

Corrosion Resistance of GGBS Concrete

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ABSTRACT

Owing to the fact that corrosion of steel is the key concern of service life of reinforced concrete structures, researchers have been dealing with this subject for many years. Pozzolanic materials, most of which are by products of industries, are widely used in concrete production, especially to increase the durability properties. Fly ash, ground granulated blast furnace slag (GGBS) and silica fume are the most common pozzolans together with natural pozzolans used in concrete technology.

In this experimental research, resistance to chloride induced corrosion of reinforcing steel bars embedded in GGBS concrete has been studied. Two classes of concrete have been prepared; such as C25 and C35 at two different binder ratios. Cement in the concrete was replaced with GGBS at the ratios of 30%, 50% and 70%. Lollipop specimens with steel bars located in the center were prepared and stored in 1M NaCl solution for corrosion testing. Two levels of continuous potential difference, i.e. 6V and 12V, were applied to accelerate the corrosion and corrosion rate, corrosion potential and resistivity of concrete were monitored by using the linear polarization method. Efficiency factor of GGBS on corrosion initiation and threshold chloride concentration are calculated. Test results showed that higher the GGBS content in concrete lower the chloride diffusion and longer the corrosion initiation time.

KEYWORDS

Slag, Reinforcement corrosion, Chloride

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1 INTRODUCTION

It is well known that the most common cause of deterioration of reinforced concrete structures is corrosion of reinforcing bars. Under normal conditions, high alkalinity of concrete keeps the embedded steel passive; however corrosion may initiate due to either carbonation of cover, or chloride attack or both. Permeation of such aggressive substances through concrete cover controls the time to corrosion onset.

Sustainability of construction industry can only be achieved by using supreme amount of pozzolanic material replacements in concrete [Mehta 1997]. Pozzolanic materials improve the impermeability by both filling and pozzolanic effects, the latter occurs between pozzolans and Ca(OH)_2 , generated during the hydration of C_3S and C_2S components of cement, to form calcium silicate hydrate (C-S-H). Hence, utilization of mineral admixtures in concrete mitigates the heat of hydration, improves the durability, recycles the waste products and reduces the cost.

Fly ash and GGBS are widely employed in concrete production. In the production of GGBS, grinding is needed, however, the energy requirement for grinding is only 25% of that of clinker production [Song & Saraswathy 2006]. Neville [1993] denoted that the content of GGBS must be at least 50% by mass of the total cementitious material, and preferably 60-70% to be effective. In order to maintain a significant influence in reducing reinforcement corrosion, more than 40% of cement in concrete should be replaced by GGBS [Mangat & Molloy 1991]. Aldea *et al.* [2000] reported an increase on compressive strength up to 25% slag replacement and a decrease above this level, and concretes with 50% slag replacement had compressive strength similar to control mixture. However, increasing slag replacement continuously improved microstructural properties and decreased chloride penetrability. In another study [Thomas & Bamforth 1999], it is estimated that diffusion coefficients for slag or fly ash concretes decrease to one or two order of magnitude than similar grade Portland cement concrete during 100-year service life. Robins *et al.* [1992] obtained lower permeability values for slag concretes just in case of water curing under hot climate conditions. In a more recent study, significant improvements in corrosion rate, corrosion potential and carbonation depths of slag added concretes were reported compared to those of plain concrete having similar compressive strength [Pal *et al.* 2002]. Leng *et al.* [2000] found 50% reduction in the coefficient of chloride permeability, provided 30% of cement is replaced with GGBS.

2 EXPERIMENTAL

2.1 Materials

Concretes were cast by using CEM I 42.5 cement. The aggregates were composed of crushed stone II, crushed stone I, crushed stone sand and natural sand, with the specific weights of 2.70, 2.70, 2.66, 2.59 kg/dm^3 and in the percentages of 0.25;0.25;0.25;0.25, respectively. Physical and chemical properties of cement and GGBS are presented in Table 1.

In order to observe the effect of concrete quality on the corrosion behavior of embedded steel bars, two water/cement ratios of 0.65 and 0.49 were tested. A lignin based water reducer was employed in the dosages of 0.7% and 1.2% (as wt. percentage of cement) for high and low water/cement ratios, respectively. Mixture proportions of concretes are given in Table 2. Cubes of 150x150x150 mm specimens were cast for compression tests and lollipop cylinders of $\phi 100 \times 200$ mm specimens containing a $\phi 10$ steel bar located in the center for corrosion tests were cast. Prior to casting concrete, steel bars were cleaned by a metal brush and partially coated with an epoxy based coating as shown in Figure 1. Thus, the exposed area of each steel was equal to 31.4 cm^2 . Two sets of lollipop specimens were prepared for each batch. Following demoulding the specimens, uncoated parts of the steel bars of the lollipop specimens were

coated with vaseline to avoid corrosion and specimens were partially immersed in a water tank for 28 days for curing.

Table 1. Physical and chemical compositions of cement and GGBS

		Cement	GGBS
Physical properties	Specific gravity	3.17	2.92
	Fineness	Passing 32 μ (%)	87.2
		Blaine cm ² /g	3071
	Compressive Strength, MPa	2-day	25.7
		28-day	56.8
	Setting time (h:min)	Initial	2:49
		Final	3:49
Chemical analysis	Strength activity (N/mm ²)	-	13.3
	Silicon dioxide (SiO ₂)	20.73	38,02
	Aluminum oxide (Al ₂ O ₃)	4.14	10,12
	Ferric oxide (Fe ₂ O ₃)	3.65	2,75
	Calcium oxide (CaO)	65.10	34,06
	Magnesium oxide (MgO)	0.99	10,16
	Sulfur trioxide (SO ₃)	2.60	3,13
	Sodium oxide (Na ₂ O)		0,52
	Potassium oxide (K ₂ O)	0.50	1,10
	Free lime	1.11	-
	Loss on ignition (%)	1.35	0.00
	Bogue potential compound composition	C ₃ S	62.51
		C ₂ S	12.28
		C ₃ A	4.80
		C ₄ AF	11.11

Table 2. Mix design of concretes

Mix code	Cement [kg/m ³]	GGBS [kg/m ³]	W/B	Water reducer
C25	280	-	0.65	0.7
C25-30%	196	84	0.65	0.7
C25-50%	140	140	0.65	0.7
C25-70%	84	196	0.65	0.7
C35	340	-	0.49	1.2
C35-30%	238	102	0.49	1.2
C35-50%	170	170	0.49	1.2
C35-70%	102	238	0.49	1.2

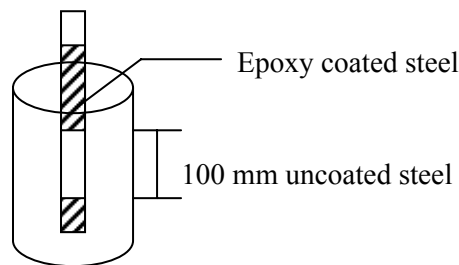


Figure 1. Lollipop specimens

2.2 Methods

The corrosion in rebars was electrically accelerated by using a 6-volt direct current to find out the time to corrosion initiation and 12-volt direct current to observe crack propagation. Each exposing cycle consist of keeping the lollipop specimens in 1M NaCl solution for 24 hours, followed by 48 hours of drying in air (Fig. 2a). All the specimens were monitored by the Gecor 8 corrosion ratemeter (Fig. 2b) which can perform in accordance with linear polarization method and can also measure half-cell potential and resistivity, at the end of each cycle. Chloride profiles of specimens for corrosion initiation were measured at the end of acceleration.

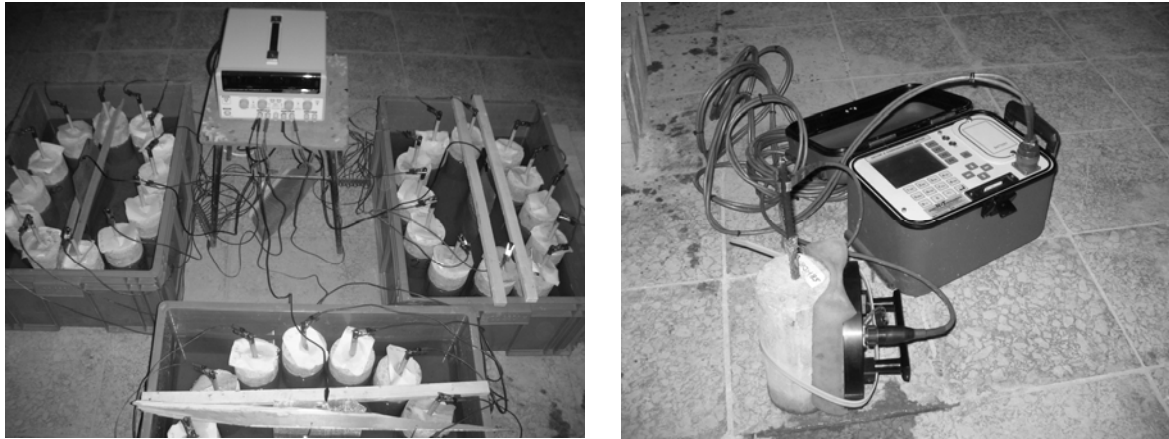


Figure 2. a) Accelerated corrosion test setup, **b)** Gecor 8 corrosion ratemeter

3 TEST RESULTS AND DISCUSSION

Compressive cube strengths of concretes with and without GGBS are demonstrated in Figure 3. For both type of concrete classes, increasing amount of GGBS exhibited reduced 7-day to 28-day compressive strength ratios. This ratio decreased from 0.80 to 0.28 for C25 and from 0.82 to 0.21 for C35 grade concretes, which can be attributed to the lower hydration reaction rate of GGBS at early ages.

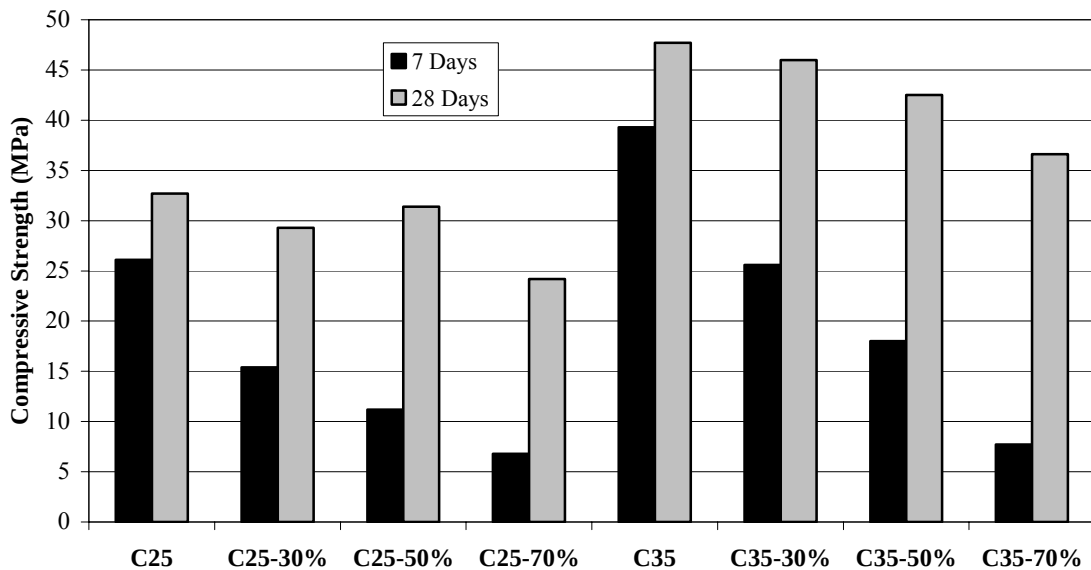


Figure 3. Compressive cube strengths of concretes

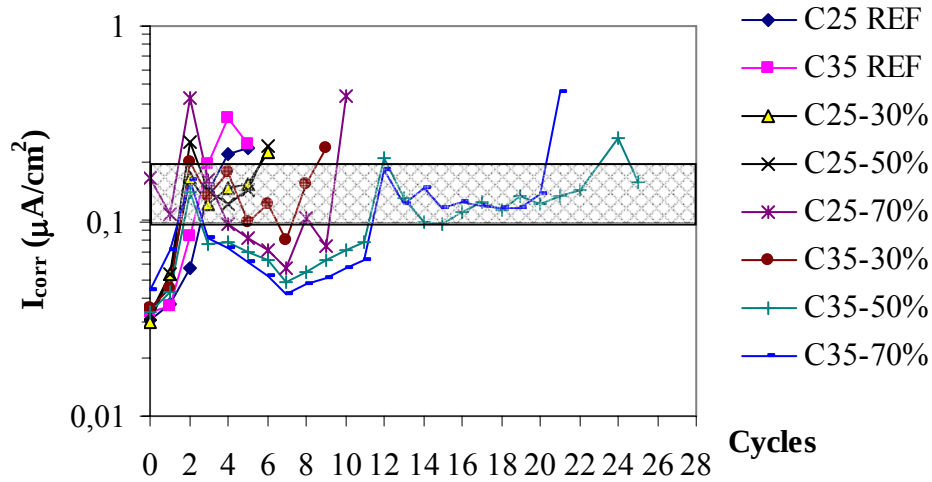


Figure 4. Corrosion rate measurements of lollipop specimens subjected to 6V potential difference.

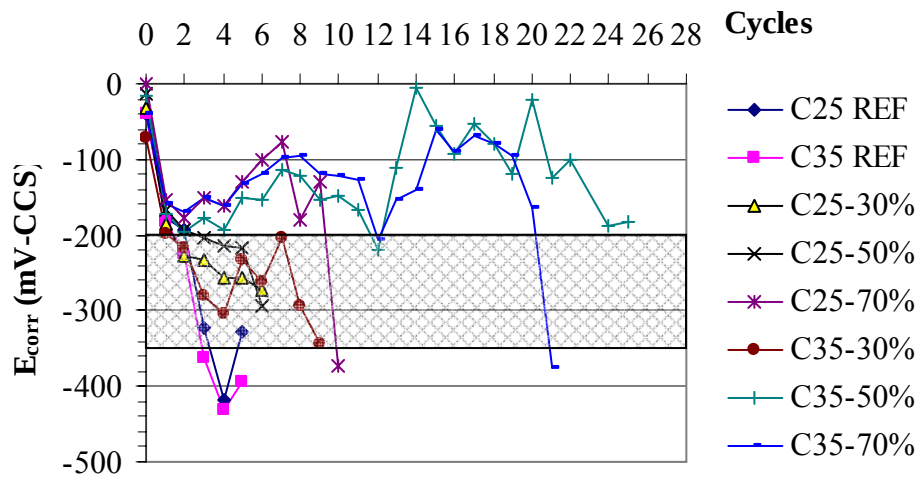


Figure 5. Corrosion potential measurements of lollipop specimens subjected to 6V potential difference.

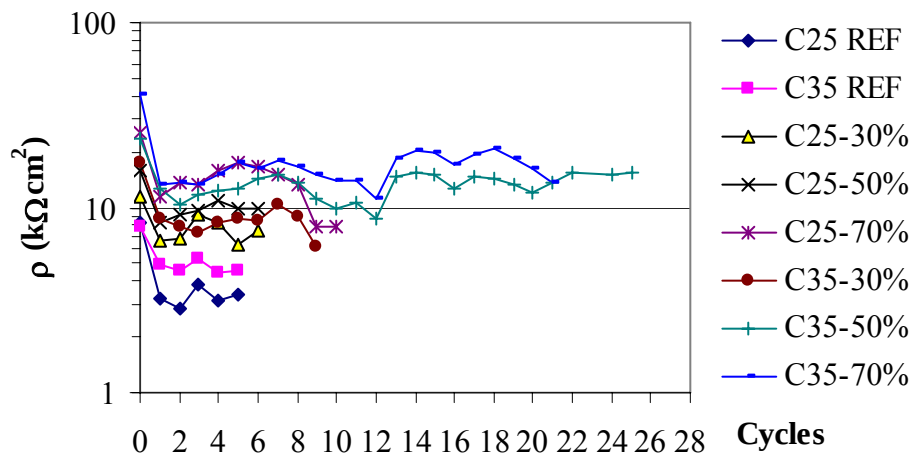


Figure 6. Resistivity measurements of lollipop specimens subjected to 6V potential difference.

In order to determine the corrosion initiation time of the lollipop specimens, corrosion rate (I_{corr}), corrosion potential (E_{corr}) and resistivity (ρ) tests were carried out under a potential difference of 6V

and the results are shown in Figures 4-6, respectively. Critical zones for I_{corr} and E_{corr} values are shaded in these figures and tests were finalized when the I_{corr} values exceeded the critical zones. Test results exhibited that for the 70% GGBS replaced specimens of C25 grade concretes, the longest corrosion initiation times were obtained and those of 30% and 50% replaced specimens followed them. No difference was seen between the performances of 30% and 50% replacement levels for C25. On the other hand, for C35 concretes, the best performance belongs to the specimens of 50% GGBS replacement instead of 70% replaced ones, showing a kind of optimum GGBS replacement ratio. The tests of E_{corr} supported the results of I_{corr} , as can be seen in Figures 4 and 5.

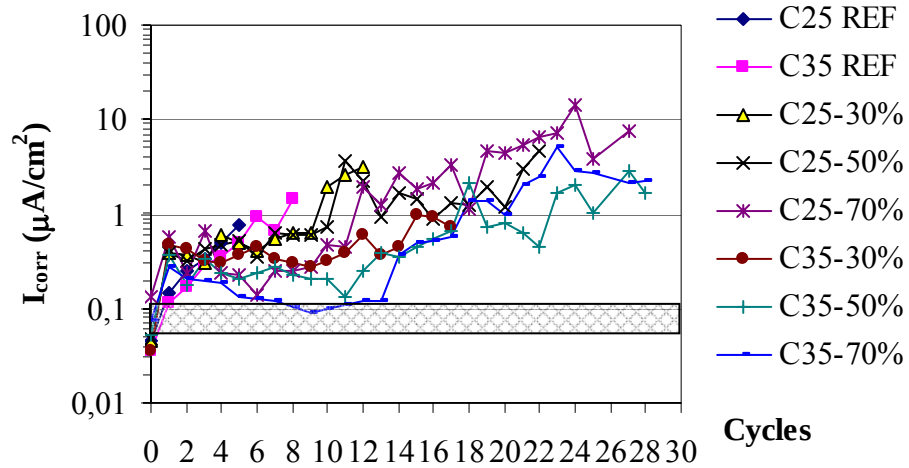


Figure 7. Corrosion rate measurements of lollipop specimens subjected to 12V potential difference.

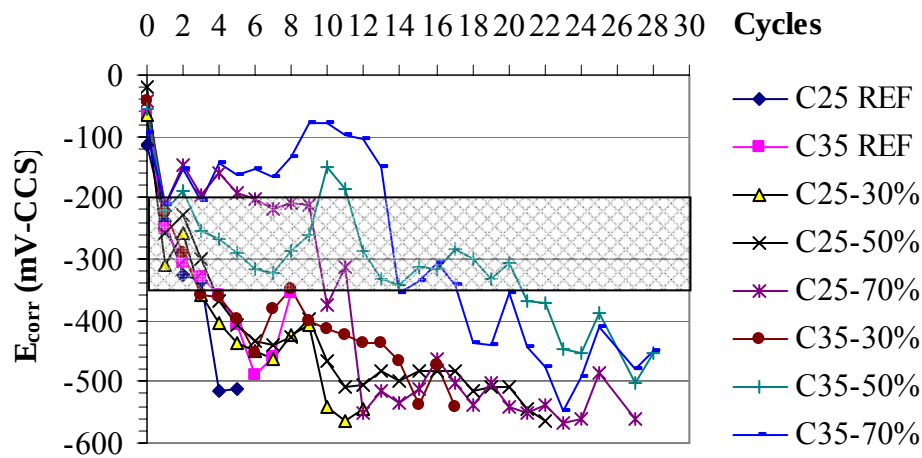


Figure 8. Corrosion potential measurements of lollipop specimens subjected to 12V potential difference.

In the corrosion data obtained from the specimens subjected to 12V potential difference (Figures 7-9) no cracks were seen below the corrosion rate of $1\mu\text{A}/\text{cm}^2$ and above the corrosion potential of -500 mV (vs. CCS). Besides, resistivity values were seen as the main indicator on failure of concrete cover, particularly after corrosion onset. Concretes with higher resistivities, as a function of binder composition, cracked at elevating corrosion rates. Increasing slag content prevented crack formation even at very high corrosion rates and at very low corrosion potentials for longer periods. In other words, for 45 mm concrete cover (for lollipop specimens), C25 grade specimens with GGBS contents of 0, 30%, 50% and 70% cracked at corrosion rates of $0.78\mu\text{A}/\text{cm}^2$, $3.19\mu\text{A}/\text{cm}^2$, $4.54\mu\text{A}/\text{cm}^2$ and $7.58\mu\text{A}/\text{cm}^2$, respectively. At the end of 28 cycles, no cracks have been observed yet on the C35-50% and C35-70% specimens.

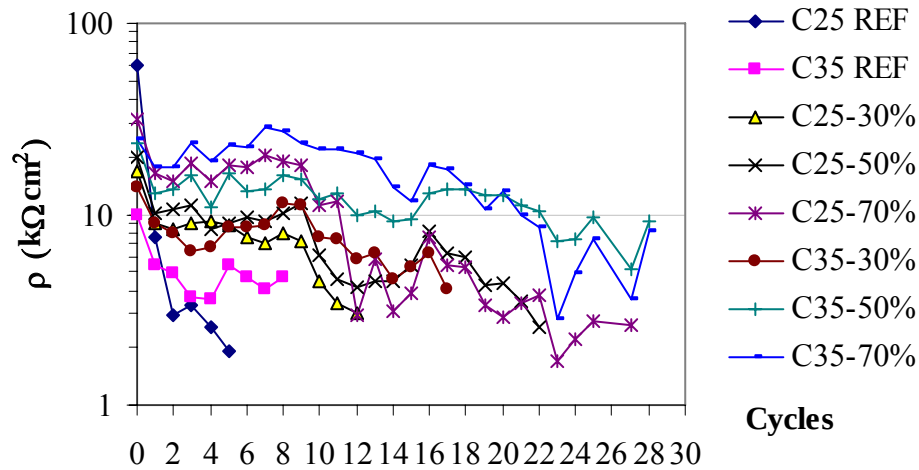


Figure 9. Resistivity measurements of lollipop specimens subjected to 12V potential difference.

Figure 10 demonstrates the number of cycles needed for corrosion initiation (CI) and crack formation (CF) of all concretes. Apart from C35-50%, it can be concluded that higher the GGBS content longer the time to corrosion initiation and the time to crack formation.

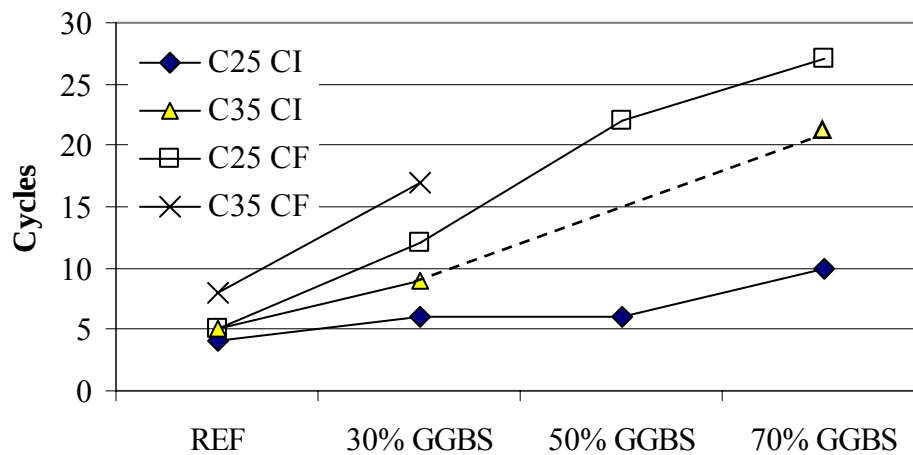


Figure 10. Number of cycles needed for corrosion initiation (CI) and crack formation (CF) of concretes

Chloride profiles of C25 coded concretes with the number of cycles for corrosion initiation are illustrated in Figure 11. Similar profiles of C35 were not shown, because corrosion has not initiated yet for high content slag added concretes at this grade. Figure 11 shows that, regardless of the number of cycles for corrosion onset, the higher the chloride content at peak values, the greater the binding capacity. Therefore, it can be deduced that ascending chloride binding capacity extends corrosion initiation period. Critical chloride concentration of reference concrete is higher than those of GGBS concretes, probably due to the consumption of hydroxide ions in pozzolanic reaction of slag.

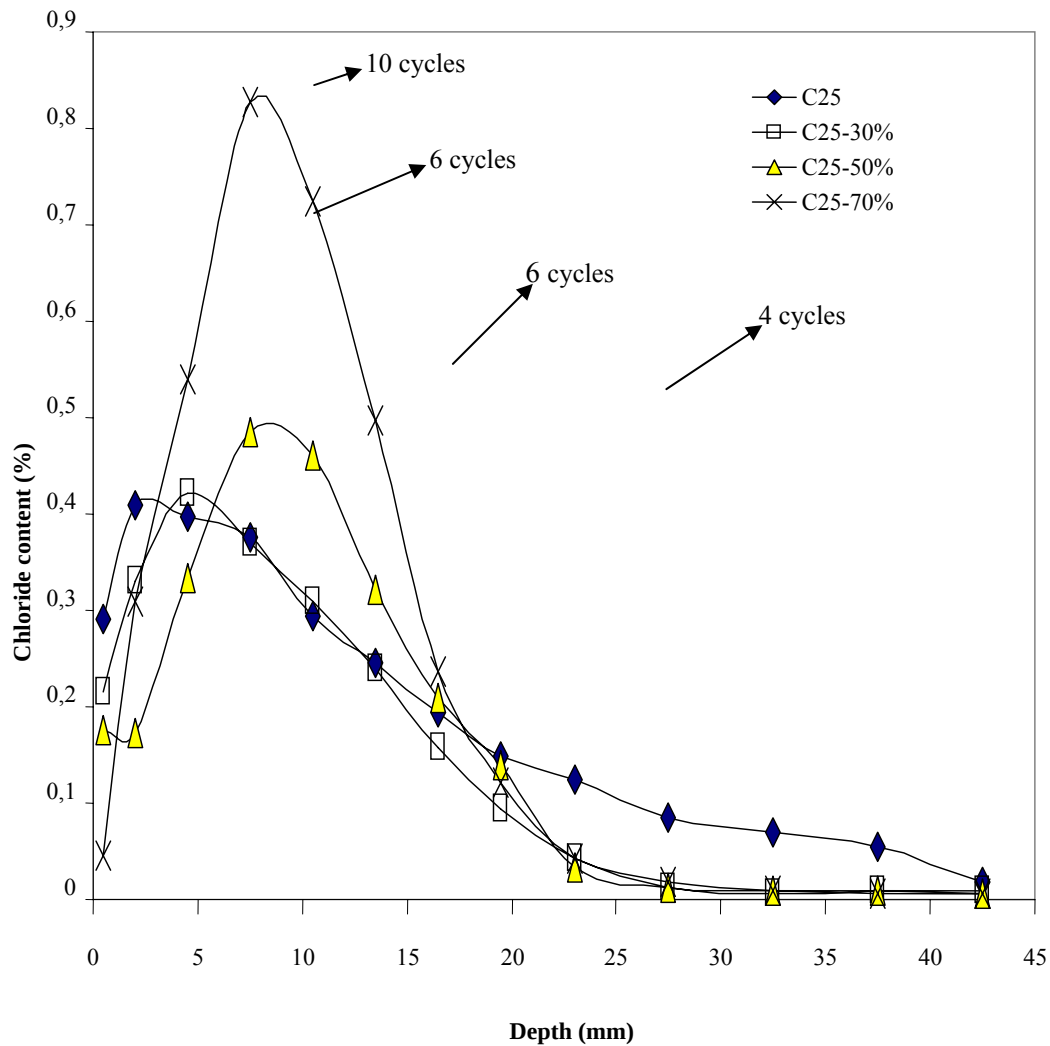


Figure 11. Chloride profiles of C25 coded concretes subjected to 6V potential difference.

4 CONCLUSION

In this paper, resistance of GGBS concrete against chloride-induced corrosion phenomenon with respect to migration test is studied. Significant reductions in compressive strength were obtained for high amount of slag replacement compared to OPC concretes. Besides, time to corrosion onset of C25 concretes containing %30, %50 and %70 GGBS, took 1.5, 1.5 and 2.5 times longer than that of plain concrete, respectively, while extension was 1.6, 4.2 and 5 times for C35 ones, in the same order.

More importantly, crack formation period, indicating the end of service life, for C25-30%, C25-50% and C25-70% concretes, extended 2.4, 4.4 and 5.4 times longer than that of OPC concrete, respectively.

Improvement in corrosion resistance of slag added concretes can be due to the chloride binding capacity of slag and affecting the resistivity by changing the pore solution chemistry. It can be concluded that usage of slag as cement replacement in concrete seems to be a good solution against chloride-induced corrosion, such as in marine environment.

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