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Corrosion performance of blended concretes exposed to different aggressive environments

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HIGHLIGHTS

- Impress voltage and wetting/drying cycles were used as chloride induced corrosion.
- The MK, SF and OPC concretes subjected to accelerated corrosion were examined.
- In the simultaneous exposition to CO_2 and Cl^-, SF-concrete greatly reduces corrosion.
- Under carbonation MK and SF concretes shown higher corrosion rates than OPC.
- Use of metakaolin and silica fume enhances chloride resistance of concrete.

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ABSTRACT

The research study presented herein evaluates the corrosion behaviour of the reinforcing steel in blended concretes using two pozzolanic additives—metakaolin (MK) and silica fume (SF)—at 10% replacement of cement weight. They are exposed to CO_2 and chlorides. The corrosion process was followed by monitoring of open-circuit potential (OCP), polarisation resistance (Rp) and electrochemical impedance spectroscopy (EIS). Electrochemical measurements show that the addition of MK and SF enhances corrosion resistance exposed to chlorides, however under accelerated carbonation these concretes show higher corrosion rates. In the simultaneous exposition to carbon dioxide and chlorides, SF-concrete shows a decrease of corrosion rate.

1. Introduction

Concrete has become the most utilised material in the construction sector worldwide because of its versatility and low cost [1,2]. Portland cement concrete is a ceramic material that supports compressive stresses. However, it is susceptible to fracture under other types of mechanical loads, such as flexion, traction, torsion, and shear. As a result, reinforced concrete, which is a composite material that is composed of concrete and structural steel, has been developed. This material has been extensively utilised in the construction of bridges, buildings, and tunnels. One of the most important characteristics of concrete, in addition to its mechanical properties, is its durability, which can be associated with the service life of a structure that has been exposed to aggressive environmental conditions [3,4]. The primary problem related to the durability of reinforced concrete is corrosion of the reinforcing steel, which causes the loss of mechanical and structural properties as corrosion progresses [5]. Corrosion of the reinforcing steel is primarily caused by exposure to aggressive environments that contain chloride ions and/or carbonation [4]. The presence of chlorides in the interior of concrete can originate from two main sources: the concrete mixture (contaminated aggregates, seawater or polluted water, and additives with a high chloride content) and the external environment. Once the chloride ions penetrate concrete, they spread as bound chlorides and free chlorides. The former correspond to chlorides that are chemically bonded via reaction with tricalcium aluminate (C_3A) in cement, which

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subsequently form calcium chloroaluminate—a compound known as "Friedel's salt" that is not expansive. For this reason, it is advisable to utilise cements with high contents of C_3A for marine environments. Conversely, free chlorides diffuse through the cementitious matrix until they reach steel; this diffusion causes localised dissolution of the passive layer and attacks at specific points, which can significantly reduce the structural properties of steel [4].

The process of carbonation is due to the entry of CO_2 from the atmosphere to the interior of the concrete; urban environments and environmental pollution are necessary sources of this phenomenon. Concrete is an alkaline material with a pH between approximately 12.6 and 13.6, which provides natural protection against corrosion of reinforcing steel. However, carbonation decreases the pH of concrete to approximately nine; consequently, the passive layer is destabilised, which causes corrosion of reinforcing steel [4–7]. To achieve carbonation, carbon dioxide must contact the water and alkaline components in the concrete pores. The rate of CO_2 penetration is dependent on environmental factors, such as relative humidity between 50% and 70%, the temperature, and CO_2 concentration. The last factor can attain a maximum value of approximately 0.1% in urban environments [8–10]. Other factors that contribute to the propagation of CO_2 are inadequate curing, poor compaction, and high water-to-cement (W/C) ratios, which generate highly permeable concrete.

The incorporation of pozzolan can prolong the service life of a structure and contribute to the mechanical properties of a structure by decreasing the permeability of a material, which reduces the entry of aggressive agents from the environment. Despite the benefits of incorporating pozzolan in concrete, studies have indicated controversial findings [11–14]. The commercial pozzolans utilised in the production of high-performance concrete are metakaolin (MK) and silica fume (SF). In recent years new pozzolans have been studied as a cement replacement such as fluid cracking catalyst spent (SFCC), which shows an evidence of a pozzolanic activity and good corrosion performance [15–17].

MK is a material that is obtained from the calcination of kaolinitic clay at temperatures between 500 and 800 °C [1,4,18]. MK is an aluminosilicate-type pozzolan, whose particle size is slightly finer than the particle size of cement [1]; its primary characteristic is its high reactivity with the calcium hydroxide in cement and its ability to accelerate the hydration of cement [18]. Based on its characteristics, this additive increases the mechanical properties (compressive and flexural strengths) and the durability (lower permeability and greater resistance to chemical attack [4,18–20]) of concrete. The corrosion resistance of reinforcing steel increases with the addition of MK on the order of approximately 10–15% [4] by reducing the diffusion of chloride ions in the cementations matrix, which prolongs the service lives of structures. Güneyisi et al. [21] note that the rate of corrosion decreases by 50% for concretes that were blended with MK and exposed to chlorides. Keleştemur and Demirel [18] conclude that the replacement of cement with 15% MK increases the compressive and tensile strengths and improves the corrosion resistance of reinforcing steel. Conversely, controversial studies have investigated the performance of concrete in the presence of CO_2. Mejía de Gutiérrez et al. [22] determined that the depth of carbonation for specimens blended with MK after 28 days of curing is slightly greater than the depth of carbonation for specimens of unblended concrete. However, the carbonation rate decreases after increasing the curing time. Kim et al. [23] assert that the carbonation depth increases in blended concretes.

SF is a by-product of the silicon and ferrosilicon industry. The reduction of high-purity quartz at temperatures greater than 2000 °C produces silica vapours, which oxidise and condense to form small particles of amorphous silica [1,24]. SF has a high content of silica of approximately 85–95%, a fine particle size of approximately 0.1 to 0.5 μm, and a large specific surface area [1,4,24]. Because of its high reactivity, SF accelerates the hydration processes in cement; because of its small particle size, it refines the pores in the cementitious matrix and considerably decreases the porosity of the material [23]. The advantages of concrete that has been blended with SF are an increase in the mechanical properties of concrete and an improvement in the durability properties of concrete. To attain high compressive strengths and low chloride-diffusion coefficients, 5–10% loading in place of cement is suggested [26,27]. Chao and Lin [28] have observed that SF-blended concrete reduces the permeability due to a decrease in capillary pores, increase the resistance to chloride and reduces the probability of corrosion of a reinforcing concrete. Regarding carbonation, Kulakowski et al. [29] assert that concrete with W/C ratios of 0.45–0.50 are more resistant to carbonation. However, some authors have noted controversial results [25].

The objective of this investigation was to compare the performance of concrete that is blended with 10% MK and SF with respect to the mass of cement with corrosion of the reinforcing steel. The evolution of the corrosion process was evaluated via non-destructive techniques, such as open-circuit potential (OCP), electrochemical impedance spectroscopy (EIS), and linear polarisation resistance (LPR), on specimens that were exposed to different aggressive environments, such as carbonation, chlorides, and a mixed environment (carbonation and chlorides). In all cases, a reference concrete that contains 100% Portland cement was employed.

2. Experimental procedure

2.1. Materials and specimen preparation

Raw materials were selected for the production of the materials that are available on the domestic market, such as general-use Portland cement, reinforcing steel, and aggregates. Additives for reducing permeability, such as the commercial MK Metamax®, supplied by BASF and the commercial SK from Sika®, were employed. Table 1 shows the chemical compositions of the utilised materials. A W/C ratio of 0.55 and a 10% replacement of cement with each of the additives were utilised in the production of the concrete, considering the results of previous studies [4,30,31]. The concrete was fabricated in a mixer with a capacity of 210 L. Table 2 shows the composition of the concrete mixtures. For the concrete mixture with SF, the superplasticiser additive Sika® Viscocrete® 20HE was employed. After mixing, the fresh concrete was poured into metal moulds with dimensions of 76.2 × 152.4 mm and compacted with a smooth metal rod. The specimens were unmoulded after 24 h and left to cure in water for 28 days. Each specimen had a steel rod with a length of 150 mm and a diameter of 6.4 mm embedded in its centre. These steel rods were cleaned with acetone to eliminate fats on the surface. In addition, a 60 mm-long exposure zone was defined, which corresponds to the area that was embedded within the concrete. The remainder of the rod was coated in corrosion-resistant epoxy paint.

2.2. Electrochemical measurements

To monitor the evolution of corrosion in reinforced concrete, different non-destructive techniques have been utilised, such as OCP, LPR, and EIS.

Table 1
Chemical composition of Portland cement, metakaolin and silica fume.

Chemical constituent (%)	Cement	Metakaolin	Silica fume
SiO_2	19.13	52.36	85.3
Fe_2O_3	4.32	0.37	0.5
Al_2O_3	4.42	44.25	0.3
CaO	57.70	–	0.5
MgO	1.6	–	3.6
SO_3	2.32	–	0.5
TiO_2	–	1.76	–
K_2O	–	–	2.4
Na_2O	–	–	2.1
Cl	–	–	0.8
LOI[a]	9.78	0.86	3.78

[a] LOI: Loss on ignition at 1000 °C.