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Study of chloride penetration in concretes exposed to high-mountain weather conditions with presence of deicing salts

J. Bernal [a], M. Fenaux [b], A. Moragues [b], E. Reyes [b], J.C. Gálvez [b],*

[a] *Escuela de Ingeniería Mazatlán, Universidad Autónoma de Sinaloa, Av. Ejército Mexicano y de los Deportes, Cd. Universitaria, C.P. 82017 México, Mexico*
[b] *Departamento de Ingeniería Civil: Construcción, E.T.S de Ingenieros de Caminos, Canales y Puertos, Universidad Politécnica de Madrid, C / Profesor Aranguren, s/n, 28040 Madrid, Spain*

HIGHLIGHTS

- The transport process of chloride ions in non-saturated concrete is studied.
- The influence of the silica fume and blast furnace slag is studied.
- High-mountain environment with presence of deicing salts is experimentally reproduced.
- Numerical modelling of chloride ion transport considers diffusive and advective flux.
- Modelling takes into account pore network, chloride binding and precipitation.

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ABSTRACT

The durability of reinforced concrete (RC) is a challenge. One of the most aggressive and frequent ions is chloride, which frequently affects RC structures by steel corrosion. Many studies have concluded that the use of mineral admixtures improves concrete durability. This paper examines the transport process of chloride ions in non-saturated concrete. Three types of concrete have been designed and tested: the first one with only CEM I 52,2 R (CP), the second with 10% of silica fume (CPHS) and the third with 20% of blast furnace slag (CPEAH). An experimental programme was designed with the aim of studying the influence of external condition variation in a high-mountain environment with presence of deicing salts. The total time duration of the programme was 210 days. The specimens were conditioned at different temperatures, relative humidity and chloride surface concentrations in five phases to reproduce the seasons annually. The experimental chloride concentration profiles were obtained at the end of each phase for each concrete. These profiles were mainly influenced by two transport mechanisms: diffusion and capillary suction. The chemical chloride binding and physical adsorption of chlorides in the concretes with silica fume (CPHS) and blast steel furnace (CPEAH) were two decisive factors in the chloride penetration processes. A numerical model for simulating chloride ion transport in non-saturated concrete is presented. It considers the diffusive and advective flux. In addition, the concrete pore network and the associate properties, such as chloride binding capacity and chloride precipitation, are also taken into account. The model has been implemented in a finite element programme. The chloride concentration profiles obtained by the model at the end of each phase for each concrete properly fit the experimentally obtained.

1. Introduction

The durability of reinforced concrete depends on external parameters defined by the environment where the concrete structure is located. The aggressive agent type and transport mechanism depend on the external conditions. One of the most aggressive and frequent ions is chloride, which frequently affects reinforced concrete structures by steel corrosion. Corrosion of reinforcement bars is a primary cause of the deterioration of concrete structures, which may lead to failure and even collapse of the structure. This causes enormous repair and maintenance costs [1,2]. For that reason, published research on durability both in general and particularly in chlorides, has recently enjoyed substantial interest [3–5].

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* Corresponding author.
E-mail address: jaime.galvez@upm.es (J.C. Gálvez).

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The ingress of chloride into reinforced concrete may cause the initiation and acceleration of steel bar corrosion [6]. There are several environments where ion chloride is present, with the most important being marine and high-mountain environments, understanding for the last the environmental conditions of elements intended for the vehicular and pedestrian traffic in areas with frequent snowfalls or with temperatures below 0 °C and being subject to the effects of deicing salts. The main transport mechanisms of chloride ions in concrete are diffusion, capillary suction and convection [7], in which the most influential environmental parameters are temperature and relative humidity. The chloride ions in the concrete can be free, bound or adsorbed into calcium silicate hydrate [8].

Many studies have concluded that the use of mineral admixtures improves concrete durability, as it increases the chloride binding capacity [9], reduces the total porosity and permeability and improves the pore-size distribution of the cement matrix [10,11]. In addition, some admixtures such as fly ash and silica fume are employed as a partial replacement of the cement, achieving a significant improvement of the concrete strength [12,13]. Furthermore, admixtures of ground-granulated blast-furnace are used due to a capacity of hydraulic reaction, which provides hydrated products that increase mechanical resistance.

Numerous factors affect the penetration of chloride into the concrete, with the characteristics of the cement matrix such as binding capacity, total porosity, pore-size distribution, connectivity and tortuosity being significant. The ingress of chloride has been studied by calculating the diffusion coefficient (D), which determines the penetration rate of chlorides [14]. These studies usually consider a constant chloride surface concentration into the material (Cs) and assume that the chloride penetration capacity does not change with the passing of the time. It should be noted, however, that these assumptions are only approximations and the experimental chloride penetration profiles obtained in real structures show a different behaviour because of the complexity of the process.

In this article three different mix types of concrete are studied. The first one is the reference concrete (CP) prepared with initial high-strength Portland cement (CEM I 52,5 R). The second (CPHS) and third (CPEAH) involve two mixes where the cement was partially replaced by silica fume (10%) and blast furnace slag (20%), within the limits allowed by the current Spanish Code on Structural Concrete [15]. Several tests were carried out for characterising the mechanical and microstructural properties of the concrete. In addition, an experimental campaign was designed to reproduce conditions similar to high-mountain environments with de-icing salts acting on concrete samples. The experimental programme was divided into five phases by combining distinct surface chloride concentration, external relative humidity and temperature. The duration of the programme was 210 days. The age of the tested concrete samples was 90 days. At the end of each phase, a chloride concentration profile was obtained from each mix type, with the aim being an analysis of the influence of external conditions on the chloride profiles. In order to expand the scope of the research, a mathematical model based on the finite element method (FEM) was implemented. This model simulated the experimental programme and took into account the most relevant environmental and microstructural parameters. The chloride profiles obtained at the end of each experimental phase were compared with profiles obtained by numerical simulations to analyse the correlation between them.

Table 1
Chemical composition and physical properties of cementitious materials.

Parameters (%)	CEM I 52.5 R	Silica Fume	Blast Furnace Slag
SiO_2	19.20	95.37	37.00
Al_2O_3	6.07	0.34	11.48
Fe_2O_3	1.7	0.16	0.60
CaO	63.41	0.08	43.50
MgO	2.56	0.04	6.35
Na_2O	0.33	0.18	0.18
K_2O	0.82	0.30	0.45
SO_3	3.38	0.15	–
Cl^-	0.03	–	0.01
Loss to fire	–	–	–
Loss due to calcination	2.09	2.7	–
Insoluble residue	0.3	–	–

2. Experimental programme

2.1. Material and specimens

In this study, the behaviour against chloride attack of three types of concrete manufactured with initial high-strength Portland cement, CEM I 52,5 R [16] was evaluated. The first concrete mix was prepared without any admixture, the second with 10% of silica fume and the third with 20% of blast furnace slag (as cement replacements in the second and third) cases. Table 1 summarises the chemical compositions and physical properties of the cement, the silica fume and the blast furnace slag. The fine aggregate used was natural siliceous sand with 2.66 fineness modulus. The coarse aggregate was crushed limestone with a maximum size of 16 mm and 6.91 fineness modulus. In order to achieve proper workability, a superplasticizer was used as a high-range water reducing agent. Table 2 shows the composition of the mixes, in accordance with the Spanish Code on Structural Concrete [15].

In order to carry out the casting, curing, and testing of the concrete specimens, the procedures provided by the UNE-EN-12390-2 Standard [17] were adopted. A standardised steel cylinder mould with a diameter of 150 mm and height of 300 mm was used for casting the samples used for mechanical characterisation and one with a diameter of 100 mm and height of 200 mm for the microstructural characterisation and the chloride transport tests. The casting and finishing of specimens were performed under laboratory conditions at a temperature of 23 °C. The moulds were removed 24 h after casting and then cured in a solution saturated of $Ca(OH)_2$. From each concrete type a total of 24 cylindrical specimens of the largest size and 28 cylindrical specimens of the smallest size were made.

2.2. Experimental procedure

The curing procedure was carried out under laboratory conditions, with the samples being submerged in a saturated $Ca(OH)_2$ solution to avoid leaching of the material. The tests carried out consisted in the measurement of mechanical properties, transport capacity of chlorides and pore network characterisation.

Table 2
Details of concrete mixtures (kg/m^3).

Material	CP	CPHS	CPEAH
Cement	400	320	320
Silica fume	0	40	0
Blast furnace slag	0	0	80
Water	160	180	180
Coarse aggregate	970	1014	970
Fine aggregate	846	861	846
SP (%)	1.5	1.5	1.1
w/c ratio[a]	0.40	0.45	0.45

[a] CP = w/c, CPHS = w/(c + kF) and CPEAH = w/(c + kF), where: k = admixture efficiency factor and F = admixture quantity. Silica fume k = 2 and blast furnace slag k = 1.