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Corrosion-induced reduction in compressive strength of self-compacting concretes containing mineral admixtures

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HIGHLIGHTS

- A study on the corrosion resistance of self-compacting concretes containing mineral admixtures is carried out.
- A simulation of rebars corrosion and its effect on compressive strength is applied.
- Various corrosion values on cracking templates in the mixtures are evaluated.

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ABSTRACT

In this study, the corrosion resistance of square and rectangular concrete cubes is evaluated and the correlation between the corrosion and the concrete compressive strength reduction is examined. Concrete specimens with different admixtures were prepared and exposed to accelerated corrosion, and the compressive-strength reduction coefficients of the Vecchio-Collins relation were also modified. The concrete-covering effect on compressive-strength reduction was also investigated by applying corrosion to rectangular block samples. The test results revealed that corrosion resistance and compressive strength are not always directly related. The mixtures with lower compressive strength and mineral admixtures demonstrated the highest corrosion resistance. By maintaining and protecting structures, or by increasing the curing duration from 1 to 3 months, it is possible to increase the time before structural corrosion by 2–4 times. When crack width was increased by about 1 mm (which reflects 7–12% corrosion in rebars) compressive strength dropped by about 20%.

1. Introduction

Concrete's pH value approaches 13 due to the production of $Ca(OH)_2$ during cement hydration, and also due to large amounts of KOH, NaOH, and Na_2SO_4 dissolved into it [1]. This level of alkalinity protects the rebars inside the concrete from corrosion by forming a passive thin layer of Fe_2O_3. Unfortunately, the alkalinity is counteracted by penetration of chloride ions in coastal regions, and penetration of CO_2 in polluted cities both of which usually lead to corrosion of reinforced concrete structures [2,3]. Rebar corrosion is the major cause of destruction of reinforced concrete structures or their premature cessation of operational life. For example, it was rebar corrosion that led to the collapse of the Dickson bridge in Montreal (Canada) [4] and the Ynys-y-Gwas bridge near Talbot (United Kingdom) [5] before the end of their design lifetime. In spite of the diverse and comprehensive studies on corrosion and its effect on structural capacity [6–8], no study has seriously investigated the effects of corrosion-induced cracking on the reduction of concrete's compressive strength.

In 1986, Vecchio and Collins [9] calculated the reduction in cracked concrete's compressive strength through finite element analyses. They used in-plane normal and shear loading for two-dimensional elements in their studies. Although not originally developed to specifically calculate corrosion-induced reduction in compressive strength, due to the similarity of the proposed relation and the effects of rebar corrosion, their model has been the most important reference for this purpose. The model has been used by many researchers such as Yalciner et al. [10], Zandi Hanjari et al. [11], and Coronelli and Gambarova [12]. In this model, the reduction in concrete's compressive strength due to rebar corrosion was calculated based on the width of a corrosion-induced

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crack. Molina et al. [13] developed a model for calculating reduced compressive strength; Coronelli and Gambarova [12] used that model to develop another model for calculating crack width. Similarly, Li et al. [14] developed a model for calculating crack width, and Yalciner et al. [10] combined this model with the Vecchio-Collins model to develop a new model for calculating reduction in compressive strength. Stewart et al. [15,16] used a constant to estimate the corrosion-induced reduction in compressive strength. Analysis of the effect of different admixtures on concrete's compressive strength and corrosion properties has also been done in various studies [17,18]. However admixtures effect has not been evaluated comprehensively, therefore, this effect was also investigated in the present study.

Chloride ions and salt penetrate into beams and cause corrosion of reinforced concrete structures. Such corrosion leads to a reduction in the load-bearing capacity of reinforced components such as walls, foundations, beams, and columns. These effects are highly significant and evident, particularly when section compressive rebars demonstrate corrosion. This study examined the effect of rebar corrosion on compressive strength using experimental samples and simulations. Details of these samples are presented in the following section. Moreover, the samples' corrosion resistance and their reduction in peak compressive strength were also examined based on the degree of corrosion and size of crack width. Also a comprehensive study on the concrete mixture's corrosion resistance is conducted, and various corrosion values on the cracking templates in the mixtures are evaluated.

2. Corrosion-induced reduction in concrete compressive strength

2.1. Corrosion-induced process and products

Over time, as the penetration of Cl^- or CO_2 destroys a rebar's passive layer covering, every iron atom loses 2 or 3 electrons (depending on its valence). The destroyed region of the passive layer is known as the anodic area. The combination of penetration by oxygen and water (which also exist inside the concrete), along with the arrival of the electron released by iron (which moves inside the rebar toward the cathodic area), generates hydroxyl ions (OH^-). These ions move toward the anodic region and react with Fe^{2+} to produce ferrous hydroxide $Fe(OH)_2$. Furthermore, in the anodic region, ferric hydroxide $Fe(OH)_3$ results from trivalent iron atoms. The resulting atoms react with dissolved oxygen to produce the following products: hydrated ferric oxide ($Fe_2O_3{\cdot}H_2O$), known as red-brown rust; black magnetite (Fe_3O_4); and green hydrated magnetite ($Fe_3O_4{\cdot}H_2O$) [19]. Table 1 shows the increase in volumes of these corrosion products compared to the volume of iron [20,21].

Table 1 demonstrates that the product is much larger than the initial volume of materials before reaction. This volume occupies the small space between the concrete and the rebar, and, consequently, exerts internal pressure on the concrete, thereby causing cracking.

2.2. Effect of corrosion process on compressive strength

The following relation was proposed by Vecchio and Collins [9] to calculate the reduction in concrete's compressive strength due to corrosion.

Table 1
Volume of corrosion products compared to iron volume.

Corrosion products	Fe	FeO	Fe_3O_4	Fe_2O_3	Fe $(OH)_2$	Fe $(OH)_3$	$Fe(OH)_3$ $3H_2O$
Volume (cm^3)	1	1.8	2	2.1	3.8	4.25	6.5

$$f_c^* = \frac{f_c'}{A + K\frac{\varepsilon_1}{\varepsilon_{C0}}} \tag{1}$$

where f_c^* is the corrosion-induced reduction in concrete's compressive strength and f_c' denotes concrete's compressive strength. Constants A and K were assumed to be 0.8 and 0.34, respectively, by Vecchio and Collins [9]. In addition, ε_{C0} is the strain corresponding to the maximum compressive strength, and is assumed to be 0.002 for plain concrete. ε_1 is the mean primary tensile strain perpendicular to corrosion cracking. According to the studies by Yalciner et al. [10] and Cape [23], constants A and K are suggested to be equal to 1 and 0.1, respectively. Eq. (2) computes the value ε_1 in Eq. (1) for sections with a width of b_0 and corroded compressive rebars.

$$\varepsilon_1 = \frac{b_f - b_0}{b_0} \tag{2}$$

where b_f is the increased section width resulting from the corrosion-induced cracks. Denoting the width of such cracks in each rebar as w_{cr}, for a section with n compressive rebars the transverse strain is calculated as in Eq (3).

$$\varepsilon_1 = \frac{b_f - b_0}{b_0} = \frac{n_{bars} w_{cr}}{b_0} \tag{3}$$

Researchers such as Stewart et al. [15,16] defined a constant for calculating the corrosion-induced reduction in the compressive strength of concrete. However, their constant does not properly reflect the compressive strength of concrete under different degrees of corrosion. In fact, using a constant for different degrees of corrosion is not accurate.

3. Formulated experimental program

3.1. Materials

In the present study, a locally available ordinary Portland cement type II conforming to ASTM C150 [22] was utilized. The mineral admixtures were limestone powder (LP), silica fume (SF), metakaolin (MK), fly ash (FA), and a type of low-activity ground and granulated blast-furnace slag (SL). Two types of river sand (coarse and fine) with a specific gravity of 2550 kg/m^3 were also used as fine aggregate. Crushed limestone with a maximum size of 19 mm and specific gravity of 2600 kg/m^3 was used as coarse aggregate. High-range water reducing admixture (HRWRA) with a base of polycarboxylate was also used. To evaluate the impact of corrosion on the reduction in compressive strength of normal and self-compacting concretes (SCC), samples were built with a water to cementitious materials (w/cm) ratio of 0.4. Table 2 shows the details of the used mixtures' proportioning.

3.2. Making the samples

For the purpose of compressive strength reduction tests, 20 square cubic samples and 8 rectangular block samples were built by placing 1 and 2 rebars into concrete, respectively. For the purpose of studying the effect of concrete cover and spalling on the reduction in compressive strength, rectangular block samples were built by placing 2 rebars with diameters of 10, 12, and 16 mm at a distance of 10 cm from the sample length (Figs. 1 and 2). The length of rectangular block samples with cross-sectional area of 10 × 10 cm^2 varied between 12 and 15 cm. After casting the concrete and performing the vibration operations, the samples were kept 24 h in the molds, and subsequently were kept 28 days in a water tank with a constant temperature of 22 °C (±2).

In order to exert uniform pressure and prevent the difference between the distribution of concrete and steel during loading, rebars were cut such that they had smooth and flat section areas (Fig. 3). Moreover, before being placed into the molds, the rebars were precisely weighed; this enabled us to measure the exact amount of corrosion by comparing their weights at various times during the experiment.

3.3. Workability tests of self-compacting concrete

The following workability tests were performed according to PCI methods [24]: slump flow, J-ring, T_{50}, V-funnel, and visual stability index (VSI).