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Evaluation of corrosion resistance of Portland pozzolana cement and fly ash blended cements in pre-cracked reinforced concrete slabs under accelerated testing conditions

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Abstract

In this paper, attempts have been made to analyse the corrosion characteristics of three kinds of cements, namely ordinary Portland cement (OPC), pozzolana Portland cement (PPC) and 25% fly ash replaced in ordinary Portland cement (FA) by designing two grades of concrete, M20 and M40 mixes under accelerated exposure conditions. Reinforced concrete slabs of size 900 mm × 180 mm × 100 mm were cast, cured and pre-cracked to crack width of 0 mm and 0.10 mm, exposed to accelerated testing conditions in 3% NaCl environments and evaluated for their corrosion resistance using various electrochemical tests like open circuit potential, linear polarization technique, free chloride, alkalinity and weight loss measurements and the results obtained were discussed in detail.

Keywords: Mineral admixture; Electrochemical tests; Corrosion resistance; Chloride environment; Pre-cracked concrete

1. Introduction

Chloride induced corrosion of steel rebars is one of the most serious problems in reinforced concrete structures. Cracked concrete allows corrosion process to initiate much faster than uncracked concrete [1]. The initiation of rebar corrosion in cracked concrete is dependent on the surface crack width [2]. Wider surface crack widths have been found to induce corrosion much faster than relatively smaller ones [3–5]. Other researchers [6,7] reported a slower initiation of steel corrosion in cracked concrete when the cover was increased. This is because corrosion of steel depends on the availability of oxygen, not at the crack, but in the sound concrete on the cathodic end of the steel and hence, on the rate at which oxygen can diffuse through the cover [8]. Thus, it is recognized that both crack width and cover thickness do affect the initiation of steel corrosion in concrete.

1.1. Effect of crack width

In concrete, micro cracks already exist due to its unstable condition as a composite material. Some other cracks develop when concrete is exposed to both environmental gradients and service loads. Therefore, studies on cracked reinforced concrete for corrosion resistance are essential.

In the past, some researchers have attempted to determine the effect of cracks on the generation and development of corrosion in reinforced concrete. The problem to identify whether cracks cause corrosion or corrosion causes cracking of concrete has been discussed by Metha and Gerwick [9]. They suggested that crack width does not play an important role for significant corrosion to occur, but that the total area covered by cracks next to the surface of the steel does. However, in their study only w/c ratios higher than 0.4 were considered.

According to Sagüés and Kranc [10], cracks in concrete may cause localized chloride ingress and the initiation of rebar corrosion. 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.

Crack width has also been reported to have a significant effect on corrosion of low w/c concrete [11]; however, this study was performed considering only two w/c ratios and was conducted over a very short period of time.

In another study [12] it was reported that crack width of less than 0.5 mm affects the development of corrosion, but its width

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has not a significant influence at later stages in the corrosion process. However, the same authors concluded later that the development of corrosion is not influenced by the crack width or by the crack itself [13].

After an extensive review of the influence of cracking on the deterioration of concrete, Jacobsen et al., concluded that crack widths smaller than 0.4 mm do not adversely affect the corrosion of steel as compared to steel in uncracked concrete [14], and some other factors such as environment, quality and thickness of the cover are more important. They also pointed out that most of the studies considered have been carried out on conventional concretes and more information about the effect of cracking on high performance concrete is necessary.

Schiessl and Raupach [15] performed an extensive review on the influence of crack width on chloride-induced corrosion and concluded that corrosion is only slightly affected by the presence of cracks and corrosion protection must be assured by the use of adequate quality concrete and suitable cover depth. However, calcium nitrite based corrosion inhibitor (CNI) has been reported to be effective in high and low *w*/*c* ratio concrete in cracked reinforced concrete when subjected to short and extended periods of simulated marine exposure [16].

The use of corrosion inhibitors in cracked concrete tends to “reinforce” the cathodic region in the uncracked area, thus raising the “throwing power” of a corrosion macrocell formed in the cracked concrete has been reported [17,18]. In recent studies in cracked concrete, the CNI was found to be relatively ineffective in preventing corrosion of small slabs subjected to a natural marine environment [19]. Consequently, more work in this area is necessary to provide additional information about the influence of the CNI, crack width and the possible interaction between them in the development of corrosion of reinforcing bars in concrete.

In the present investigation, three different types of cements namely, OPC, PPC and OPC replced with 25% fly ash in M20 (1:2.20:3.95, *w*/*c* ratio 0.58) and M40 (1:1.71:2.06, *w*/*c* ratio 0.48) grade concretes were evaluated for their corrosion performance under 0.1 mm crack width under alternate wetting and drying conditions in 3% NaCl solution by using various electrochemical techniques.

2. Experimental

2.1. Materials used

The following are the materials used for casting the concrete slabs.

Table 1
Chemical composition of OPC, PPC and fly ash

	Chemical components (%)		
	OPC	PPC	Fly ash
SiO_2	20.0–21.0	28.0–32.0	45.0–59.0
Al_2O_3	5.2–5.6	7.0–10.0	23.0–33.0
Fe_2O_3	4.4–4.8	4.9–6.0	6.0–15.0
CaO	62.0–63.0	41.0–43.0	5.0–16.0
MgO	0.5–0.7	1.5–2.0	1.5–5.0
Loss on ignition	1.5–2.5	3.0–3.5	1.92

The composition of ordinary Portland cement (OPC), Portland pozzolana cement (PPC) and fly ash used for the investigation is shown in Table 1. The fine aggregate and course aggregate used is of having fineness modulus of 2.75 and 7.25, respectively. The details of mix proportions used for the investigation are shown in Table 2. Sodium chloride used for the investigation is of commercial grade. Deionized water was used for mixing of concrete.

2.2. Techniques used

2.2.1. Open circuit potential (OCP) measurements

Triplicate concrete slabs of size 900 mm × 180 mm × 100 mm were cast with OPC, PPC and OPC replaced by 25% fly ash using M20 (1:2.20:3.95, *w*/*c* ratio 0.58) and M40 (1:1.71:2.06, *w*/*c* ratio 0.48) grade systems of concrete with 8 mm dia bar of 17.5 cm length rebar were embedded at a cover depth of 25 mm exactly below the notch. The rebars were cleaned with pickling acid and pre-weighed before embedded in concrete. Electrical lead connections were taken from the rebar in order to take potential measurements. After casting the specimens were subjected to water curing for 28 days. After 28 days curing the slabs were taken out and dried for 24 h and the slabs were assembled in the pre-cracked cantilever arrangement for cantilever loading as shown in Fig. 1. The slabs were subjected to a crack width of 0.1 mm beneath the notch and the crack width is maintained throughout the test period. The cracked slabs and uncracked slabs (0 mm) were subjected to alternate wetting and drying in 3% NaCl solution in order to accelerate the corrosion process. One cycle of exposure consists of 3 days ponding in 3% NaCl solution and 3 days drying in open atmosphere.

At the end of 3 days ponding in 3% NaCl solution, open circuit potential measurements were monitored with reference to saturated calomel electrode (SCE) as reference electrode. After taking the potential measurements, the NaCl solution was drained out and kept dry for 3 days. The experiment was continued up to 15 cycles of exposure. From the above results potential versus time plot is drawn using the average potentials obtained for different systems.

2.2.2. Determination of corrosion rate using RCC corrosion rate monitor

Corrosion rate of the rebar was monitored using the RCC corrosion rate monitor working on the principle of linear polarization [20]. In this technique using unconfined stainless steel auxiliary electrode a dc potential of 20 mV was applied and the change in current (dc) was measured. For IR compensation (because of high resistance of concrete) an ac frequency of 1000 Hz was applied and change in current (ac) was measured. From the ac and dc current

Table 2
Mix proportions used for the investigation

Grade of concrete	Mix ratio C:fly ash:FA:CA	Cement ($kg\,m^{-3}$)	Water ($kg\,m^{-3}$)	Fly ash ($kg\,m^{-3}$)	Fine aggregate ($kg\,m^{-3}$)	Coarse aggregate ($kg\,m^{-3}$)	*w*/*c*	28 days Compressive strength (MPa)
M20-OPC	1:2.20:3.95	305	177	0	671	1205	0.58	26
M20-PPC	1:2.20:3.95	305	177	0	671	1205	0.58	24
M20-FAC[a]	1:0.25:2.19:3.73	229	177	76	671	1205	0.58	23
M40-OPC	1:1.71:2.06	410	197	0	767	890	0.48	43
M40-PPC	1:1.71:2.06	410	197		767	890	0.48	35
M40-FAC[a]	1:0.25:1.71:2.06	334	210	76	767	890	0.48	36

[a] FAC, fly ash admixed concrete.