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Mechanical and Durability Properties of High-Performance Concrete Incorporating Fibers and Algerian Natural Pozzolans in Chloride Attack

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Abstract

This study aims to assess the effect of sodium chloride attack on the mechanical and durability properties of high-performance concrete (HPC) based on fibers and natural pozzolans. The resistance of specimens against chemical attack is determined by the unit weight, compressive strength, splitting-tensile strength, chloride ion permeability, apparent gas permeability, and visual inspection after 28, 90, 180, and 365 days of testing. A total of three types of concrete are assessed: reference concrete (RC), HPC, and high-performance fiber-reinforced concrete (HPFRC) stored in tap water and aggressive water (i.e., a 10% NaCl solution). The test results demonstrate that the presence of fibers negatively affects the permeability of HPC. However, HPC and HPFRC remain stable and are not influenced by the NaCl solution compared to RC. The natural pozzolans attenuate the side effect of fibers by occupying voids (i.e., the filler effect) and generating denser products (i.e., the pozzolanic reaction) in the cement matrix.

Keywords: concrete, natural pozzolan, fibers, durability properties, chloride attack

1. Introduction

The durability of concrete structures is considered an important aspect during the design process of civil infrastructure. In other words, durability describes the ability of concrete to withstand physical, chemical, and mechanical aggression during its expected service life.

Reinforced concrete structures exposed to seawater are susceptible to a series of physical and chemical degradation, affecting their structural serviceability and resulting in high repair costs [1]. Physical degradation includes salt crystallization, freezing/thawing, and erosion by wave action. Chemical degradation includes the reaction of sulfate and chlorides with cementitious products. This reaction results in the formation of expensive compounds (e.g., Friedel's salt, ettringite, etc.) and the disintegration of hydrate phases [2]. Most of the attack promotes the initiation of cracks, which facilitates the passage of aggressive agents such as chloride ions. Once a sufficient quantity of chloride ions has accumulated on the surface of the reinforcement metal, the oxide layer protecting the reinforcement is destroyed, which is accompanied by the initiation of corrosion. This phenomenon is known as a major problem affecting the durability of reinforced concrete.

The penetration of aggressive chloride ions within concrete is principally linked to transport mechanisms, which are: capillary absorption, diffusion, and permeability [3]. Permeability is defined as the ability of a liquid or gas to move through a porous mass under a gradient of pressure. Therefore, the study of the permeability of concrete plays a vital role in assessing the durability of structures.

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The use of high-performance concrete (HPC) can be a good answer against the penetration of harmful substances susceptible to initiating reinforcement corrosion [4]. Indeed, this type of concrete is characterized by a dense cement microstructure and a disconnected capillary and pore network. In other words, the durability in a severe environment is drastically improved [5]. For technical, economic, and environmental purposes, silica fume, blast furnace slag, fly ash, and natural pozzolans are introduced as pozzolanic materials in HPC [6]. Past studies have emphasized the beneficial employment of pozzolans in cementitious composites [7].

Natural volcanic pozzolans are silico-alumina materials resulting from the accumulation of lava debris released into the air following a volcanic eruption [8]. The use of the Algerian natural pozzolans as partial substitution for cement results in significant reductions in carbon dioxide emissions, substantial gain in economic aspects, and improvement of the long-term compressive strength and durability properties [9]. However, there is still a lack of studies on the behavior of natural pozzolans under aggressive environmental solutions.

Despite the beneficial behavior provided by HPC in a severe environment, natural volcanic pozzolans exhibit brittle behavior with a weak strain capacity and poor resistance to crack opening and propagation. These weaknesses seriously affect their utilization in civil structures. Therefore, the incorporation of discontinuous steel fibers, randomly distributed in the cement composite, allows the crack control and modification of the brittle nature of concrete to become ductile [10].

In some cases, fibers may play a more active role than traditional steel reinforcement. Fibers can be used differently depending on their roles in structures. On the one hand, they can be used as the secondary reinforcement in slabs and pavements to reduce the propagation of cracks resulting from variations in temperature and humidity. On the other hand, they can be used as the main reinforcement of thin structures to improve the strength and toughness of concrete [11].

The Mediterranean Sea is a moderately aggressive medium of concrete with a relatively uniform composition, characterized by the presence of approximately 3.5% mass soluble salts. The main salts dissolved in seawater are sodium chloride, magnesium chloride, and sulfate [2].

This study aims to experimentally investigate the possibility of producing high-performance fiber-reinforced concrete (HPFRC) with locally available pozzolans and study the effect of incorporating steel fibers on the performance of the concrete exposed to aggressive water (AW) (i.e., a high-concentration sodium chloride solution (10%)).

In order to achieve this objective, three mixtures are cast: reference concrete (RC), HPC containing natural pozzolans (6%), and HPFRC containing natural pozzolans (6%) and steel fibers (1%). The concrete specimens are immersed in tap water (TW) and AW and then compared on the basis of unit weight, compressive strength, splitting-tensile strength, chloride ion permeability, and apparent gas permeability after 28, 90, 180, and 365 days of immersion. A visual inspection is also provided and discussed in this experimental research.

2. Literature Review

Sodium chloride can chemically react with calcium hydroxide $Ca(OH)_2$ and with tricalcium aluminate C_3A to form Friedel's salt $C_3A.CaCl_2.10H_2O$ [2]. The formation of this new product represents the primary threat to cement materials in contact with the NaCl solution.

As reported by Chen et al. [12], the addition of minerals (such as fly ash) to concrete can result in lower chloride ingress when exposed to the 5% NaCl + 5% Na_2SO_4 solution under drying-wetting cycles. Darwin et al. [13] noticed that at a lower sodium chloride concentration (3%), the solution has a negligible impact on the properties of concrete.

Anowai et al. [14] studied the effect of fly ash on fiber reinforced concrete (0.5% volume fraction) on the compressive strength stored in a 5% chloride sodium solution. The concrete containing fly ash and fibers is observed to have satisfying resistance to chemical attack, with a slight loss of the compressive strength of 2.7% and 3.31% for 10% and 20% replacement of cement, respectively.

Chen et al. [12] studied the behavior of concrete containing silica fume and carbon fibers after 28 days of curing in water and 188 days of exposure to a chloride solution with a 3% concentration. The concrete containing solely fibers increased the air content, which reduced the compressive strength and the resistance to the chemical attack. However, the concrete containing both fibers and silica fume showed better strength and chemical resistance.

Numerous studies were conducted on fiber-reinforced concrete (FRC) [15-16]. Despite the benefits derived from the use of steel fibers in concrete, there is still a lack of knowledge of FRC behavior in aggressive environments such as those encountered in chloride attack. Furthermore, several studies have focused on a low concentration of chloride (less than 5%). However, very few studies reported the long-term behavior of FRC in a high concentration of sodium chloride environment.

3. Materials and Methodology

3.1. Cementitious materials

Portland cement with no mineral addition, referred to as CEM I 42,5 N-SR3, is employed in this study. This cement complies with the European standard EN 197-1. The natural volcanic pozzolans extracted from the Beni-Saf deposit in northwest Algeria are used as a partial cement replacement. The natural pozzolans are crushed until a finely divided powder is formed with a specific surface area value of 9400 cm²/g and a specific gravity value of 2.73. The grain size of the pozzolan powder is very fine, ranging between 2 and 15 µm. The chemical compositions of cement and natural pozzolans are summarized in Table 1.

Table 1 Chemical composition of cementitious materials

Component	CaO	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	MgO	SO_3	LOI
Cement	62.98%	21.05%	3.99%	5.09%	0.59%	0.18%	1.30%	2.42%	1.81%
Natural pozzolan	9.47%	43.87%	16.63%	10.68%	1.23%	1.37%	4.46%	0.23%	8.93%

3.2. Aggregates

This study uses local natural rolled sand (0/5) with a specific gravity value of 2.61 and a fineness modulus value of 3.2. Coarse gravels of two fractions (3/8 and 8/16) with a specific gravity value of 2.71 are also employed. The particle size gradation for fine and coarse aggregates is given in Fig. 1.

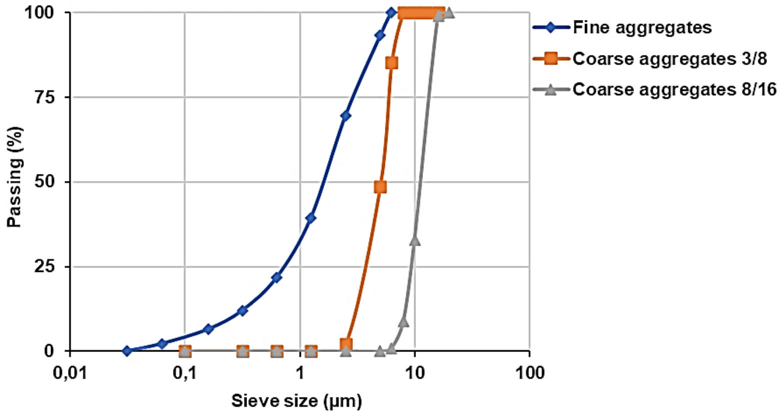

Fig. 1 Grading curves of aggregates

3.3. Superplasticizer

In order to obtain satisfying workability of concrete, an admixture is used. The admixture is a superplasticizer (SP) Sika ViscoCrete Tempo 12, based on an acrylic copolymer. The total content of chlorides and sodium oxide is less than 0.1% and 1%, respectively.

3.4. Fibers

Hooked-end steel fibers used in this study are Sika Metal Fibres RC-80/50. The shape, length (l), diameter (d), aspect ratio (l/d), tensile strength, and specific gravity of the fibers are given in Table 2. Fig. 2 shows the visual appearance of the fibers used in this research study.

Table 2 Geometrical properties, tensile strength, and specific gravity of fibers used

Fiber type	Fiber shape	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)	Specific gravity
Steel fiber	Hooked-end	50	1.050	48	1000	7.8

(a) Group of fibers (b) Fiber length

Fig. 2 Hooked-end steel fibers employed in this study

4. Mixture Composition

In order to investigate the durability of HPFRC conserved in AW, three different concrete mixtures are formulated: RC, HPC containing 6% of natural pozzolans, and HPC containing 6% of natural pozzolans and 1% of steel fibers. The water-to-cement ratio (w/c) for the RC is 0.5, while the water-to-binder ratio (w/b) for the HPC and HPFRC is 0.3. The proportions of all concrete mixtures and their workability are given in Table 3.

Table 3 Proportions of concrete mixtures and their workability

Mixture description	W/B	Water	Cement	Pozzolan	Sand 0/5	Gravel 3/8	Gravel 8/16	SP (%)	Fiber content (%)	Slump (cm)
(kg/m^3)										
RC	0.5	200	400	-	718	145	927	-	-	6.5
HPC	0.3	120	376	24	718	145	927	1.25	-	23.0
HPFRC	0.3	120	376	24	718	145	927	1.25	1	20.5

*Note: The superplasticizer (SP) is given as a percentage (%) per weight of cementitious materials.

5. Mixing, Casting, and Conservation

All concrete mixtures are mixed in a power-driven revolving pan mixer (Fig. 3(a)). The mixing procedure is selected as follows. The aggregates, cement, and natural pozzolans are initially introduced into a mixer and mixed for about 1 minute. Then, half of the water and SP are gradually added to the mixture and mixed for about 2 minutes. The remaining water and SP are then added and mixed for another 2 minutes. Lastly, fibers are gradually introduced and mixed until a uniform mixture is obtained.

(a) Pan mixer (b) Molds (c) Conservation

Fig. 3 Mixing, casting, and conservation of concrete

The obtained concrete is cast into molds (Fig. 3(b)), and the fresh specimens are compacted using a vibrating table. Subsequently, the molded specimens are covered with a plastic sheet in order to conserve adequate humidity. After 24 hours, the specimens are demolded and cured in two environmental conservations: TW and AW after 28, 90, 180, and 365 days of testing time. Fig. 3(c) shows the concrete conservation.

6. Testing Methods

The tests of unit weight, compressive strength, splitting-tensile strength, chloride ion permeability, apparent gas permeability, and visual investigation are performed on three different specimens with various shapes and dimensions as per the standards summarized in Table 4.

Table 4 Shapes, dimensions, tests, and standards used

Shapes	Dimensions (mm)	Test	Standard
Cubic	150 × 150 × 150	Unit weight	ASTM C642
Cubic	150 × 150 × 150	Compressive strength	ASTM C39
Cylinder	160 × 320	Splitting-tensile strength	ASTM C496
Cylinder	110 × 220	Chloride ion permeability	ASTM C1202
Hollow cylinder	160 × 320	Oxygen permeability	-

6.1. Unit weight

The unit weight of all concrete is determined using three cubic specimens (150 × 150 × 150 mm) following the ASTM C642. The concrete specimens are weighed with a precision balance of 0.1 g after 28, 90, 180, and 365 days of curing.

6.2. Mechanical strengths

Compressive strength tests are conducted on 150 × 150 × 150 mm cubic specimens in accordance with ASTM C39. Splitting tensile strength tests are evaluated on 160 × 320 mm cylinder specimens according to the specification of ASTM C496. The mechanical strength experiment is measured on three specimens by means of a 2000 kN capacity testing machine. The experimental setup of each test is shown in Fig. 4.

(a) Compressive strength (b) Splitting-tensile strength

Fig. 4 Experimental setup of mechanical strength

6.3. *Chloride ion permeability*

The rapid chloride permeability test (RCPT) is performed on the cylindrical specimen of hardened concrete (110 × 50 mm) according to the recommendations of the ASTM C1202 standard, as shown in Fig. 5. The specimen is positioned in a test cell containing fluid reservoirs on both ends of the specimen. One reservoir is filled with a 3% NaCl solution and the other with a 0.3 N NaOH solution. An electrical potential of 60 V is applied across the cell.

The negative terminal of the potential source is connected to the electrode in the NaCl solution, and the positive terminal is connected to the electrode in the NaOH solution. The negatively charged ions will migrate towards the positive terminal resulting in a current through the specimen. The resulting intensity is measured for 6 hours during a 30-minute interval using a data logger. The total charge passed through the tested concrete is then calculated from the following formula:

$$Q = 900\left(I_0 + 2I_{30} + 2I_{60} + \ldots + 2I_{300} + 2I_{330} + I_{360}\right) \tag{1}$$

where Q represents the charge passed in coulombs. I_0 represents the current in amperes immediately after the voltage is applied. I_t represents the current in amperes at t minutes after the voltage is applied.

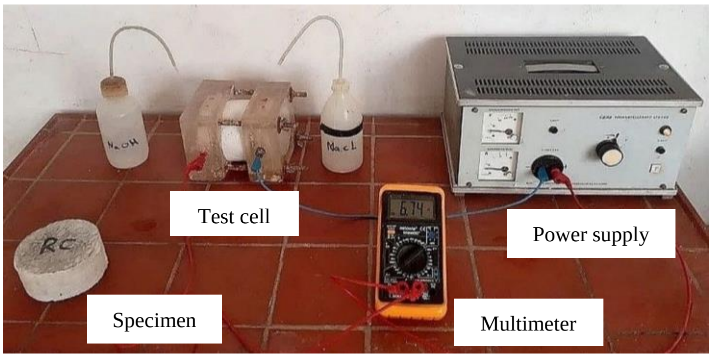

Fig. 5 General view of RCPT

6.4. *Gas permeability*

The assessment of concrete gas permeability is performed using the Talah and Kharchi method [17]. The aforementioned method consists of maintaining a sample of hardened concrete at constant oxygen pressure. The cylindrical specimens (160 × 100 mm) sawn from hollow cylindrical specimens (160 × 320 mm) are used (Fig. 6(a)). The apparent permeability (k_a) is determined by measuring the flow Q (m^3/s) in a steady state with the assumption of a laminar flow, using the following equation (Eq. (2)):

$$K_a = \frac{2 \times Q \times P_{atm} \times \left(R_2^2 - R_1^2\right) \times \mu}{\left(P^2 - P_{atm}^2\right) \times \pi \times h \times \left(R_2 + R_1\right)} \tag{2}$$

where h is the specimen thickness (m); Q is the gas debit (m^3/s); P and P_{atm} are the inlet and outlet (atmospheric) pressure respectively (N/m^2); R_2 and R_1 are the inner and outer radius of the concrete specimen (m) respectively; μ is the gas dynamic viscosity ($N\ s/m^2$) for the oxygen which is the gas used in this test $\mu = 20.2 \times 10^{-6}\ N\ s/m^2$ at 20°C. A specific preconditioning procedure (Fig. 6(b)) is required to ensure the dry condition of specimens. The specimens are first dried at 80°C for 28 days, then subjected to 105°C, until the obtention of a constant mass variation as per AFPC-AFREM [18]. After that, the specimens are protected laterally and held vertically, ensuring a unidirectional radial flow of oxygen. The measurement of the apparent permeability is carried out at a pressure of 0.2 MPa, and the results given are for this pressure for all concrete mixtures. Fig. 7 shows the general view of the test apparatus used. It is worth mentioning that the time ranging from 30 minutes to 6 hours is necessary to perform a single measurement, depending on the specimen composition.

(a) Concrete sawn

(b) Preconditioning

Fig. 6 Preparation of concrete for the gas permeability test

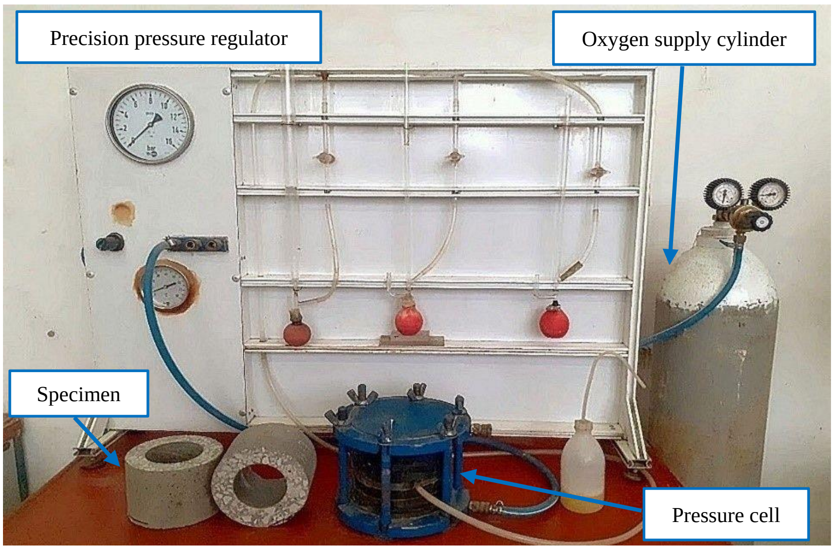

Fig. 7 Visual aspect of oxygen permeability setup [17]

7. Results and Discussion

7.1. Unit weight

Fig. 8 shows the unit weight of concrete immersed in two conservation environments for a curing period of 28, 90, 180, and 365 days. The unit weight of HPC and HPFRC mixes shows a superior value in comparison with RC. The maximal values reached by these specimens range between 2574 kg/m^3 for HPC, 2584 kg/m^3 for HPFRC, and 2448 kg/m^3 for RC. This difference is linked to the addition utilized in the concrete, consisting of natural pozzolans and steel fibers. Fig. 8 also shows an increase in the unit weight with the introduction of fibers into HPC. This increase can be related to the high density of metallic fibers (7.8 kg/m^3).

Test results show no severe influence of the NaCl solution on the RC during the first month. However, as the conservation continues, the unit weight variation begins to become more prominent, especially in the long term. For instance, the unit weight variation of the RC stored in AW (RCAW) is 6% lower in comparison with the RC stored in TW (RCTW) after 365 days. On the other hand, a negligible loss is noticed for the HPC and HPFRC specimens with curing advancement. For instance, the difference in the unit weight between HPC and HPFRC in the two conservation environments is less than 1%. This difference is attributed to the highly fine pozzolans as well as its interaction with the calcium hydroxide (CH) to form new compounds. This reaction increases the compactness of concrete and contributes to densifying its microstructure. Hence, the chloride ions are prevented from reacting with the anhydrate and hydrate aluminate products to form new phases [2].

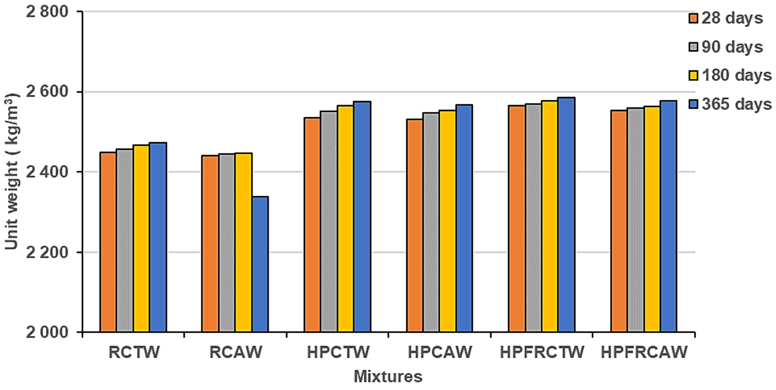

Fig. 8 Unit weight of all mixes conserved in two environments

7.2. Mechanical strengths

Fig. 9 and Fig. 10 show the development of compressive and splitting tensile strengths of all concrete immersed in TW and AW. Regardless of the environment of conservation or the testing age, the strengths of all concrete increase with curing time.

Test results clearly show that the RC is adversely influenced by the sodium chloride attack with time advancement, while HPC and HPFRC mixes are not affected by the chloride solution. For instance, in the case of RC, there is a loss ranging from 18% to 25% in the compressive strength and 19% to 17% in the splitting-tensile strength after curing in a sodium chloride solution for 28 to 365 days, respectively. This loss may be attributed to the movement of chloride ions from the external solution into the cement matrix. Thus, the chlorides chemically react with the hydrates to form new soluble compounds (calcium chloride).

The formation of calcium chloride ($CaCl_2$) is accompanied by the decalcification of calcium hydroxide (CH) and calcium silicate hydrate (C-S-H), which ultimately negatively affect the pore structure and mechanical strength of concrete [4]. On the other hand, the HPC without and with fibers (cured in the two media) shows almost the similar strength growth over the testing age. The strength loss varies from 2% to 6%. This implies that HPC and HPFRC specimens remain stable against the sodium chloride attack and are not altered over time. This is attributed to the highly fine pozzolans added to the cement matrix as well as the formation of secondary C-S-H derived from the pozzolanic activity between the reactive silica contained in the natural pozzolans and the free calcium hydroxide available in the cement matrix.

In the same sense, Fodil et al. [19] also reported that the pozzolanic concrete exposed to a chloride sodium solution showed better performance compared to RC. Chousidis et al. [20] studied the effect of fly ash as a partial replacement of cement (5% and 10%) on concrete in contact with a 3.5% NaCl solution. Fly ash concrete showed better strength than the RC and is not affected by the exposure period, especially between 100 and 130 days.

Fig. 9 and Fig. 10 show that the incorporation of steel fibers into pozzolan concrete immersed in the two-conservation water slightly decreases the compressive strength and strongly increases the splitting-tensile strength. The improvement of the tensile strength may confirm the efficiency of metallic fibers in bridging cracks. In other words, this may suggest that most of the steel fibers are still passivated and not corroded by the deleterious solution.

Fig. 11 shows the failure modes of cylindrical specimens (RCAW, the HPC stored in AW (HPCAW), and the HPFRC stored in AW (HPFRCAW)) immersed in a sodium chloride solution. The RCAW and HPCAW specimens containing no fibers show a brittle failure mode. In addition, a large crack is observed in the two concrete samples, which results in the separation of the concrete into two half-cylinders. The HPFRCAW cylinder is not divided into two parts; they remained connected. This phenomenon may be related to the bridging action of the steel fibers, which alters the failure mode from brittle to ductile. This may be the reason why no major cracks are observed on the cylinder.

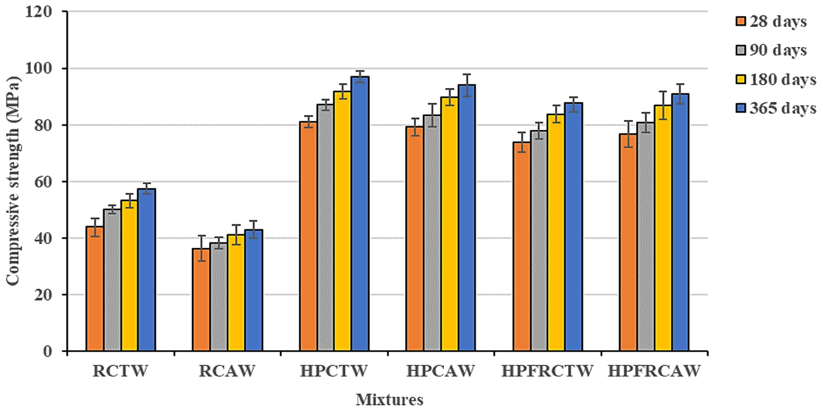

Fig. 9 Compressive strength of all concrete mixtures conserved in two environments

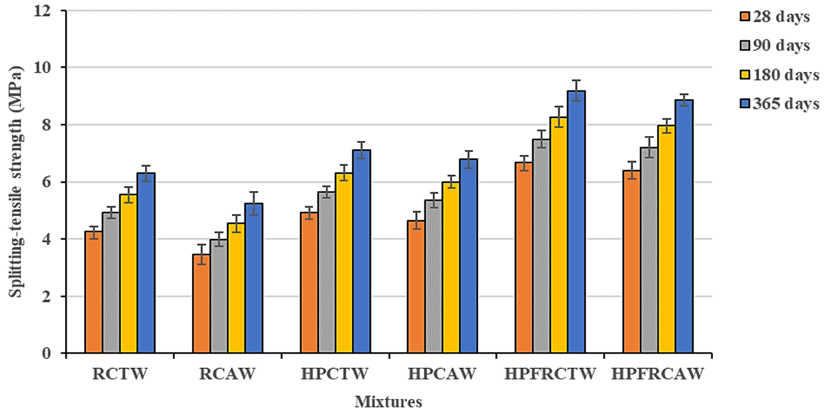

Fig. 10 Splitting-tensile strength of all concrete mixtures conserved in two environments

(a) RCAW (b) HPCAW (c) HPFRCAW

Fig. 11 Failure mode of cylindrical specimens immersed in AW

7.3. *Chloride ion permeability*

Fig. 12 shows the chloride ion permeability results measured on all concrete mixtures. The classification of the concretes according to their resistance to chloride ion penetration is given by ASTM C1202 and illustrated in Table 5. From the results obtained, it is noted that the charge passed through RC and HPFRC mixes is almost similar between 28 and 90 days of conservation in TW and the NaCl solution. The concrete obtains a “moderate” classification for the resistance to chloride penetration, compared to HPC without fibers, which are “low” and “very low”. Based on the results, it is clear that the use of metallic fibers has a negative effect on HPC chloride ion permeability regardless of the storage medium. Fig. 13 shows the visual aspect of concrete after performing the RCPT for 6 hours.

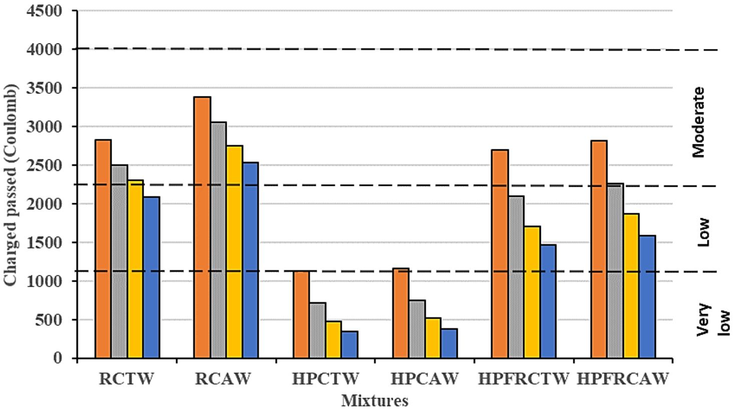

Fig. 12 Chloride ion permeability results of mixes conserved in two environments

Table 5 Chloride ion penetration based on the charge passed

Charge passed (coulomb)	>4000	2000-4000	1000-2000	100-1000	<100
Chloride ion penetration	High	Moderate	Low	Very low	Negligible

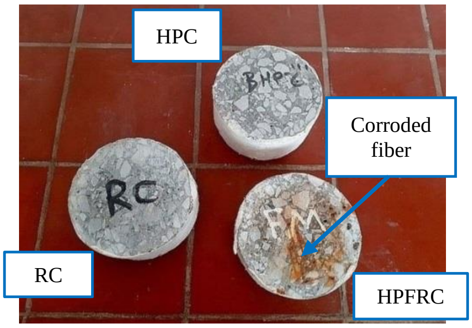

Fig. 13 Visual aspect of concrete specimens after performing RCPT

The observation of brown stains on the surface of the concrete discs is a characteristic of the corrosion of metallic fibers. Thus, the corrosion of metallic fibers confirms their electrical conductivity and may explain the excessive increase in permeability recorded for FRC. According to Afroughsabet et al. [21], the addition of steel fibers to concrete intensifies its electrical conductivity and provides higher chloride penetration due to the conductivity characteristics of the fibers. This trend is consistent with the findings of previous studies [22].

After 90 days of testing, the charge passed through the HPFRC is reduced compared to the RC. The HPFRC obtains “low” resistance to chloride ion penetration after 180 and 365 days. This reduction is attributed to the activation of the pozzolanic reaction and the formation of new cementitious products that will occupy larger voids and disrupt the connected pores. Hence, the addition of natural pozzolanic materials counteracts the negative influence of fibers on the permeability of concrete [23]. This trend is confirmed by the study of Rabehi et al. [16]. The authors reported that the introduction of pozzolanic materials into FRC improves its electrical resistivity due to the compactness of concrete, which subsequently enhances the serviceability of FRC. Toutanji et al. [24] showed that the addition of fibers caused an adverse effect on the chloride permeability of concrete. However, the addition of silica fume resulted in a significant decrease in permeability. On the other hand, the metallic fibers remain unaffected by the NaCl solution over time. For instance, the difference in the charge passed through the HPFRC stored in TW (HPFRCTW) and HPFRCAW mixes are lower than 10% for a cure between 28 and 365 days, which proves the impermeability of these mixes against chloride attack.

These findings are in line with the results of numerous studies [23]. For instance, Merida et al. [25] attributed the impermeability of HPC to the dense and low porosity of the matrix, which consequently prevents the penetration of the deleterious solution.

7.4. Apparent gas permeability

Gas permeability is well known as one of the most important indicators to assess the durability of concrete, particularly for HPC. The evolution of apparent gas permeability of all mixes at various testing ages (28, 90, 180, and 365 days) and cured in two environments (tap and chloride water) is given in Fig. 14.

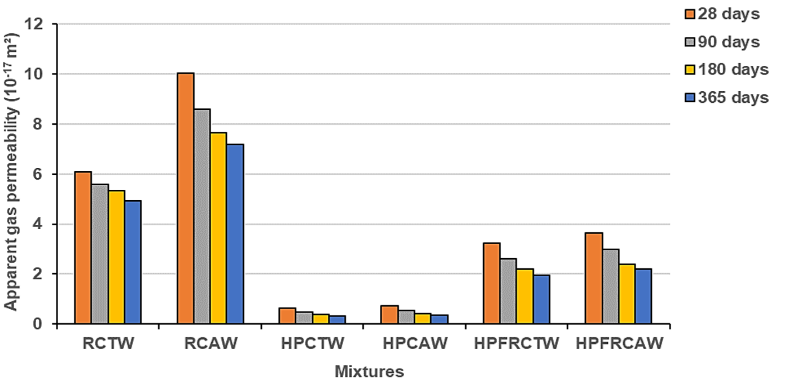

Fig. 14 Variations of apparent gas permeability of different concrete conserved in two environments

Test results show a clear decrease in the apparent permeability of all concrete immersed in the two-surrounding conservation with time advancement, particularly for the pozzolan-based concrete. This decrease is associated with the continuous hydration of cement and natural pozzolans with calcium hydroxide.

The consumption of calcium hydroxide intensifies the development of secondary C-S-H gel, restricts the number of interconnected pore networks, and consequently limits the gas flow through the pore structure of concrete. Chaid et al. [26] found a similar pattern of decreasing gas permeability from concrete containing powder marble compared to the control mix. The authors attributed this decrease to the fineness of the marble powder that reduces the pore size distribution compared to control concrete. Similarly, for the compressive strength, no major permeability differences were observed for the unreinforced and reinforced HPC immersed in the two media. For example, the difference in the variation of the apparent gas permeability between HPFRCTW and HPFRCAW was less than 13%, regardless of water conservation and time testing. This proves the beneficial contribution of natural pozzolans in reducing the inter-connectivity and pore size distribution of concrete, as well as its positive effect on concrete degradation in a chloride solution [7].

Similar results were reported in previous studies. For instance, Talah et al. [9] confirmed the positive influence of natural pozzolans on the properties of concrete under hydrochloric media ($CaCl_2$). The authors indicated that the pozzolana concrete immersed in the running water and the $CaCl_2$ solution had similar permeability after 365 days of conservation.

From test results, it can be observed that HPFRC leads to higher permeability regardless of the duration of the water conservation tests compared to plain HPC. It seems that fibers add porosity content and act as a bridge between pores, which in turn results in an increase in the connectivity and ease of gas transport through the concrete body. These results are in agreement with the findings of previous studies [27]. For example, Rahmani et al. [28] reported an increase in the gas permeability of concrete containing steel and polypropylene fibers compared to the control mix. On the contrary, Mahoutian et al. [29] observed that fiber inclusion in concrete results in lower permeability than the control mix. The authors attributed the low permeability of FRC to the fiber blockage of the gas flow through the porous network.

7.5. Visual inspection

Fig. 15 shows the visual appearance of RC and HPFRC stored in TW and AW after 365 days. As can be seen, the concrete conserves the original dimensions and cubic shapes without the occurrence of cracking, or expansion, regardless of the storage water. However, the natural color of the specimen surfaces immersed in the NaCl solution is changed and covered with a thin green layer for the RC and a brown layer for the HPFRC. Moreover, dark brown stains emerge and are located on the surface of the HPFRC, which is a sign of the corrosion of metallic fibers.

Despite the manifestation of deterioration observed on the surface of FRC, this concrete presents very similar strength and permeability compared with the concrete preserved in TW. The correspondence of these results proves that the chloride environment slightly affects the performance of the HPFRC.

(a) RC (b) HPFRC

Fig. 15 Visual appearance of RC and HPFRC conserved in TW (left) and AW (right) for 365 days

The HPFRC produced in this study shows the impermeability to AW in the long term. Thus, HPFRC can be successfully used in concrete structures to withstand chemical aggression from the Mediterranean Sea at a lower concentration of salt (about 3.5%).

8. Conclusions

This study aimed to study the mechanical and durability properties of HPFRC cured in two conservation environments: TW and AW. According to the experimental results, the following conclusions were obtained:

(1) The addition of natural pozzolans and steel fibers increased the unit weight of HPC. The NaCl solution had a negligible effect on the unit weight of HPC and HPFRC (loss lower than 1%) compared with RC (loss of 6%) after 365 days of testing.

(2) The mechanical strength of RC was negatively influenced by the sodium chloride attack, while the HPC and HPFRC mixtures were not impacted by the NaCl solution. For RC, there were a loss of 18 to 25% in the compressive strength and a loss of 25 to 17% in the splitting-tensile strength after 28 and 365 days of testing. The strength loss of HPC and HPFRC varied between 2% and 6% for the same testing age. The incorporation of steel fibers into pozzolan concrete immersed in the two-conservation environment slightly decreased the compressive strength and strongly increased the splitting-tensile strength. The improvement of the tensile strength may confirm the efficiency of metallic fibers in bridging cracks. In other words, this may suggest that most of the steel fibers were still passivated and not corroded by the deleterious solution.

(3) The HPFRC obtained similar permeability (moderate) with RC until 90 days of testing. After this period, the total charge passed through this concrete was reduced (low permeability). However, the HPC reinforced with steel fibers remained unaffected by the sodium chloride attack (loss lower than 10%) from 28 and 365 days.

(4) The addition of steel fibers in HPC increased the apparent gas permeability values. The NaCl solution had no severe influence on the permeability of HPC with and without fibers, compared with RC between 28 and 365 days. The permeability difference between the HPFRC conserved in TW and AW was lower than 13%.

(5) Fiber corrosion is visually observed on the surface of HPCs exposed for one year to AW. However, no evidence of cracking or expansion was noticed.

Nomenclature

SP	Superplasticizer	RCTW	RC stored in TW
RC	Reference concrete	RCAW	RC stored in AW
HPC	High-performance concrete	HPCTW	HPC stored in TW
HPFRC	High-performance fiber-reinforced concrete	HPCAW	HPC stored in AW
FRC	Fiber-reinforced concrete	HPFRCTW	HPFRC stored in TW
NaCl	Sodium chloride	HPFRCAW	HPFRC stored in AW
TW	Tap water	RCPT	Rapid chloride permeability test
AW	Aggressive water (10% NaCl)		

Conflicts of Interest

The authors declare no conflicts of interest.

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