reviewed and discussed. © 2006 Elsevier B.V. All rights reserved.

Keywords: Corrosion resistance; GGBFS; Durability; Chloride diffusion

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1. Introduction

At present, most industrial slags are being used without taking full advantage of their properties or disposed rather than used. Ground granulated blast furnace (GGBFS) has been used for many years as a supplementary cementitious material in Portland cement concrete, either as a mineral admixture or as a component of blended cement [1]. GGBFS typically replaces 35–65% Portland cement in concrete. Thus a 50% replacement of each ton

of Portland cement would result in a reduction of approximately 500,000 t of CO₂. The use of GGBFS as a partial replacement takes advantage of the energy saving in Portland cement is governed by AASHTO M302 [2]. Three types of ground granulated slag cements are typically manufactured. They include Portland cement as covered by AASHTO M85 [3], Portland blast furnace slag cement and slag cement as per AASHTO M240 [4]. The use of GGBFS as a partial replacement of ordinary Portland cement improves strength and durability of concrete by creating a denser matrix and thereby enhancing the service life of concrete structures. Grinding slag for cement replacement requires only about 25% energy needed to manufacture Portland cement.

The use of these slags as cementing components needs only grinding, it will save substantial amounts of energy compared

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with the production of Portland cement. In North America, most metallurgical slags are used as aggregates for different applications, and only a small portion of ground granulated blast furnace slag is used for a partial Portland cement replacement. The partial replacement may decrease the early strength, but increase the later strength and improve microstructure and durability of hardened Portland cement and concrete very significantly [5]. Research results have indicated that clinker less alkali-activated slags show higher strengths, denser structure and better durability than Portland cement under both normal and hydrothermal conditions [6–10]. Thus, the optimum use of these slags is as cementing material components rather than as aggregates or for base stabilization. Water cooling of blast furnace slag is increasing in frequency in response to the needs of the cement industry. Rapid cooled slag contains rough textured granules of 93–99%. This glass is inherently unstable and will form into stable crystals in the presence of water. But when the granulated slag is finely ground and an activator catalyst is present which will form an alkaline stable crystalline compounds very similar to hydrates of Portland cement. The most versatile in terms of its potential use as cementing material is that, by virtue of its good technical properties and in particular its usefulness as binding agent. Blast furnace slag is a non-metallic material consisting essentially of silicates and aluminosilicates of calcium [11]. It is considerably used in the production of light weight aggregate. When the slag is allowed to cool slowly in air, it solidifies into gray crystalline material known as crystallized slag. This slag is used as aggregates. When the slag is cooled very rapidly by water, it solidifies and granulates as a granulated slag. The chemical composition of slag can vary over a wide range depending on the nature of the ore, the composition of the limestone flux, coke consumption and the type of iron being made [12].

Detwiler et al. [13] investigated the effectiveness of using supplementary cementing materials to increase the chloride resistance of accelerated cured concrete and they found that concretes containing supplementary cementing materials performed better than the Portland cement concretes. As well, use of supplementary cementing materials can also prevent deleterious expansions related to both delayed ettringite formation [14] and alkali-silica reaction [15].

It has been observed that GGBFS can be effectively used to reduce the pore sizes and cumulative pore volume considerably, leading to more durable and impermeable concrete. According to Hwang and Lin [16], GGBFS has the potential to replace cement in high percentages because of its in-built cementitious property. The continued use of slag cement in the construction industry requires consideration of the effect of electrochemically reducing pore solution on depassivation of steel reinforcement in cement system [17]. It is expected, however, that the pore structure of concrete with slag is drastically altered and can contribute significantly to the reduction of corrosion by increasing the resistivity of concrete.

In this paper, the effectiveness of using GGBFS in reinforced concrete structures has been reviewed by considering the major factors affecting the durability of concrete such as chloride and corrosion resistance, microstructure and

porosity, long term durability of GGBFS concrete have been discussed.

2. Chloride and corrosion resistance of GGBFS concrete

Corrosion of reinforcing bars embedded in concrete is the most common cause of deterioration of concrete structures in aggressive environments [18]. Corrosion of steel reinforcement results in cracking and eventual spalling of concrete. In general, good quality concrete provides excellent protection for steel reinforcement. Due to the high alkalinity of concrete pore fluid, steel in concrete initially and, in most cases, for sustained long periods of time, remains in a passive state. Initiation of corrosion occurs either due to reduction in alkalinity arising from carbonation or the breakdown of the passive layer by the attack of chloride ions. The time to initiation of corrosion is determined largely by the thickness and the quality of concrete cover as well as the permeability of concrete. High quality and durable concrete is required to reduce the rapid deterioration of concrete under severe environmental conditions. In this context, the beneficial effects of alternative cementing materials should be considered. When alternative cementitious materials such as GGBFS is used in concrete, not only reduced the porosity but also the pores become finer and the change in mineralogy of the cement hydrates leads to a reduction in the mobility of chloride ions [19]. Torri [20] reported that the resistance to chloride ion penetration of 50% GGBFS concrete was almost the same as that of 10% silica fume concrete.

Studies have shown that use of cement replacement materials such as fly ash, silica fume, blast furnace slag, etc. may reduce greatly the probability of steel corrosion as well as the permeability of concrete [21–25]. It has been reported that most of GGBFS used were blended with American Society of Testing Materials (ASTM) Type V sulfate-resistant cement rather than ASTM Type I Portland cement, in order to protect the constructed structures from sulfate attack. Although Type V cement can increase the chemical resistance to the sulfate attack that causes expansion and cracking of concrete [26], corrosion resistance of reinforcement in concrete is aggravated, because the tri-calcium aluminate (C_3A) contents of Type V cement is much lower than those of Type I cement. The C_3A phase of the Type I cement plays a dominant role in binding the chloride ions [27]. Hussain [28] reported that the chloride binding capacity and reinforcement corrosion initiation time can be increased by 2.43 and 2.45-folds, respectively in accordance the increase of C_3A content from 2% to 14%. Rasheeduzzafar [29] found that Type I cement containing 9.5% C_3A by weight binds almost 1.6 times more chloride than the cement that contains 2.8% and thus Suryavanshi [30] suggested that cement containing abundant C_3A phase is recommended for structures in coastal and marine environments.

Yeau and Kim [31] evaluated the corrosion resistance of two types of Portland cement mixed with GGBFS varying from 0 to 50% and carried out permeability, diffusivity, surface area of corrosion on embedded steel and potential measurements and found that the coefficient of permeability of Type I cement concrete was lower than that of Type V cement concrete. The

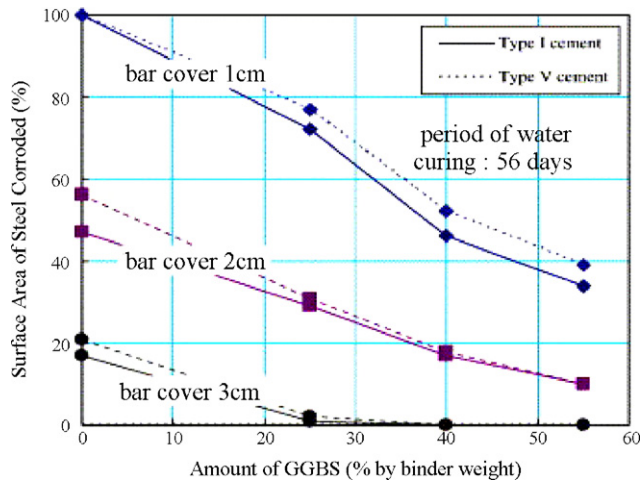


Fig. 1. Surface area of corroded steel bars in concrete specimens [31].

corrosion probability of steel rebar (Fig. 1) in Type V cement concrete was higher than that of steel rebar in Type I cement concrete. The results showed that the corroded surface area (%) depends on the thickness of the concrete cover, as well as the amount of GGBFS replaced. These results suggest that the resistance to steel corrosion is better in Type I cement with higher amount of GGBFS. It is also reported by Cheng et al. [32] that, Type I cement can be replaced with 40% or more in order to increase the corrosion resistance of steel rebars and decrease the probability of corrosion. Similarly, RCPT (Rapid Chloride Permeability Test) results indicate that the highest total charge-passed (10271 C) obtained in mix A specimen and the lowest total charge passed (1864 C) in mix C specimen, which represent highest chloride-ion penetration resistance as given in Fig. 2.

Studies revealed that the inhibition of corrosion in slag concrete, due to its low electrical conductivity, caused a refined pore structure [33–36]. Mcphee and Cao [37] indicated that the effectiveness of passive layer may be weakened as the iron (III) species are reduced by the reducing agents from GGBFS. Due to drastic alteration of pore structure at high volume slag replacement, however, the resistivity of concrete increases many fold

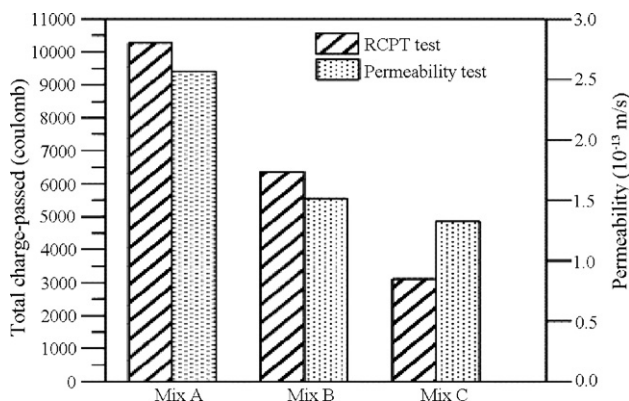


Fig. 2. Comparison of total charge-passed and permeability [32].

Table 1

Comparison of weight loss, i_{corr} , half cell potential and carbonation depth for different slag replaced concrete [38]

Concrete	Weight loss (mg)	i_{corr} (A/m ²)	Half cell potential (mV)	Carbonation depth (mm)
Reference concrete	0.33	0.1169	−503	2.0
30% slag concrete	0.27	0.0823	−108	2.0
50% slag concrete	0.29	0.1239	−176	1.0
70% slag concrete	0.26	0.0842	−31	1.0

and thus, the corrosion rate is significantly reduced. Pal et al. [38] studied the corrosion behaviour of embedded reinforcement under different proportions of slag. In this study corrosion of steel has been examined electrochemically and also by an accelerated carbonation test. The results obtained from the above study are reported in Table 1.

It was reported from the above Table 1 that as the slag content increases, the corrosion rate, weight loss, half cell potentials and the carbonation depth are found to be decreased.

Jau et al. [39] evaluated the slag cement subjected to seawater corrosion by conducting various investigations such as compressive strength, permeability, electrical resistance, concentration of chloride ions corrosion potential and pore size distribution at various ages and concluded that slag concrete with 20–30% substitution has best corrosion resistance properties.

Mangat et al. [40] investigated steel reinforcement electrodes embedded in different matrices of concrete exposed to simulated marine splash zone exposure for about 600 days after initial curing in air for 14 days. The corrosion potentials and polarization resistance were monitored at regular intervals to determine the state and rate of corrosion. The concrete matrices included different cement replacement levels of pulverized fuel ash, GGBFS and microsilica at a water/cementitious ratio of 0.58. The Cl^- and OH^- concentration in pore fluid and the acid soluble Cl^- in concrete were also determined. The results show that resistivity of concrete increases with increasing content of cement replacement materials such as GGBFS at 60% replacement level and it was also concluded that the replacement of cement by up to 40% GGBFS has no significant influence on rebar corrosion.

A number of studies [41–43] have been conducted on the corrosion of steel in concretes made with cement containing mineral admixtures. Baweja et al. [34] determined lower corrosion current density of concrete containing 35% GGBFS than without GGBFS. Also, Huang et al. [44] determined that concrete with 15% and 30% GGBFS have high corrosion resistance. Similar findings were also reported by Arya and Xu [45]. Hope and Ip [42] found that corrosion of the steel rebars in concretes decreased with increasing GGBFS content, except during the first 7 days after casting. Baghabra Al-Amoudi et al. [46] investigated the long-term corrosion resistance of steel rebars in 5% sodium chloride solution. The results of regression analyses indicated excellent correlation between corrosion resistance and porosity for both plain and blended cement concretes. It was found that the corrosion rate of the steel rebar in GGBFS containing concrete specimens was about between one-half and one-twelfth of those in plain concrete specimens.

Bentur et al. [47] indicated that for two reinforced concrete members with different crack widths, the time required to initiate corrosion is shorter for one with wider crack. It was reported that crack width less than 0.5 mm affects the development of corrosion, but its width has not a significant influence at later stages in the corrosion process. However, the early cracks due to service loading in reinforced concrete structural members exposed to an aggressive environment may open a direct path to the rebar and thus provide ideal conditions for the corrosion process to start. Concrete subjected to sustained loading would cause initiation, connection and propagation of concrete cracks. It was stated that sustained loading and loading ratio in response to pre-determined cracks are key parameters affecting the corrosion behavior of reinforced concrete members no matter whether GGBFS is used in the mix or not. Test results suggest that the corrosion rate of reinforcing steel in concrete is controlled mainly by crack width. For a given reduction percentage in flexural rigidity, the GGBFS concrete beam exhibits lower corrosion rate or higher corrosion resistance.

Most of the previous studies have been focused on the corrosion behavior of concrete without loading [44,48,49]. The durability of GGBFS concrete and the corrosion behavior of reinforced concrete beams under various loading ratios were investigated by Cheng et al. [32]. Prismatic beam specimens with a size of 150 mm × 150 mm × 900 mm were subjected to various sustained loadings (37 and 75% of the ultimate load) and exposed to 3.5% NaCl solution. A direct current (1 mA cm⁻²) was applied to accelerate the corrosion process. Open circuit potential (OCP) and direct current polarization resistance were obtained to evaluate the rebar corrosion. In addition, rapid chloride penetration test (RCPT) and permeability test were conducted on GGBFS concretes. Test results indicate that partial replacement of cement by GGBFS has inhibiting effects on both total charge-passed and permeability. Slag addition and sustained loading have significant effect on corrosion rate and flexural rigidity of reinforced concrete beams.

It was also reported [48] that the chloride-ion diffusion coefficient of concrete with 60% GGBFS and 0.5 water/cementitious ratio is ten times smaller than concrete with pure Portland cement. The reduction in corrosion probability of reinforcing steel is also demonstrated by GGBFS replacement for Portland cement corresponding to the comparative results of RCPT and permeability. The study revealed that, up to 50% replacement there was no carbonation found due to the denser microstructure or lower porosity results from higher C–S–H content that represents higher GGBFS replacement percentage and higher durability of concrete and they also found that carbonation effect was more when the replacement level is beyond 50%. Finally they concluded that the reduction of pH value due to the addition of GGBFS seems no adverse effect on the corrosion resistance of GGBFS concrete.

The fineness of GGBFS is an important parameter, influencing the durability of reinforced concrete structures. Song et al. [50] studied the resistance to chloride ion penetration in GGBFS concrete with various percentages (30, 50 and 70%) by varying the fineness from 4000 to 8000 cm²/g by conducting chloride penetration test and compared the results with OPC. The results

Table 2
Free chloride content for each penetration depth [50]

Specimen type	Depth (cm)	Free chloride content (%)
OPC	0.0–1.0	0.02920
	1.0–2.0	0.02555
	2.0–3.0	0.01330
	3.0–4.0	0.00730
S38—GGBFS: 30%, fineness: 8000 cm ² /g	0.0–1.0	0.02738
	1.0–2.0	0.02008
	2.0–3.0	0.01095
S58—GGBFS: 50%, fineness: 8000 cm ² /g	3.0–4.0	0.00730
	0.0–1.0	0.01886
	1.0–2.0	0.00913
S78—GGBFS: 70%, fineness: 8000 cm ² /g	2.0–3.0	0.00730
	0.0–1.0	0.01278
S76—GGBFS: 70%, fineness: 6000 cm ² /g	1.0–2.0	0.00730
	0.0–1.0	0.01199
S74—GGBFS: 70%, fineness: 4000 cm ² /g	1.0–2.0	0.00730
	0.0–1.0	0.01278

showed that the GGBFS concrete has better resistance to chloride ion penetration than OPC as shown in Table 2. Thus for better performance, the fineness of GGBFS must be greater than that of cement.

3. Long term durability of GGBFS concrete

The long term performance of GGBFS concrete was studied under laboratory and field exposure conditions at the Building Research Establishment [51]. This paper summarizes the results on field and laboratory studies. Comparisons were made on the properties and performances of the slag cement concretes with normal Portland cement concretes as of similar mixture proportions and concluded that GGBFS concrete reduced the heat evolution, increased the compressive strength at later ages, decreased chloride ion penetration, increased resistance to sulphate attack and alkali-silica reaction. In this paper a number of recommendations are given for the effective use of GGBFS in concrete. An example of the use of GGBFS in structural concrete in the UK is the Humber Bridge and a more recent structure containing GGBFS is the Tees Barrage [52,53]. The main findings of this study have been reported [54] on important concrete properties such as carbonation, permeability, strength and on the longer time durability. These studies have shown that slag cement concrete, particularly at high levels of replacement, such as 70 and 80%, carbonated significantly more than Portland cement concretes of similar mixture proportions when specimens were subsequently stored in dry internal environments. However, the concretes stored in water or those from the exposure sites that had been subjected to moist conditions, attained their design strengths and showed little or no carbonation. From the above studies it was found that the use of high levels of slag gave the added benefit of reducing ingress, which provided enhanced protection to steel reinforcement and based upon the above studies, it was recommended that for thin sections

Table 3
Reported carbonation of site stored concrete blocks taken at different locations [51]

Block no. (each 750 mm thick core taken at different locations)	Total cement (kg/m ³)	Slag %	Mean depth of carbonation (mm)	
			2.5 years	7.5 years
1	390	50	<0.5	0
2	390	50	1	1
3	393	50	1	0
4	397	0	0	0
5	390	30	0.5	0.5
6	390	70	4.5	5.5
7	390	50	1	1
8	391	70	8	5
9	390	50	1.5	1.5

particular attention should be given to both curing and cover of reinforcement and in environmental situations where there is a risk of excessive carbonation, slag levels should be restricted to 50%. Comparisons made between the different concretes of 390 kg/cm³ cement content which contained a range of GGBFS levels in cement are given in Tables 3 and 4. From Table 3 it is observed that concretes with 50% slag as replacement achieved resistance to carbonation similar to that of normal Portland cement concretes of equivalent mixture proportions, in most of the locations. However carbonation was greater in the high slag content (70%) cements, especially if associated with a sheltered or drying climate. From Table 4 it is observed that the predominant factor that affect the rate of carbonation of these and other concretes was the microclimate around the vertical columns and floor slabs of the structure. The level of GGBFS as replacement for Portland cement and total cementitious content was also important, as the concretes with 70% GGBFS produced high rates of carbonation in certain situations, such as in a sheltered windy environments. Carbonation had extended to a depth of 26 mm in 9.5 years and also it has been reported that even after 9.5 years of exposure there were no signs of corrosion.

Basheer et al. [55] carried out the investigation on monitoring the electrical resistance of concretes containing alternative cementitious materials like pulverized fuel ash, micro silica and ground granulated blast furnace slag in marine environment and highway structures. The results indicated that, the resistance of concrete decreased initially due to the penetration of chlorides and in the long term, the resistance of concretes containing alternative cementitious materials outperformed the control concrete made with ordinary Portland cement.

A series of investigations [56] were carried out on six concrete structures along the North Sea coast in The Netherlands. The structures aged between 18 and 41 years and most of them were made using blast furnace slag cement. Visual inspections showed corrosion damage in only one structure related to relatively low cover depths. All structures showed considerable chloride ingress with a large scatter within the relatively small tested areas. The interpretation was based on the Duracrete model for chloride ingress. Comparison was made to previously published data on chloride ingress and electrical resistivity of similar concretes. It was found that a single mean value and standard deviation applied to all concrete up to 7 m above mean sea level for the chloride surface content. Above 7 m, the local microclimate had a decisive influence, either increasing or reducing the chloride surface content.

4. Microstructure and porosity of GGBFS concrete

The beneficial effects of GGBFS in concrete results from the modified microstructure of cementitious paste, which has more capillary pores filled with low density C–S–H gel than Portland cement paste [45,56,57]. It can be observed that GGBFS can be effectively used to reduce the pore sizes and cumulative pore volume [58]. It appears that higher GGBFS replacement percentage has denser structure and prevents concrete from water penetration. The GGBFS reacts with water in alkali environment and then with calcium hydroxide to form cement hydration product through pozzolanic reaction to form extra C–S–H gel in the paste and slow down the strength development at early age. Denser microstructure or lower porosity results from higher C–S–H content that represents higher GGBFS replace-

Table 4
Reported carbonation data from site cores [51]

Concrete element	External environment	Mean depth carbonation (mm)		
		East side	West side	
		5 years	5 years	9.5 years
Vertical columns	Open/sheltered	11–13.5	14–15	16.5–26
	Exposed to the marine environment	5.5	–	–
Floor slab	Fully exposed	4.5	0.5	1.0

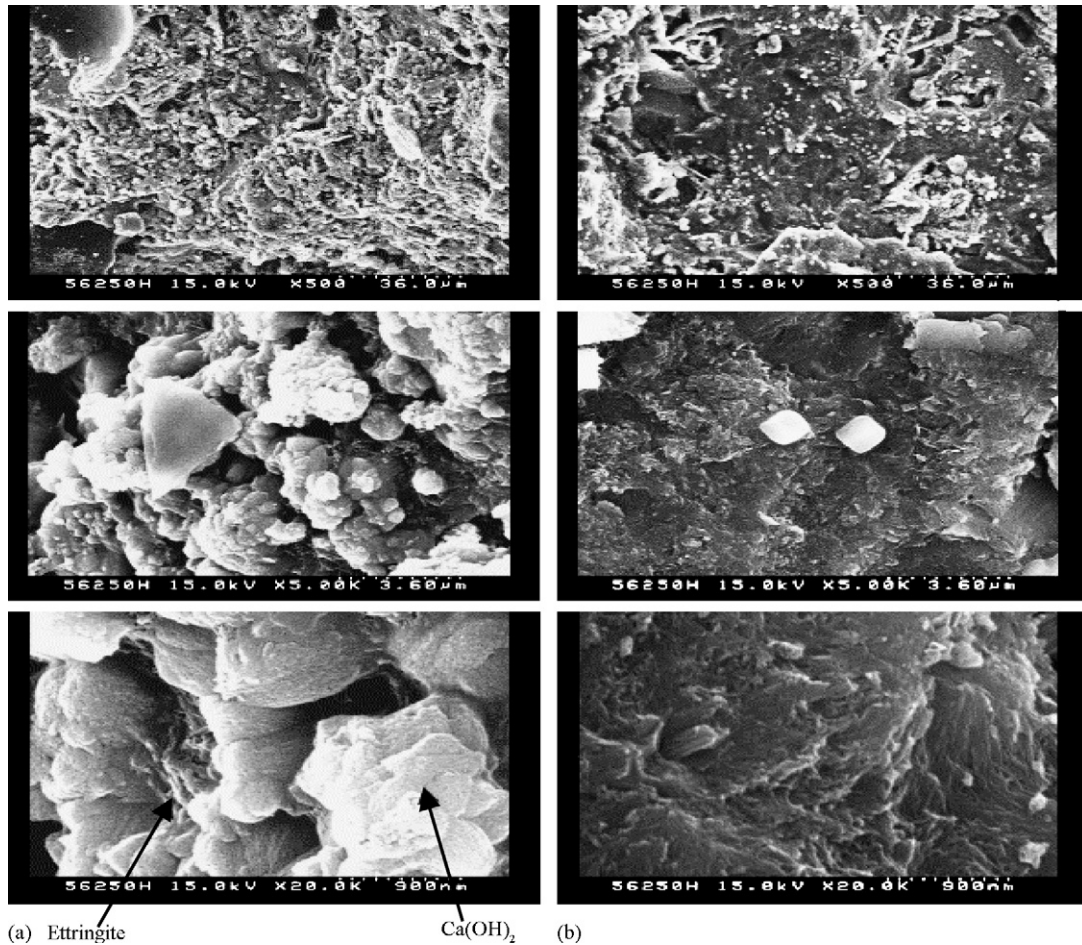


Fig. 3. SEM micrograph of: (a) ordinary Portland cement concrete and (b) GGBFS (60%) concrete [59].

ment percentage and higher durability of concrete. SEM micrographs (Fig. 3) indicate that the addition of GGBFS modifies the products and the pore structure in a hardened cementitious material, which is also verified by the results of permeability test and rapid chloride penetrating test. It was found that a great number of calcium hydroxide and large capillary pores ($0.05\text{--}60\ \mu\text{m}$) were found in OPC specimens. But few needle-shape ettringite existed in GGBFS concrete specimens and the capillary pores were less than ($10\text{--}50\ \mu\text{m}$) in which could be filled up with pozzolanic reaction product such as low density C–S–H gel. The permeability (Fig. 3) was 2.56 , 1.52 , and $1.32 \times 10^{-13}\ \text{m s}^{-1}$ in OPC, and 60% GGBFS concretes, respectively [59].

Portland cement is usually used with GGBFS and the hydration product of $\text{Ca}(\text{OH})_2$ activates the slag hydration to form a mixture of low CaO/SiO_2 (C/S) ratio $\text{CaO}\text{--}\text{SiO}_2\text{--}\text{H}_2\text{O}$ (C–S–H) and AFm (cementitious product from the reaction of reactive alumina and calcium hydroxide) phases. Pozzolanic reaction is also found to increase the C/S ratio to a value of about 1.7 in slag-cement blends due to unstable low calcium C–S–H and $\text{Ca}(\text{OH})_2$ mixture. When supplementary cementitious material like GGBFS are used in concrete, they do not only reduce the porosity but also the pores become finer and the change in mineralogy of the cement hydrates leads to the reduction in mobility of chloride ions.

5. Conclusions

This paper has reviewed the corrosion resistance of reinforced steel in concrete with ground granulated blast furnace slag and the following conclusions were made based on the durability considerations:

1. GGBFS is an important breakthrough to traditional concrete. It is characterized by energy saving, clinker saving, low cost, environmental protection and social benefits as well as economic profit.
2. This kind of new building material can be called green concrete. It has good properties and its application should be more widespread.
3. GGBFS used as a partial replacement of Portland cement can improve the durability of OPC and at the same time has a positive impact on environment.
4. Durability studies revealed that,
 - a. Replacement of cement by 40% GGBFS has no significant influence on corrosion rates of rebar in concrete. At 60% GGBFS content the corrosion rate is significantly reduced.
 - b. The reduction of pH value due to the addition of GGBFS seems no adverse effect on the corrosion resistance of GGBFS concrete.

- c. An increase in slag proportion decreases the rate and amount of corrosion of reinforcement in slag concrete.
5. Resistivity of concrete increased with increase in GGBFS up to 60%.
6. At higher percentage of replacement of GGBFS, it showed lower resistance to carbonation, possibly due to the effect of the reduction in calcium hydroxide over pore refinement. Hence adequate curing is essential in order to enhance the resistance of concrete containing GGBFS.
7. It is recommended that for thin sections particular attention should be given to both curing and cover concrete of reinforced steels, and in environmental situations where there is a risk of excessive carbonation, slag levels should be restricted to 50%.
8. Diffusion coefficients and chloride ion permeability were decreased as the amount of GGBFS or the period of curing was increased.
9. When GGBFS is used in concrete, it not only reduced the porosity but also the pores become finer and the change in mineralogy of the cement hydrates leads to the reduction in mobility of chloride ions.
10. Use of GGBFS for making binary and ternary blended cements and use of these cements in structural and reinforced concrete construction will pave the way for large scale application of slag cement in construction industry will lead to increase the service life of concrete with enhanced durability.

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