The ingress of chlorides in concrete under compressive or tensile loads

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Abstract

One common aggressive mechanism acting in reinforced concrete is chloride attack which induces steel corrosion. Although it has mostly been studied and analyzed separately it has been observed that loads acting on concrete may modify the deteriorating effect.

In this research the effect that combined attack provokes on concretes made of ordinary Portland cement (OPC), high sulfate-resistance cement (SR) and blast furnace slag (BFS) cement is investigated. Five mixes were made with these materials, 2 of them using a type 52.5 N (OPC) cement, 2 replacing OPC by 50 and 70 % of BFS and 1 made of 52.5 N (SR) cement type. Cubic samples made with all binder types were exposed to a 3% by weight sodium chloride solution while applying a permanent splitting tensile load corresponding to 50 % of their breaking capacity. Prismatic samples (100 x 100 x 400 mm) made of OPC binder were exposed to a 3% by weight sodium chloride solution while maintaining a compressive load equal to 30 % of their maximum capacity. After the exposure time, ground layers were obtained from the samples to determine the chloride ingress into the concrete by means of potentiometric titration. To define chloride transport in concrete an error function solution was applied to Fick's second law.

In terms of their diffusion coefficient and chloride surface concentration in decreasing order of performance were found: the concrete with 70 % replacement by BFS, followed by the concrete with 50 % BFS substitution, then pure OPC concrete and finally the sulfate resistant cement concrete.

Load levels of 30 % in compression and 50 % in splitting tensile testing, improved the resistance of concrete to chloride attack.

Originality

Heterogeneity of concrete is one of problems that makes it difficult to setup a representative experiment to reproduce in the laboratory the impact that a given applied load has on service life of reinforced concrete structures when subjected to a certain environmental condition. In the case of the combined chloride attack to concrete exposed to compressive loading the laboratory simulation is simple, thanks to the good capacity this material has under compression which makes any heterogeneity inside the material less perceptible. Considering this, laboratory simulation of salt attack on concrete structures under compression is easier than similar attack on concrete exposed to tensile loads, this mainly due to concrete's low resistance to tensile loading which makes any material heterogeneity more noticeable.

Application of conventional tensile tests such as concrete bending tests or direct axial tensile tests on prisms plus salt attack are difficult to design, the former are sensible to concrete's heterogeneities in the part subjected to traction while the latter can face eccentricity problems leading to the occurrence of torque which makes it more difficult to setup the required test.

In this study the indirect tensile stress caused by axially opposed compressive loads offer an easy alternative to study combinations of tensile loads and chloride attack to concrete.

The simplicity of the test setup is the main originality of this study.

Keywords: *combined attack; chlorides; splitting tensile test; compression.*

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1. Introduction

Hardened concrete made with cementitious binders is a porous material. Cement paste pores depend on cement-binder material characteristics such as chemical and physical nature, water/binder ratio, hydration time and aggregate/paste ratio. Under normal conditions the voids within this solid are partially occupied by aqueous solutions. Aggressive salt bearing waters in contact with concrete can enter its pores by capillary absorption through a process denominated convection. The penetration rate and depth will depend on concrete characteristics such as pore size distribution and connectivity, cracks existence, degree of saturation. After deleterious salts have entered the pore system they can travel further inside via diffusion, the rate of salt ingress is called the diffusion coefficient, its magnitude depends as well on voids volume, size and degree of saturation, but also on the physicochemical nature of the cement gel and its interaction with the aggressive ions in solution. Migration of deleterious ions into concrete is also influenced by cycles of wetting and drying, pressure and temperature, factors that contribute to the complexity of the salt transport into the concrete.

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 migration 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 diminished when a minor compressive load is applied to concrete but the opposite effect is noticed when the applied load overcomes a certain limit, usually 30 or 50 % (Fuxiang *et al.*, 2012; Qiwei *et al.*, 2008) of the concrete's maximum compressive capacity. At this instant some micro-cracks are formed generating fresh pathways that increase the chloride intrusion. Under direct tensile load the rate of chloride penetration increases progressively as the load is increased (Donghun *et al.*, 2010)

The main task in this research is to obtain a more realistic reflection on concrete's durability when a combination of environmental and mechanical loads act simultaneously on this material. To accomplish this, concrete specimens made of ordinary Portland cement (OPC), high sulfate-resistant Portland cement (HSR) and concrete in which Portland cement was partly replaced by blast furnace slag (BFS) applying 2 different replacements levels, were exposed to a 3% sodium chloride solution while maintaining permanent compressive and splitting tensile loads.

2. Experimental

2.1. Raw Materials and sample preparation

Two types of Portland cements were used, type I 52.5 N with no special durability properties and type 52.5 N HSR (High Sulfate Resistant cement). Blast furnace slag was also used in two mixtures to replace 50 and 70 % by weight of the type I Portland cement. The chemical composition of the binders is presented in table 1.

Tab. 1 Chemical composition of binders (%)

	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	CO_2	Na_2O	Cl^-	Sulp.	Ins. Res.	LOI
OPC	63.37	18.90	5.74	4.31	3.34	0.89	0.73	0.50	0.47	-	-	0.41	1.51
BFS	41.24	36.37	9.83	0.26	1.62	7.41	0.41	0.90	0.28	0.02	0.79	0.43	1.30

Five concrete mixes were proposed for this research and they are presented in table 2. The aggregates were gravel and a natural sand where quartz is the predominant material .

In order to improve the fresh concrete properties (slump between 160-210 mm) a superplasticizer (Polycarboxylate based) is used in amounts between 0. 2 – 0.4 % by weight of total binder.

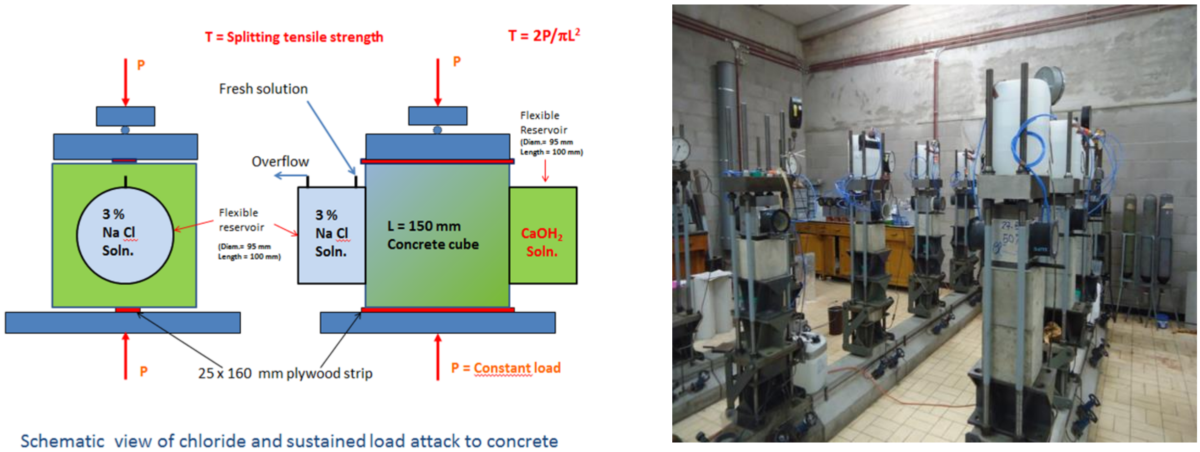
Concrete mixes S_0, S_{50}, S_{70} & S_R, were prepared to obtain cubical samples (side=150mm) for splitting tests, and stored for 7 days at 20˚ C and RH > 95%. The samples were then demoulded and exposed to an additional curing time of 21 days at 20 ± 2 ˚C and 60 ± 5 % RH. Mix $S_{0\text{-b}}$ was prepared to cast concrete prisms (100 x 100 mm^2, h 400 mm) for compression tests, stored after demoulding for 28 days at 20˚ C and RH > 95%

Tab. 2 Mix proportions (kg/m^3)

MATERIAL TYPE	S_0	S_{50}	S_{70}	S_R	$S_{0\text{-b}}$
CEM I 52.5 N	345	173	102	0	369
CEM I 52.5 N HSR	0	0	0	347	0
BFS	0	173	238	0	0
WATER	156	156	154	157	166
SAND 0/4	771	771	759	774	840
GRAVEL 2/8	611	611	601	614	575
GRAVEL 8/16	474	473	466	476	450

2.2. Experimental procedure

For the splitting load operation, at 28 days after casting 3 cubes for each of the S_0, S_{50}, S_{70} & S_R series were tested for splitting tensile strength and the average shown in table 3 was taken as a reference for the combined setup. For each sample two cubes were vacuum saturated, the non-exposed faces covered with black silicon and aluminum foil leaving two opposite open faces to put the solution reservoirs. The samples were subjected to 50% of the splitting tensile breaking load, in a hydraulic jack connected to a pressurized cylinder (nitrogen/oil mixture) then an exposed face was put in contact with a 640 cm^3 capacity reservoir containing 3% chloride solution which was continuously recycled from a 8 liter stock solution tank at a flow rate of 23 l/h using an aquarium pump. Another reservoir of the same capacity as the chloride solution but filled with saturated $CaOH_2$ solution was placed at its opposite face as shown in figure 1.



Schematic view of chloride and sustained load attack to concrete

Figure 1. Chloride and load combined attack setup (Splitting)

For the compressive load operation, 2 prisms corresponding to the $S_{0\text{-b}}$ mix were tested after 28 days from casting for compressive strength and their average is shown in table 4, this value was taken as a reference for the combined setup. Two prisms were loaded coaxially to reach 30% of their compressive breaking load using a hydraulic jack connected to a pressurized cylinder (nitrogen/oil mixture). Then an exposed face was put in contact with a 80 x 160 x 50 mm^3 capacity reservoir containing 3% chloride solution following the same procedure as for the splitting setup as shown in figure 2.

Tab. 3 Average splitting loads for 3 cubes (150 mm side)

Sample #	Av. load (100%) kN	Var. coeff. %	Splitt. strength MPa	50% of max. load kN
S_0	145.5	1.9	4.12	72.8
S_{50}	142.5	4.9	4.04	71.3
S_{70}	124.0	1.8	3.51	62.0
S_R	168.7	1.8	4.78	84.3

Tab. 4 Average compression loads for 2 prisms (100 x 100 mm^2, h 400 mm)

Sample #	Ave. load (100%) kN	Var. coeff. %	Compr. strength MPa	30% of max. load kN
$S_{0\text{-}b\text{-}1}$	568.9	1.1	56.89	170.7

Figure 2. Chloride and load combined attack setup (compression)

After the exposure time, samples were ground into 1-2 or 3 mm depth layers to obtain at least a quantity of 10 layers. The obtained powdered concrete was treated by acid digestion with nitric acid to extract the total (acid soluble) chloride following the procedure described in EN 14629 “Determination of chloride content in hardened concrete” by potentiometric titration with a 0.01 M silver nitrate solution. To define the obtained chloride’s diffusion profile in concrete an error function solution was applied to Fick’s second law, thus obtaining the diffusion coefficient and the modeled chloride surface concentration using the procedure suggested in ASTM C 1152 “Acid soluble chloride in mortar and Concrete”.

2.3. Obtained results and discussion

2.3.1 Attack under splitting tensile load

Cubic samples representing concrete mixes S_0, S_{50}, S_{70} & S_R were exposed for 315 days to a combination of 3% sodium chloride solution plus 50 % of the maximum splitting tensile load, 2 cubes were used to represent each mix. Another set representing the same mixes was exposed without load to serve as reference samples. With the information extracted from the samples a modeled curve, diffusion coefficient, correlation coefficient and surface concentration were obtained and shown in figure 3 and table 5.

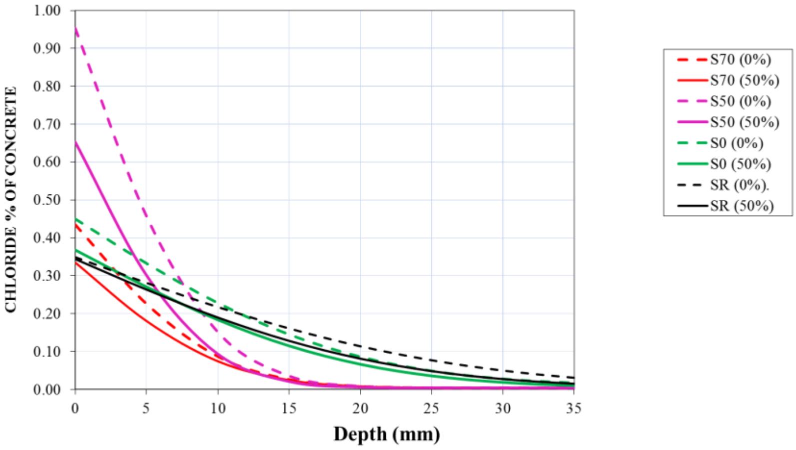


Figure 3. Chloride diffusion profiles after 315 days at 0 & 50% of failure splitting load and 3% NaCl solution

Tab. 5 Diffusion coefficients m^2/s, surface concentration % by weight of concrete and correlation coefficient

Sample	D x 10^{12} m^2/s Reference	Surf. Cl^- (%)	R^2	D x 10^{12} m^2/s 50% Splitt.	Surf. Cl^- (%)	R^2
S_0	4.0	0.45	0.973	3.9	0.36	0.963
S_{50}	0.9	0.95	0.996	0.8	0.65	0.973
S_{70}	1.1	0.44	0.998	1.1	0.33	0.941
S_R	7.5	0.35	0.988	5.1	0.34	0.944

From figure 3 and table 5 we can observe some improvement in the chloride's resistance behaviour when 50% of failure splitting load is applied to concrete. Firstly, there is a reduction tendency in chloride's penetration which is principally visible by a decrease in the modeled surface concentration of salt found in samples S_0, S_{50}, S_{70} while for S_R it is mainly perceived as a reduction on the diffusion coefficient. On the other hand the nature of the binder plays an additional role in controlling chloride's ingress thus pure Portland cement concretes, either ordinary or high sulphate resistant, shown less resistance to chloride attack than concretes whose OPC content was replaced by 50 and 70 % slag. This is proven by the comparatively high diffusion coefficients ranges of (4-3.9) x 10^{-12} and (7.5-5.1) x 10^{-12} m^2/s found in the former materials, compared to the values of (0.9-0.8)x10^{-12} and (1.1)x10^{-12} m^2/s found in the latter materials S_{50} and S_{70}. Correspondingly, this is also understood directly from the steep shape of chloride penetration profiles for the slag concretes compared to the low slope profiles obtained from S_0 and S_R in figure 3.

It was also noticed that concretes S_0 and S_R have almost the same behaviour towards chloride ingress, only that S_0 shows a somewhat higher capacity for preventing chloride ingress, probably due to a higher content of C_3A in its chemical composition compared to the lower amount present in S_R which results in a higher chloride binding capacity for S_0.

For the slag containing concretes, a larger chloride's surface concentration was noticed for S_{50}, almost twice the concentration found in S_{70}. More studies are needed to evaluate the chloride adsorption mechanism to the slag and the role of surface activators such as calcium ions and pH. Surface carbonation is another issue to be taken into account.

2.3.2 Attack under compressive load

Prismatic samples representing concrete mixes $S_{0\text{-}b}$ were exposed during 8, 15, and 39 weeks to a combination of 3% sodium chloride solution plus 30 % of the maximum compressive load from which the modeled curve, diffusion coefficient, correlation coefficient and surface concentration are obtained as shown in figure 4 for the 15 week exposure time and table 6 for all the tests.

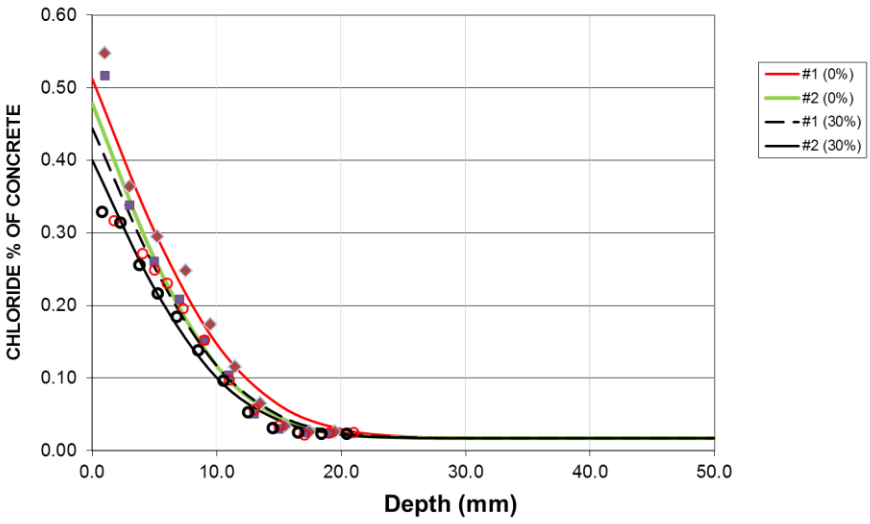


Figure 4. Chloride diffusion profiles after 15 weeks at 0 &30 % compressive load and in 3% NaCl solution

Tab. 6 Diffusion coefficients m^2/s, surface concentration % by weight of concrete and correlation coefficient

Time weeks	D x 10 ^{12} m^2/s 0% Compr.	Surf. Cl$^-$ (%) 0% Compr.	R ^{2}	D x 10 ^{12} m^2/s 30% Compr.	Surf. Cl$^-$ (%) 30% Compr.	R ^{2}
8	4.2	0.501	0.986	4.6	0.498	0.995
8	5.0	0.501	0.993	3.6	0.324	0.995
15	3.8	0.569	0.981	3.9	0.444	0.987
15	3.0	0.544	0.985	3.6	0.400	0.994
39	3.9	0.539	0.971	2.2	0.502	0.984
39	3.0	0.573	0.985	2.6	0.547	0.986

From the data results shown in table 6 it was noticed that for this single type of concrete, the diffusion coefficient diminishes while the chloride surface concentration increases with time. Also can be noticed that application of 30% of the failure load on the concrete provokes a reduction in both surface chloride concentration and in the diffusion coefficient as shown in figure 5.

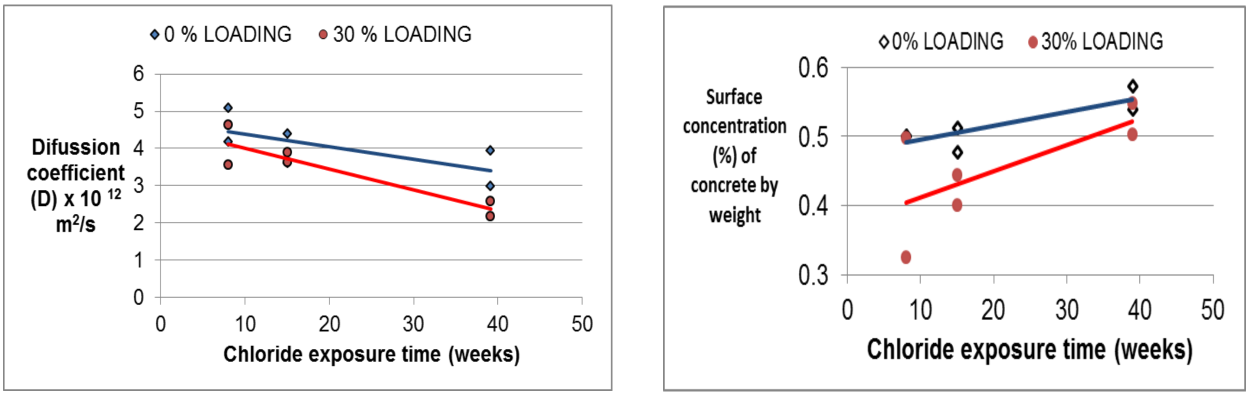


Figure 5. Diffusion & surface concentration trends for $S_{0\text{-}b}$ with time, 30 and 0 % compressive load

3. Conclusions

When concrete types with slag/binder ratio of 0.0, 0.5 and 0.7, denominated in this study as S_0, S_{50}, S_{70}, and a concrete type made with sulfate resistant cement (and no slag), called S_R, were exposed for 315 days to 3% sodium chloride solution in combination with 50 % of the maximum splitting tensile load, the chloride ingress is attenuated, this is evidenced by the reduction in the diffusion coefficients as well as by the decrease of the values of sodium chloride's surface concentration for the studied concretes.

Concretes made of BFS + OPC combinations seem to adsorb more chloride ions at the surface than pure OPC ones and also control better the chloride ingress with low diffusion coefficients of 1x 10^{-12} m^2/s compared to levels of 4 and 7.5 x 10^{-12} m^2/s found in OPC and sulfate resistant cement concretes.

When a permanent compressive load (30% of maximum load) is applied to a sample made of OPC concrete, the chloride ingress by diffusion seems to be permanently hindered. The results showed that at 39 weeks of chloride exposure the samples loaded at 30% of the maximum load, had an average diffusion coefficient (2.38 x 10^{-12} m^2/s) which represents 68% of the diffusion coefficient for an non-loaded concrete at the same age. It was also noticed that chloride diffusion coefficients decreased with time and chloride surface concentrations increased with time.

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