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Chloride interaction with concretes subjected to a permanent splitting tensile stress level of 65%

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HIGHLIGHTS

- A damage was studied for concretes under chloride and splitting tensile conditions.
- The damage has similarities to the so called Stress Corrosion Cracking (SCC).
- A more pronounced harm was perceived in mixtures made with Blast Furnace Slag-BFS.

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ABSTRACT

Penetration of chloride ions into concrete is a complex topic. These ions together with other dissolved chemical species can penetrate into cementitious materials by convection through capillary pores or cracks. Prolonged periods of drying followed by re-wetting can provoke a similar transport mechanism. Saturated cement based materials experience diffusion of water dissolved ions. Ions in the diffusing solution experience chemical interaction with a hydrated cement paste. Some ions are physically adsorbed, others react chemically and part remain free in the solution. This turns the transport into a reactive form of diffusion. The nano-pores which are part of the cement gel, act as sinks for the intruding aggressive chlorides. When concrete is subjected to splitting tensile stresses and a critical stress ratio is surpassed the presence of micro-cracks modifies the transport of chlorides within this material. It was noticed that the chloride content of concrete decreased in zones close to the surface specially where the main pattern of micro-cracks follows the loading plane. It was also observed a secondary micro-crack system which develops perpendicularly to the main splitting-crack system and is connected to it. It was found that this secondary system was also responsible of lowering the level of the chloride content in regions close to the surface even at unexpected distances located far away from the direct influence of the splitting plane. The presence of an inner peak of chloride was also observed, which represents the extent of the damaged or altered zone. This region will be called in this paper as the convection zone. It is believed that the form of the obtained chloride profiles are influenced by the type and amount of binder utilized. Thus, some similarities were found in all the studied concretes such as the formation of a convection zone. On the other hand the level of chloride content and the shape of the profile seem to vary depending on BFS replacement of OPC or when high sulfate resistant cement (HSR) is used as a single binder.

1. Introduction

Hardened concrete resists very well the applied compressive loads from external sources. However this material has a low tensile strength which is about one tenth of its magnitude in compression. This renders it susceptible to cracking under tensile loads. Consequently, a steel reinforcement is needed in the structural element in order to carry the tensile stresses provoked by applied loads. The tensile strength of concrete is practically neglected from most structural designs. Thus, cracking is expected to occur in structural elements due to the loads applied during its service life. The designer's main goal is controlling the crack width and their distribution in the structural element. Cracks are not only originated by external loads, the volume change caused by the drying shrinkage of concrete may provoke cracking. This situation can

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happen when concrete volume change in the structural element is restricted and tensile stresses are generated.

Corrosion of reinforced concrete is amongst the main causes of concrete deterioration. Every year important expenditures are consumed worldwide to rehabilitate damaged structures affected by corrosion. Chlorides are amongst the main factors that cause corrosion in concrete structures. Chloride ingress to reinforced concrete is commonly found in pavement and bridges that have been exposed to deicing salts. Other examples of structures exposed to chlorides are found in marine structures and industrial chloride rich environments.

Chloride transport into concrete is governed by several mechanisms. Capillary suction, convection, migration are some of the most common means of carrying chlorides. In saturated concrete, diffusion is the predominant mode of transporting chloride salt. The concrete cover in concrete and its cementitious hydrated paste act as an electrochemical membrane in which ions interact [1–9]. In well cured concrete this concrete cover acts as a barrier retarding the diffusion of chlorides. This retardation increases by some factors amongst which are the decrease of the water/binder ratio, the surface charge of the hydrated cement paste, the lagging motion of the corresponding cations, etc. [2–4].

Many studies have analyzed chloride ingress into concrete separately without the influence of an external load. Although it can be noticed from field observation that mechanical loads in combination with any type of aggressive agent for the concrete have an enhanced deterioration. Concrete's pore volume is never constant. It changes with time either due to continuing paste hydration or due to its deterioration and it also can be considerably modified by an applied load to the concrete. Therefore it is expected that the ingress of deleterious ions into concrete by means of convection and diffusion may be modified by the type and magnitude of the external load applied to it.

Chloride migration through convection and diffusion is usually diminished when a compressive load below one third of the concrete's maximum compressive capacity is applied to concrete [10]. When the applied load overcomes certain limit, some tensile stresses are developed within the concrete. At this instant some micro cracks are formed generating fresh pathways that raise the chloride intrusion. Under direct tensile load the rate of chloride penetration increases progressively as the load is increased [11]. This latter test method is complicated to setup, due to its high sensitivity to concrete imperfections and also due to eccentricity problems during the setting. A splitting tensile test is more simple to perform. The combined attack can be setup using a cubic sample subjected to a permanent splitting tensile load while one of its faces is exposed to a 3% sodium chloride solution. According to the Digital Image Correlation analysis (DIC) performed on the concrete samples, it was noticed that a 65% splitting stress level was enough to induce strains that would produce micro-cracks without splitting completely the sample.

Finally, a response to the chloride attack between non-loaded concretes compared to the ones that received load is analyzed for several types of binders. Thus, mixtures of Ordinary Portland Cement (OPC), High Sulfate resistant (HSR), and 50 & 70% Blast Furnace Slag (BFS) concretes were exposed to the proposed experimental conditions.

Table 1
Materials for concrete's mix design, kg/m^3.

Material	S0	S50	S70	HSR
CEM I 52.5 N	345	173	102	0
CEM I 52.5 N SR	0	0	0	347
BFS	0	173	238	0
Water	156	156	154	157
Sand 0/4	771	771	759	774
Gravel 2/16	1085	1084	1067	1090

2. Experimental procedure

2.1. Materials, concrete mixing and initial curing conditions

Four concrete mixtures without special properties regarding durability characteristics (the research purpose was to compare materials behavior without analysing specification compliance) were prepared for this investigation, as presented in Table 1. The aggregates were gravel and a natural sand of siliceous nature. The utilized binders are presented in Table 2 and are composed of an Ordinary Portland Cement (OPC) with no special durability properties and a high sulfate resistant cement (HSR), both materials complying with type CEM I 52.5 N according to European Standards. A (ground granulated) Blast Furnace Slag addition was also used to replace 50 and 70% by weight of the OPC. In order to improve the fresh concrete properties (slump between 160 and 210 mm) a superplasticizer (polycarboxylic ether based) was used in amounts between 0.2 and 0.4% by weight of the total binder content.

After mixing, concrete was cast in cubical molds (h. = 150 mm). Subsequently 7 days of wet curing at 20 °C and RH > 95% was applied and additionally, 21 days at 20 ± 2 °C and 60 ± 5% RH. A schematic view of the experimental procedure is presented in Fig. 1.

2.2. Splitting tensile strength values and Digital Image Correlation (DIC) tests

At the age of 28 days 3 cubes for each one of the S0, S50, S70 and HSR mixtures were tested for splitting tensile strength. The procedure stated on ASTM C496M-04 standard was followed but applied to cubic concrete samples. A schematic view of the test that was also used for the experimental setup is shown in Fig. 2 (left). The obtained splitting strength average values that represent each mix are shown in Table 3.

The previously acquired information was utilized to perform Digital Image Correlation (DIC) analysis. This technique consists of a stereoscopic camera system (two high-resolution cameras are placed facing the area under investigation) that, based on stereo-correlation and stereo-triangulation, reconstructs the 3D full-field deformation vector field on the material's surface. In practice, one of the samples' side area (150 mm * 150 mm) was covered with high-contrast random speckle pattern as shown in Fig. 3. The Vic-3D post-processing software tracked the speckles

Table 2
Binders chemical composition, density and specific surface area.

	Density	Blaine	LOI	Chemical composition (wt%)						
	kg m^{-3}	m^2 kg^{-1}	(%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Cl^-
OPC	3120	353	1.5	18.9	5.7	4.3	63.4	0.9	3.3	–
HSR	3140	447	1.0	21.6	3.5	4.1	63.9	1.8	2.4	0.03
BFS	2830	394	1.3	36.4	9.8	0.3	41.2	7.4	1.6	0.02