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Research Article

Effect of epoxy/water-repellent on the mechanical behavior of concrete in aggressive environment

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Abstract

Many studies have shown that concrete structures are subject to varying degrees of deterioration due to chemical attacks, often associated with high soil salinity. As concrete generally exhibits low resistance to chemical aggression, it is sometimes necessary to implement protective measures on surfaces exposed to such harsh environments. This study investigates the effect of water-induced chemical aggressiveness on the degradation of concrete structures. It aims to evaluate the significance and effectiveness of protective measures applied to concrete exposed to aggressive environments, using an external epoxy coating and an internal water-repellent additive. Concrete specimens were exposed to both a normal environment and an aggressive one (Sebkha water from the Ouargla region in Algeria). The mixtures incorporated a water-repellent additive at a dosage of 2% by cement mass, using both of Portland cement resistant to sulfates (CEM I 42.5 N-SR 3) "CRS" and a Portland cement (CEMII /BL 42.5N) "CPJ", with a constant water-to-cement (W/C) ratio of 0.61 for all mixes. The engineering properties evaluated include compressive strength, water absorption (by immersion and capillarity), and density for both protected and unprotected concrete in fresh and hardened states. In addition, the protective coating layers were characterized using scanning electron microscopy (SEM). Cubic and cylindrical specimens were tested at 28 and 90 days. The results show that concrete formulated with CPJ cement and the water-repellent additive exhibited superior compressive strength performance compared to the other specimens.

1. Introduction

Concrete is the most widespread building material in the world due to its mechanical performance, versatility, and comparatively low cost [1,2,5]. However, it is very sensitive to its microstructural integrity over the long term, particularly in the presence of environmental aggressors such as chlorides, sulfates, carbon dioxide, and freeze–thaw [6-8]. These chemicals infiltrate the porous concrete structure [6,9] and initiate internal degradation processes such as corrosion of steel, sulfate attack, and alkali–silica reaction, all of which are detrimental to the service life of concrete structures. [1,3,6]

The composition and type of cement is an important variable that affects the performance of concrete [10,11] when subjected to harsh chemical exposures. CPJ cement, commonly used for general construction [1,2,12], has a relatively high volume of calcium aluminates (C_3A) [13,14] and

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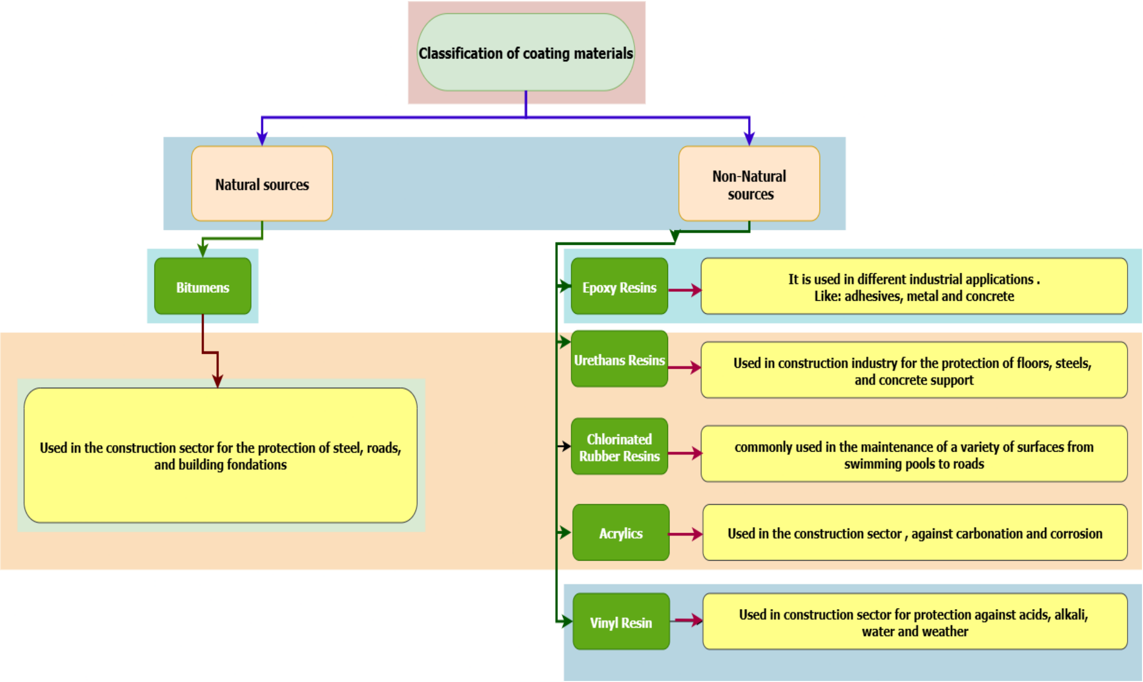
therefore can be more subject to sulfate or chloride attacks under certain conditions. CRS cement that is manufactured with ground granulated blast furnace slag typically has much greater chemical resistance due to its latent hydraulic activity, porosity, and permeability characteristics. All of these factors make pre-stressed concrete a naturally more resilient option in difficult conditions. However, it is important to understand that CPJ-based concrete can be expected to perform satisfactorily in aggressive conditions if protection techniques are properly used [4,15]. Hydrophobic agents, surface treatments such as epoxy resin (Fig. 1), or improved curing can help greatly in preventing the infiltration of harmful agents by reducing permeability and improving integrity of the matrix. While CRS cements have an innate advantage of better resistance, a CPJ system can still be cost effective and durable where protection systems are considered in many different exposure situations. It is really a matter of understanding the nature of the cement technology, the environment and the protection systems.



Used in the construction sector for the protection of steel, roads, and building fondations

It is used in different industrial applications . Like: adhesives, metal and concrete

Used in construction industry for the protection of floors, steels, and concrete support

commonly used in the maintenance of a variety of surfaces from swimming pools to roads

Used in the construction sector , against carbonation and corrosion

Used in construction sector for protection against acids, alkali, water and weather

Fig. 1. Classification of coating materials [14-16]

To reduce the ingress of harmful agents, surface treatments or admixtures like hydrophobic (water-repellent agent) products have received a lot of attention. These products, which increase the energy of the surface of the pore walls, limit capillary absorption while allowing the pore to remain open and maintain vapor permeability. Epoxy-based coatings are also often applied to concrete surfaces in severely aggressive conditions because of their durability barrier [14, 17, 18]., elongation, chemical inertness, and particularly their mechanical strength. With accurate combinations of cement formulations and protective treatments, concrete's durability performance can be dramatically improved. [19-21]

Our research is positioned within an experimental framework to assess the mechanical performance of concrete protected by surface-applied epoxy resin and an internally incorporated water-repellent admixture. Two cements were used for the concrete preparation: sulfate-resistant cement (CRS) and Portland composite cement (CPJ). The concrete specimens were subjected to two curing conditions: a standard environment (tap water) and an aggressive environment (Sebkha water from Hai Ennasr, Ouargla/ southeast of Algeria) [22,23]. Compression strength was measured on the specimens to evaluate both internal (water-repellent admixture) and external (sealed with an epoxy coating) means of protection under the various curing conditions. The results provide a platform to present comparative aspects of mechanical performance for concrete without protection and with protection applied internally and externally, while indicating the implications of protective layers for durability and resistance to external aggressors.

It should be noted that the testing period adopted in this study was relatively short, limited to 90 days, during which the specimens were exposed to a highly aggressive environment under continuous and constant conditions rather than a cyclic exposure regime. Furthermore, the scope of the investigation was restricted to the behavior of the cementitious matrix, and the effects of the aggressive environment on steel reinforcement, including potential corrosion-related phenomena, were not considered. Therefore, this study has opened new research perspectives, particularly regarding the influence of concrete age at the time of epoxy resin application. In the present work, the epoxy resin was applied at an early age; however, applying the coating at later ages, beyond 28 days, may affect its adhesion, penetration, and overall durability. This aspect is currently under investigation and will be addressed in future studies

This work will contribute to the overall optimization of protection mechanisms for concrete structures, especially of sections that will be subjected to highly aggressive environmental conditions. This work aims to contribute to a better understanding of the effectiveness of internal and external protections applied to concrete, and to provide practical recommendations to improve the durability of structures in regions with an aggressive environment, such as southern Algeria.

2. Study Materials

Before selecting of concrete materials, tests were conducted on various types of sand and gravels. This approach was intended to ensure that any potential chemical aggressions would originate from the external environment rather than from the internal constituents of the concrete, thereby allowing for more reliable and accurate study results. Therefore, the materials used in this study are described below.

2.1. Gravel

The gravel (3/8 and 8/15) used in these tests was sourced from the Ben Brahim quarry, located 40 km from the city of Ouargla/ Algeria, as illustrated in Fig. 2. The results of the various tests are presented in Table 1.

Fig. 2. Gravel used

Table 1. Characteristics of the gravel used

	Tests	Standards	Results	
			Gravel 3/8	Gravel 8/15
	Flakiness Index %	NF P 18-561	19.43	7.78
	Absolute Density (g/cm^3)	NF P 18-554	2.62	2.62
	Los Angeles Abrasion Resistance %	NF EN 1097 – 2	19.02	
	Micro-Deval Resistance %	NF P 18-572	11.8	
	Water Absorption %	NF P 18-554	1.91	1.68
	Cleanliness %	NF P 18-591	0.96	0.7
Chemical Analysis	Insoluble	NF P 18-461, BS 1377, NF P 94 048	15,3	
	Sulfate SO_3		0.31	
	Carbonate $CaCO_3$		85	
	Chloride (Cl^-)		0.014	

Both gravel fractions are whitish limestone aggregates, generally suitable for use in high-quality concrete. According to their chemical composition, assessed in accordance with the NF P18-461 standard and presented in Table 1, these aggregates are considered to be of good quality and chemically appropriate for concrete production.

2.2. Sand

The selected sand for this research is from the Djamaa quarry in El-Oued (South-East of Algeria); the choice is based on chemical analysis (low in sulfate) and a series of tests that demonstrated the chosen sand exhibits good characteristics. Table 2 summarizes the properties of the sands and the tests conducted.

Fig. 3. Sand used

Table 2. Characteristics of the sand

	Test	Standard	Results
	Fineness modulus	NF P 18-560	2.22
	Absolute Density (g/cm^3)	NF P 18-554	2.62
	Sand equivalent (SE)	NF EN 933 – 8	74.66
	Water Absorption %	NF P 18-554	0.46
	Methylene Blue Value (MBV).	NF P 94-068	0.48
Chemical Analysis	Insoluble	NF P 15-461, BS 1377, NF P 94 048	96
	Sulfate SO_3		0.58
	Carbonate CaCO3		2
	Chloride Cl^-		0.026

2.3. Cement

In this research, two types of cement were used:

- Portland cement CEM II/B-L 42.5N (cement CPJ EL Mâtine);
- Portland cement resistant to sulfates (CEM I 42.5 N-SR 3) (cement CRS AL Mokaouam).

Table 3 presents the chemical properties of both cements utilized in this research.

Table 3. Chemical characteristics of cement used (%) [13,14,24].

CPJ cement	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	LOI
	18.88	4.36	3.10	62.23	1.43	2.7	0.58	6.50
CRS cement	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	LOI
	21.45	5	5	64	1.25	2	0.4	3.5

2.4. Water

The mixing water must be clean and free from harmful impurities (organic matter, alkalis). Potable water is always suitable [22, 25]. Analyses of potable water (used for concrete mixing and standard curing) and sebkha water (used for Aggressive conservation) as illustrated in Figs. 4. The results of the chemical water analysis are summarized in the table 4, below;

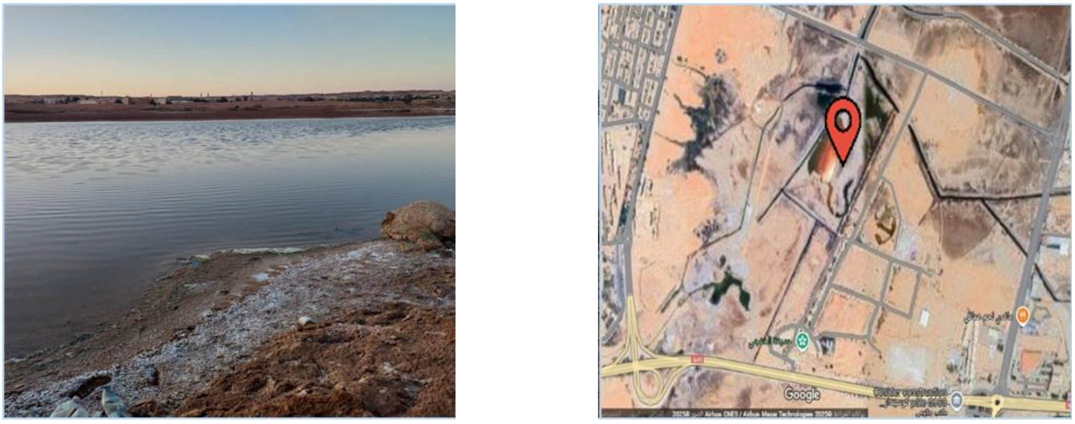


Fig. 4. The location of the Sebkha – Ouargla / Algeria

Table 4. Results of analyzed water (potable water and Sebkha)

Test	potable water	Sebkhas water	Specification NF EN 1008/July 2003
pH	7.51	7.77	PH ≥ 4
Sulfates SO_4^{-2} (mg/l)	753	11060	Max. 1 000 mg/l
Chloride Cl^- (mg/l)	883.13	82481.4	Max. 2 000 mg/l

3. Protective Products

For the protection method, we used two different products:

3.1 Internal Protection with Water Repellent

A liquid water-repellent admixture from Sika was used in the concrete during mixing. This additive acts internally by reducing the material's capillary absorption, thereby limiting water penetration through the formation of a water-repellent barrier within the concrete matrix. The detailed characteristics of the product are provided in the technical data sheets [26]

3.2 External Protection with Epoxy

We used a chemical protection product based on epoxy resin: Master Protect 1812, marketed under the name BASF 1812. This product is a two-component epoxy emulsion paint, composed of pigmented resins (component A) and cured resins (component B). It is specifically designed to protect both concrete and steel, and once applied, it forms an aesthetically pleasing and highly chemical-resistant coating.

Master-Protect 1812 is supplied in the correct proportions of resin (component A) and hardener (component B). Pour the hardener (component B) into the container of resin (component A) and ensure that container B is completely emptied. To achieve a homogeneous mixture, thoroughly mix the two components at approximately 300 rpm (27). Ensure the stirrer reaches the bottom and sides of the mixing container. Stir for at least 3 minutes or until the mixture is homogeneous (27).

4. Experimental Program

4.1 Formulation Method

The concrete mix design used for specimen preparation follows the Dreux method, resulting in a cement dosage of 350 kg/m^3 (CPJ/CRS) (see Table 5), a gravel-to-sand ratio (G/S) of 1.91, a water-to-cement ratio (W/C) of 0.61 and HF dosage 2% by cement mass. According to the European standard NF EN 12390-1, cubic molds measuring (15 x 15 x 15) cm^3 and cylindrical (7,5 x 15) cm^2 were used for specimen fabrication. The number of samples that were mixed and prepared in this study was estimated at 480 specimens.

Table 5. The percentages of formulations

Materials	Percentage	Mass for 1m^3(Kg)
Concrete CPJ / CRS	-	350
Sand	38	625.07
Gravel 3/8	10	185.26
Gravel 8/15	52	1037.45
water	-	215.95

There are four (04) compositions to be studied (fig.6):

- Concrete based on CPJ cement + water repellent (B+HF -CPJ) and control concrete based on CRS cement + water repellent (B+HF -CRS): These are concrete (mixing with water repellent) formulations using different types of cement (CPJ or CRS) and stored in two conservation environments without any protection.
- Concrete based on CPJ or CRS cement protected with epoxy coating (B+HF+EP -CPJ and B+HF+EP -CRS) and mixing with water repellent: These concrete samples are coated with an epoxy-based protective product and stored in both standard and aggressive conservation environments.

4.2 Conservation and Protection of Specimens

In this study, two environments were selected for the conservation of concrete specimens:

- Aggressive conservation environment: The specimens were immersed in water from Sebkha El-Khafdji-Ouargla under controlled conditions at 20°C ± 2°C.
- Standardized conservation environment: The specimens were stored in potable water at a temperature of 20°C ± 2°C.

After 14 days of standardized conservation for all specimens, apply two coats of 150 µm each; the second coat is applied after the first coat has dried for 4-6 hours at +40°C or 16 hours at +20°C. Two layers of protective coating were applied with a roller (See fig. 5). Before applying epoxy, it is must important to ensure that the surface of concrete has been completely dusted and that all impurities and damaged parts have been removed (27).

Fig. 5. Application of epoxy

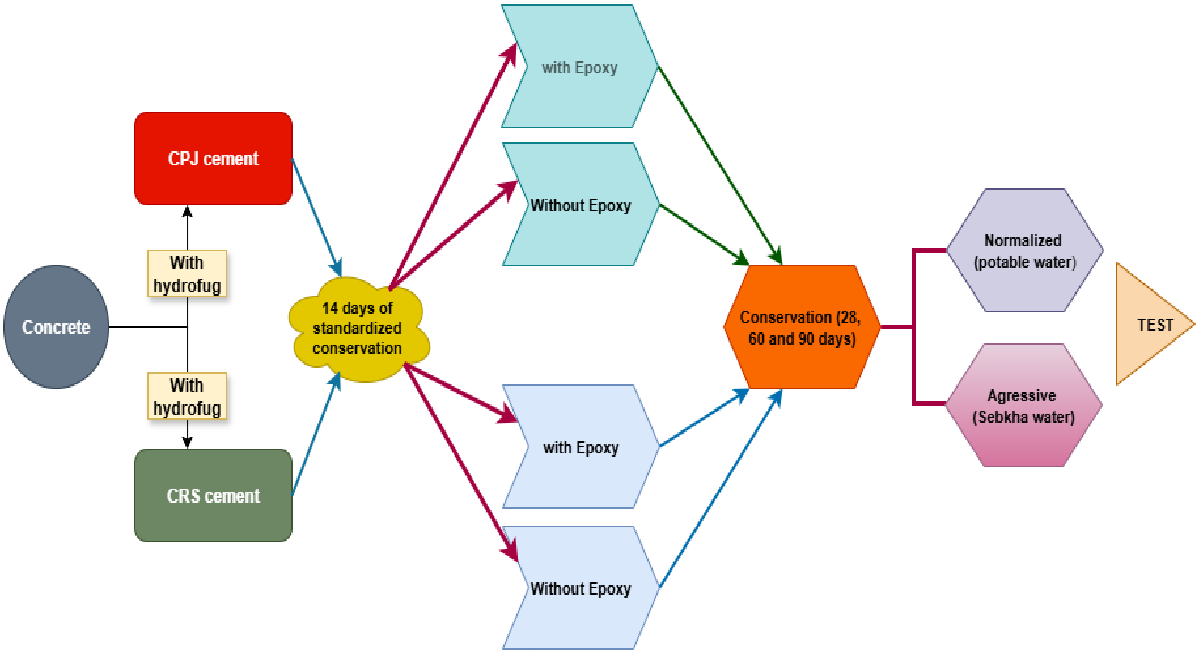


Fig. 6. Experimental protocol

4.3 Presentation of Experimental Tests

Four tests were applied to both unprotected (control) and protected concrete samples. The number of specimens tested for each result is 4 specimens (All results shown in the figures are the average result of 4 samples).

4.3.1 Compression Test

Compressive strength is defined as the ability of a material to withstand direct pressure from an applied compressive force [1,2]. In this study, compression tests were conducted following the European standard NF EN 12390-3, applying a load to a cubic specimen (15 × 15 × 15 cm) at a speed of 0.6 MPa/s, in a direction perpendicular to the casting axis, until failure. The samples were tested after air-drying.

4.3.2 Determination of Water Absorption by Immersion

This test measures the amount of water absorbed by a hardened concrete specimen (7,5x15) cm^2 (the specimens of this test, taken by drilling from a molded specimen). It indicates the concrete's porosity and durability. The test is typically performed in accordance with standards such as NF P18-459 and ASTM C642. The operations are performed in the following order:

- Immersion in a water bath at 20 ± 2 °C for a minimum of 48 hours and until a constant wet mass is reached; before weighing (Mh), the test tube is wiped with a damp chamois cloth to remove surface water;
- Drying for a minimum of 72 hours and until constant dry mass in a ventilated oven whose temperature is maintained at 105 ± 3 °C.
- The mass is considered constant when two successive weighing 24 hours apart do not show a difference greater than 0.1%.

Water absorption (Abs) is expressed as a percentage of dry mass (Ms) and is calculated using the following relationship (Eq.1):

$$Abs = \frac{Mh - Ms}{Ms} . 100 \tag{1}$$

4.3.3 Determination of Water Absorption Rates by Capillarity

The determination of water absorption by capillarity is a standardized test method used to evaluate the rate at which water is absorbed by specimen or mortar specimens (5x10 cm) through capillary action. This test was conducted following the ASTM C1585. It has provided essential information about the material's porosity, permeability, and resistance to water ingress, which are critical indicators of durability, especially in exposure to aggressive environments.

The data collected allows us to calculate the initial (Si) and secondary (Ss) sorpivity, expressed in $mm/s^{0.5}$, we can also calculate the index *I*, that it represents the *cumulative water absorption per unit area*, expressed as an equivalent height of water, hence the unit millimeters (mm).

$$I = \frac{\Delta M}{\rho .\ A} \quad (mm) \tag{2}$$

Where; ΔM = increase in mass of the specimen due to water absorption *(kg or g)*, ρ = density of water *(≈ 1000 kg/m³)*, A = area of the surface in contact with water *(m²)*

4.3.4 Analysis of Concrete with A Scanning Electron Microscope

The scanning electron microscope (SEM) is a valuable tool for the study of concrete. It allows the surface of concrete to be observed at high magnifications, revealing microscopic details such as cracks, pores and inclusions, which helps in understanding its microstructure and mechanical behavior. The magnification used in the test is 100, with a scale bars 10µm, accelerating voltage ETH=20 KV. The spectra supporting mineral identification will be presented in the next part. The SEM also makes it possible to carry out elemental analyses with an EDX spectrometer (Energy Dispersive X-ray spectrometry), which detects the X-radiation emitted by the sample and allows identifying the chemical composition of the elements. [28].

5. Results and Discussion

To facilitate comparison between the different types of concrete, all are manufactured with consistent workability, assessed by the Abrams cone slump of the consistency class for plastic concrete. Table 6 below provides information on the quantities of water actually added to the mixes, the workability, and the density of the concretes produced.

Table 6. The fresh properties of concerts

		Effective water used (*l*)	E/C	Workability (cm)	Density (g/cm³)
B HF	CPJ	215.95	0.617	7.3	2.31
	CRS	215.95	0.617	7.3	2.35

5.1. The Effect of Adding Water-Repellent and Epoxy Coating on Mechanical Strength

Figure 7 shows the mechanical performance of concrete under various conditions was evaluated through compressive strength tests at 28 and 90 days, in both normal and aggressive environments. The comparison focuses on concrete mixes incorporating a water-repellent admixture (HF) with two types of cement: Portland cement *"CPJ"* and Portland cement resistant to sulfates "*CRS*", and with or without surface protection using an epoxy coating.

At 28 days and under normalized curing, the compressive strength of CRS-based concretes was higher than that of CPJ-based concretes. For instance, the compressive strength of the B + HF + CRS reached 41.89 MPa while that of the B + HF + CPJ was 37.52 MPa. Further, at 90 days, the strengths reached 45.00 MPa and 44.22 MPa respectively. This performance is attributed to the superior sulfate resistance and lower C_3A content in CRS cement, which enhances long-term durability [29,30]. The addition of a hydrophobic admixture water-repellent (HF), perhaps leads to an enhancement of the compressive strength development by reducing internal moisture movement and decreasing pore water saturation, as also indicated in [26,31,32].

For aggressive environments (Sebkha water rich in salt and sulfates), they led to a decrease of strength especially for CPJ-based concrete. At 90 days, while CPJ + HF concrete decreased from 44.22 MPa (standard) to 37.46 MPa (aggressive), the degree of reduction was recorded at ~15%. In contrast, the CRS + HF concrete marginally increased while exposed to a harsh condition (45.00

to 46.90 MPa), which means the CRS-based concrete resistance to sulfate attack is high as supported by findings in [12,33-35].

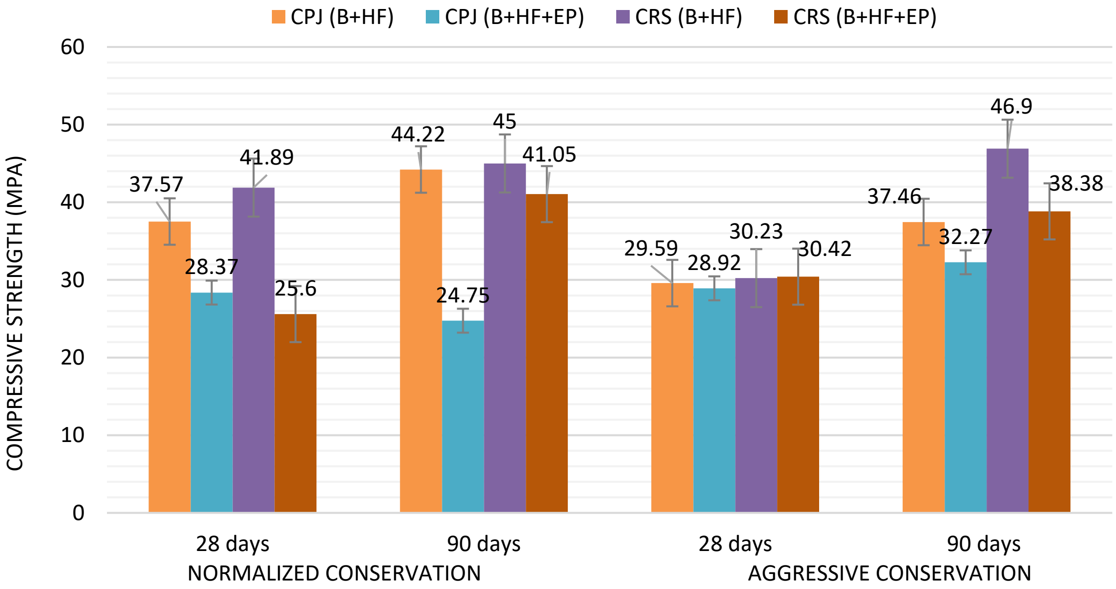
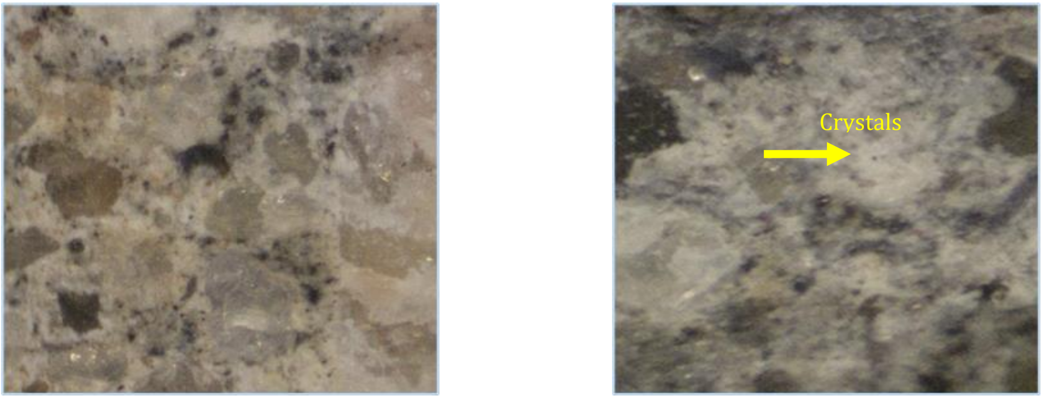


Fig. 7. Compressive strength of different concrete

Adding epoxy coating protection with the water-repellent additive produced mixed results. Under normal curing conditions, the compressive strength of CPJ + HF + Epoxy concrete decreased to 24.75 MPa at 90 days, compared to 44.22 MPa without epoxy. This indicates that the epoxy coating may have hindered cement hydration by restricting moisture exchange [3,32]. However, under aggressive exposure, the epoxy coating helped maintain strength. At 90 days, CPJ + HF + Epoxy reached 32.27 MPa, showing less loss compared to the uncoated version. This demonstrates that epoxy coatings effectively block external aggressive agents, especially when curing is properly controlled [32,36,37]

The decrease in the compressive strength of concrete with water-repellent and epoxy-protected materials in the standard medium is due to insufficient water, limited by the epoxy, which hinders the complete progression of cement hydration reactions and prevents the attainment of optimal strength. These findings align with [3] and [32], which demonstrated that epoxy coatings significantly reduce the ingress of chloride and sulfate ions. However, as noted by [36,38], early application of impermeable coatings can trap unreacted water, delaying hydration and weakening the microstructure. Medeiros et al. [32] highlighted the synergy between internal and surface water-repellent treatments in improving durability without sacrificing strength, as long as the curing process is properly managed.



(a) (b)

Fig. 8. The formation of crystalline deposits (a) Normalized environment and (b) Aggressive environment

The decrease in the compressive strength of concrete with water repellent and protected by epoxy in the aggressive environment can be explained by the formation of crystalline deposits, as supported by findings in [29,39], inside the sample indeed of Sebkha water, which is trapped between the concrete, promotes over time the precipitation of crystals as indicated in the Figure 8. Epoxy-protected concrete with water repellent did not retain moisture (fig. 9-a), like epoxy-protected concrete without water repellent (fig. 9-b), which positively influenced the compressive strength.

(a) (b)

Fig. 9. Form of rupture of specimens without and with water-repellent

Fig. 9 (a) shows the presence of residual moisture at the time of testing likely influenced the failure behavior. High internal humidity can result in:

- Reduced strength due to incomplete hydration or internal pore pressure, especially if the specimen was poorly cured [29].
- More brittle or irregular fracture surfaces, as internal water disrupts the cohesive strength between the paste and aggregates.
- An early onset of cracking along weaker zones.

The specimen demonstrates in fig. 9(b):

- Uniform failure (barrel shape) typical of a well-compacted and well-cured concrete.
- Higher compressive strength and better aggregate–matrix bond, suggesting good material homogeneity and less internal moisture disruption.
- Likely results from adequate drying or curing prior to testing, enhancing performance as shown in previous studies [40,41].

These results are in agreement with findings from Neville [29], and Ambad V . and al. [42], who highlighted the role of moisture content at the time of testing in influencing compressive strength measurements. Overly moist concrete can give misleadingly lower strength values, while properly cured, drier specimens typically yield more accurate and higher readings.

5.2 The Effect of Adding Water-Repellent and Epoxy Coating on Water Absorption Rates

5.2.1 Water Absorption Rates by Immersion

The results of the water absorption by immersion test indicate a significant difference in porosity between the tested concrete formulations. The control specimen made with CPJ cement (without any protective additive) showed the highest water absorption value at 5.36%, exceeding the commonly accepted threshold of 5% for durable concrete in aggressive environments, as specified in standards such as ASTM C642 or NF P18-459.

In contrast, the concretes incorporating a water-repellent admixture (HF) demonstrated improved performance. The CPJ + HF formulation showed an absorption of 4.25%, while the CRS

+ HF formulation presented the lowest value, at 4.07%. These results confirm the effectiveness of the water-repellent additive in reducing the capillary absorption of concrete, thus enhancing its resistance to water ingress.

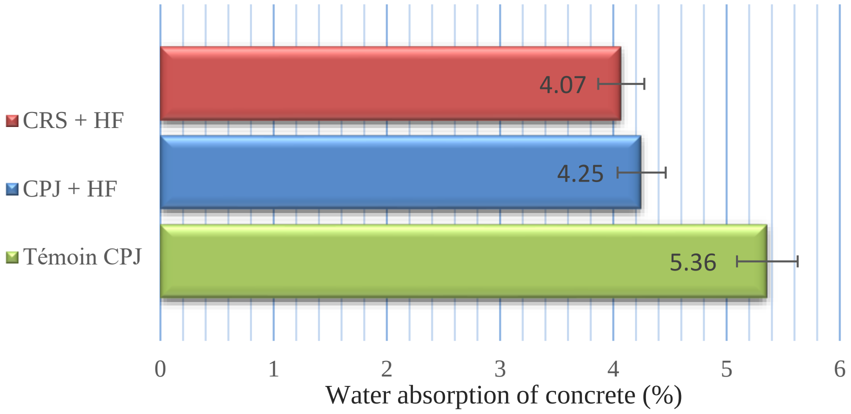


Fig. 10. Coefficient of water absorption by immersion

These results confirm the effectiveness of hydrophobic agents in reducing water ingress. The CRS-based mixture showed the lowest absorption, suggesting that the combination of CRS cement and water-repellent additive produces a denser, more water-resistant concrete. This observation aligns with findings by Djerbi et al. and Antoni et al. [43,44], who demonstrated that hydrophobic additives could significantly reduce the permeability of concrete by creating internal barriers to capillary suction. Moreover, the reduction in absorption observed with CRS-based mixes may be attributed to their lower C_3A content and higher sulfate resistance, as supported by [44-46]. These results are crucial for structures exposed to aggressive environments (e.g., marine or sulfate-rich soils), where limiting water ingress is key to improving durability and reducing chloride penetration.

5.1.2 Water Absorption Rates by Capillarity

The results of the capillary water absorption test, illustrated in figure 11 (A and B), highlight the influence of both water-repellent additives and cement type on the rate and extent of water ingress in concrete.

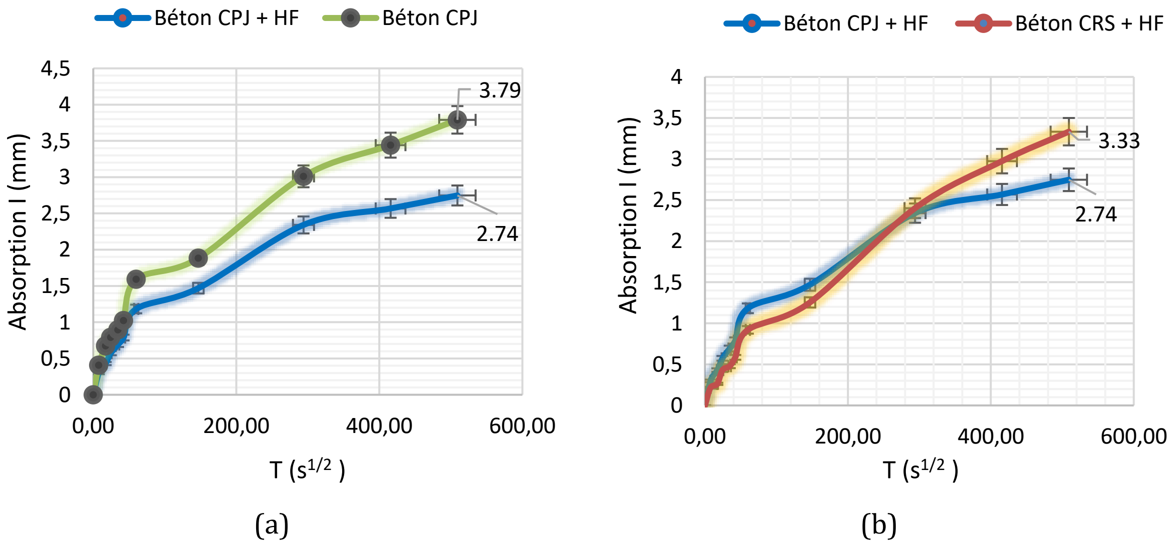


Fig. 11. Evolution of the water absorption rate of concrete by capillarity

Figure 11 (a), CPJ concrete with HF absorbs less water than control CPJ concrete at every time step. After 500√s, CPJ + HF absorbs about 2.8 mm, while control CPJ absorbs approximately 3.8 mm. Figure 11 (b), Both CPJ + HF and CRS + HF show similar trends, but CRS + HF exhibits slightly higher absorption than CPJ + HF over time. This behavior demonstrates again the effectiveness of the HF additive, which acts internally to reduce capillary water transport. It is important to note that although CRS + HF shows slightly more absorption than CPJ + HF in capillarity (Figure B), it performs better in immersion (Figure above), which may reflect different pore structures and surface interactions of the concrete. These findings support the work of Dias and al. and Snoeck et al. [47,48], who demonstrated that water-repellent admixtures significantly reduce both initial and long-term capillary water uptake, enhancing resistance to freeze-thaw cycles and chloride penetration.

Wang and al. [49] show that the capillary absorption coefficient of the CRS+HF mixture is greater compared to CPJ+HF, CPJ+HF displays greater water absorption in immersion conditions. This difference in performance suggests that there are fundamental differences in their pore structures. The greater sorptivity of CRS+HF suggests that there is a well-connected capillary pore structure that facilitates rapid water absorption. Conversely, CPJ+HF displays lower capillary absorption as a result of a refined pore system with smaller pore entry diameters. During prolonged immersion conditions, CPJ+HF displays greater water absorption as a result of more accessible pores in its pore system, which suggests that capillary absorption is mainly affected by pore connectivity, whereas immersion absorption is affected by total open porosity. [49, 50, 51]

5.2 Analysis of Concrete with A Scanning Electron Microscope

The following figures (from 12 to 16) present SEM micrographs for different concrete compositions exposed to both normalized and aggressive environments. The analysis focuses on the influence of cement type (CPJ and CRS), and the use of hydrophobic agents (water repellent) on the microstructural development of the concrete matrix.

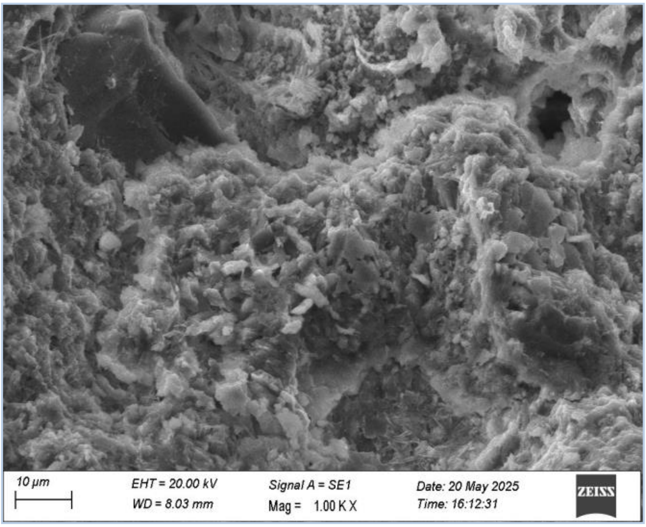


Fig. 12. CPJ Cement's concrete - normalized environment

Fig. 12 indicates the microstructure appears relatively dense with the presence of microcracks and large capillary pores, also, it reveals a granular texture, typical of partially hydrated cementitious compounds. The visible porosity indicates that the hydration is not complete, and there is a potential for permeability to water and ions.

In Fig. 13, the SEM micrograph of the samples reveals the addition of hydrophobic agent leads to significant microstructural changes. It reveals well-defined layered or crystalline hydration products, with a relatively compact structure, and shows a smoother overall surface and reduced visible porosity. Nevertheless, the surface texture appears highly compact with fewer visible pores. The morphology indicates a denser cement matrix, with abundant C-S-H gel-like formations seen on Fig. 14.

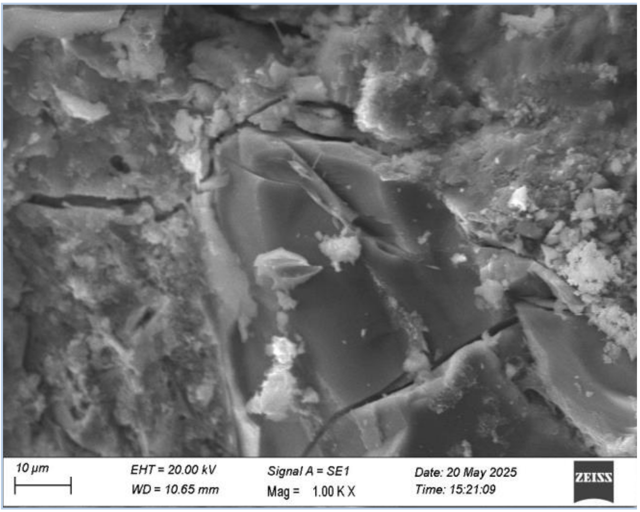


Fig. 13. CPJ Concrete with water repellent - normalized environment

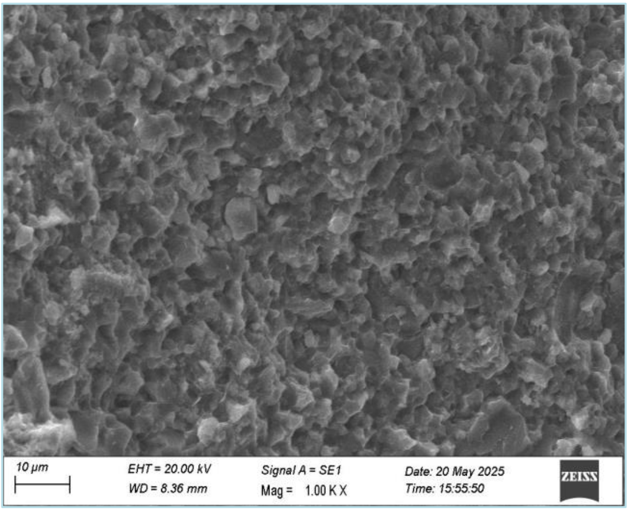


Fig. 14. CRS Concrete with water repellent - normalized environment

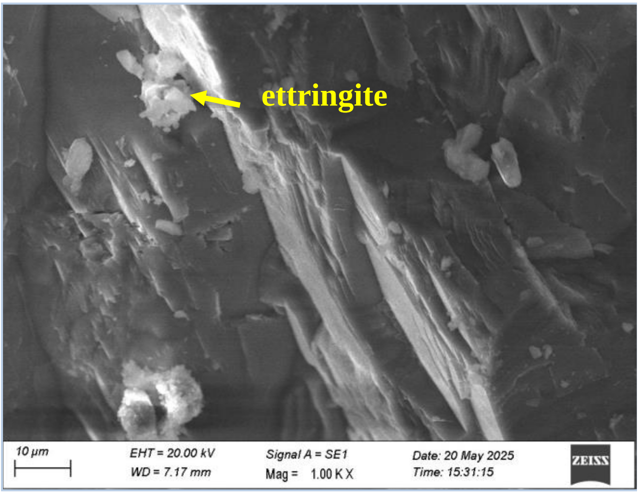


Fig. 15. CPJ Concrete with water repellent - aggressive environment

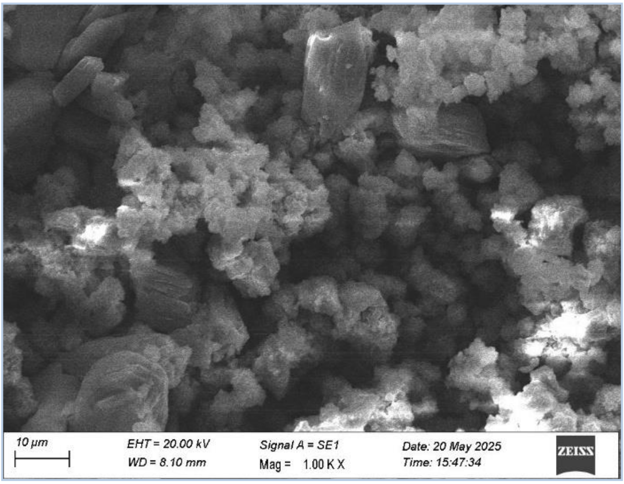


Fig. 16. CRS Concrete with water repellent - aggressive environment

Fig. 15 shows a long, needle-like or plate-like crystalline structures dominate the micrograph, indicating the presence of secondary ettringite or other sulfate-related expansive phases. Cracks are visible, suggesting damage due to chemical attack. However, Fig. 16 shows the microstructure retains a globular, dense morphology with minimal evidence of crack formation or expansive crystal growth. Hydration products are compact and interlocked. Concrete formulated with CPJ cement under normalized conditions exhibited a moderate level of compactness. Nevertheless, the presence of visible pore networks and microcracks suggests a relatively open microstructure, which could facilitate the ingress of water and aggressive ions. This porous morphology likely stems from incomplete matrix densification, potentially due to insufficient curing duration or the limited pozzolanic reactivity inherent to the CPJ formulation.

The incorporation of hydrophobic additives into CPJ-based concrete significantly modifies the pore system. The treated matrix displayed improved cohesion and reduced visible porosity, indicating that the additives contribute to filling and sealing capillary pores. This densification effect enhances water resistance and may also improve long-term durability. These observations are consistent with previous studies highlighting the ability of hydrophobic agents to enhance the microstructural integrity of cementitious systems [32,52,53].

A more pronounced improvement was observed in the concrete based on CRS (slag-based) cement with hydrophobic treatment. Under normalized conditions, this system exhibited superior microstructural refinement, characterized by a dense, gel-rich matrix with fewer interconnected voids. The enhanced compactness is attributed to the latent hydraulic activity of slag, which fosters extended hydration, as well as the synergistic action of the hydrophobic admixture in reducing pore continuity. These factors collectively contribute to a substantial decrease in permeability, as supported by literature findings [35,54].

In aggressive environments, however, the CPJ-based concrete—even when treated with hydrophobic agents—demonstrated signs of deterioration. The formation of expansive crystalline products, likely ettringite or gypsum, resulted in microcracking and internal stresses. These degradation phenomena suggest that the hydrophobic treatment alone is insufficient to mitigate chemical attack in systems with high C_3A content, emphasizing the need for chemically stable cement compositions in such conditions [6,55]. Conversely, CRS-based concrete treated with hydrophobic agents maintained a stable and compact microstructure under the same aggressive exposure. The absence of expansive products and visible degradation can be attributed to the low C_3A content of slag cement, which inherently offers improved sulfate resistance. The combined effect of the chemical stability of CRS and the physical sealing action of the hydrophobic agent provides a robust defense against both physical and chemical deterioration. These results reinforce prior evidence regarding the superior durability of slag-based cementitious systems under aggressive conditions [3,7,54,56].

EDS analysis (figures from 17 to 21) revealed Ca–Si–Al–O–rich compositions, characteristic of hydrated cementitious matrices, with minor S and Cl detected in samples subjected to aggressive environments. The Ca–Si–O signals are indicative of C–S–H–type phases, whereas the simultaneous presence of Al and S suggests the formation of aluminate–sulfate phases, consistent with the identification of ettringite observed in the SEM test.

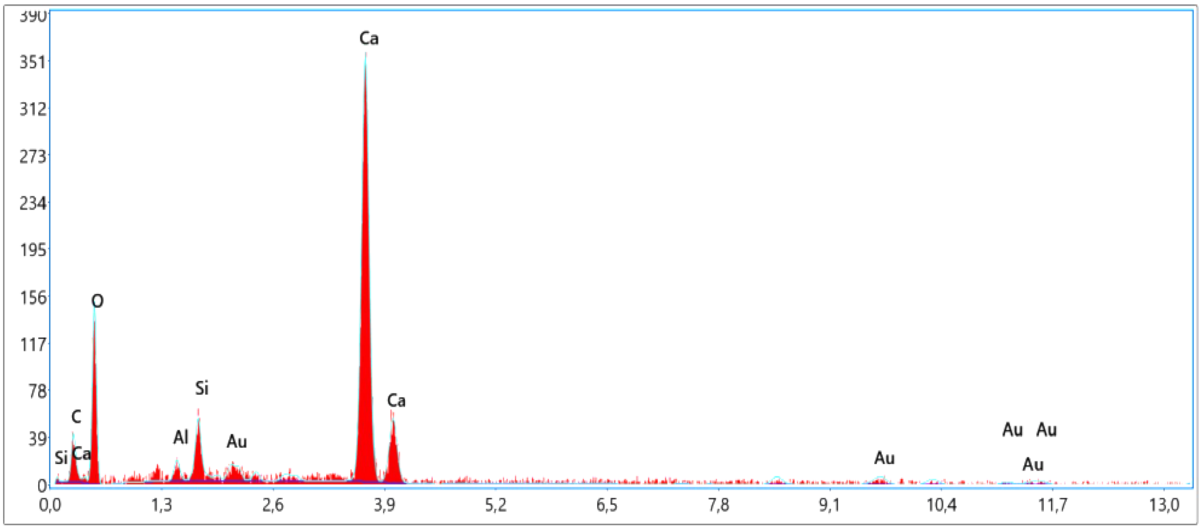


Fig. 17. CPJ Concrete without water repellent - normalized environment

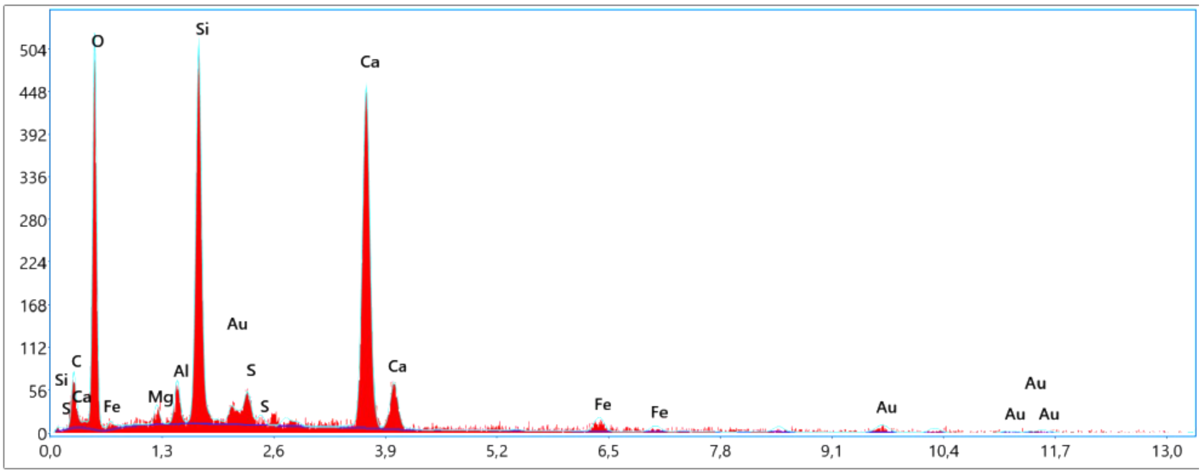


Fig. 18. CPJ Concrete with water repellent - normalized environment

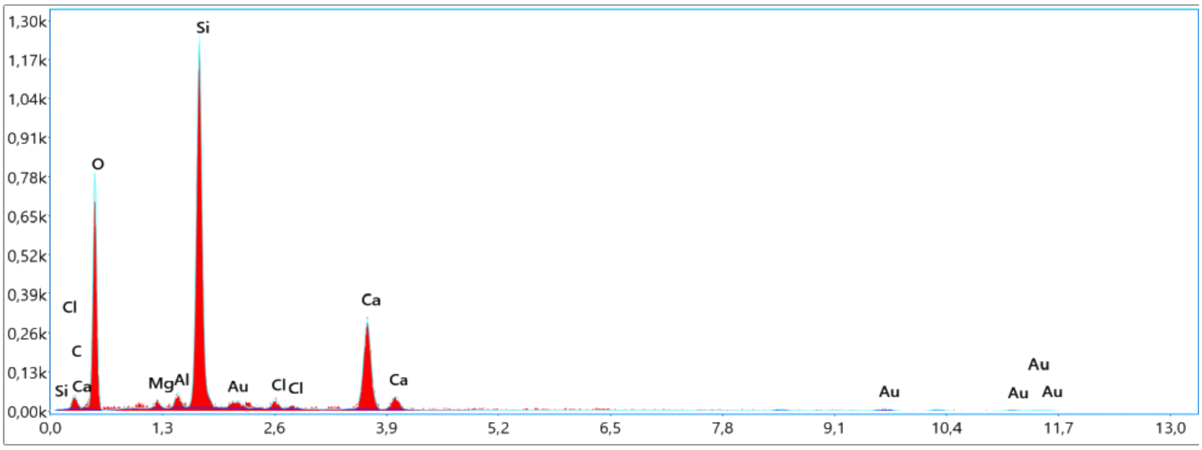


Fig. 19. CPJ concrete with water repellent - aggressive environment

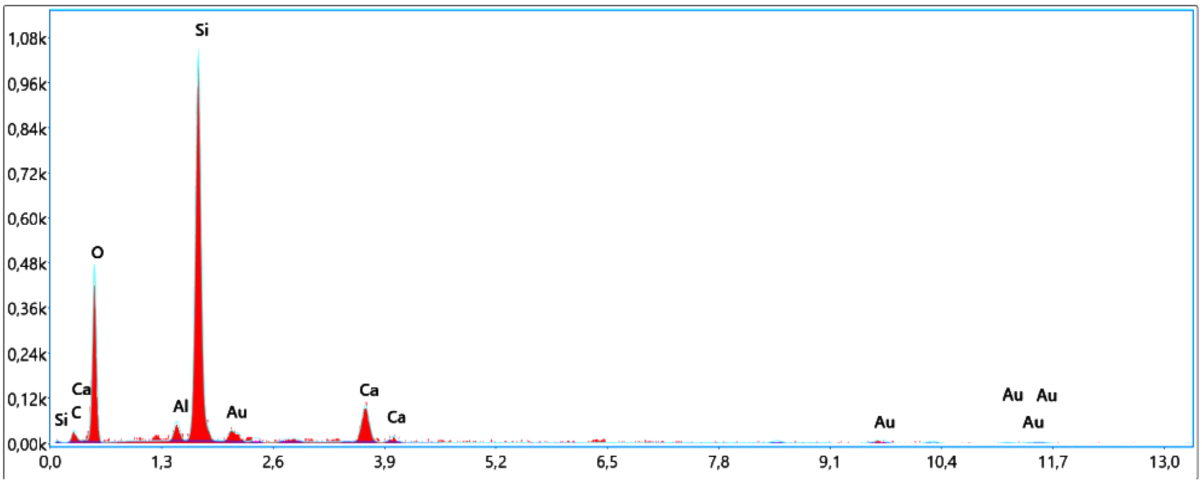


Fig. 20. CRS concrete with water repellent - normalized environment

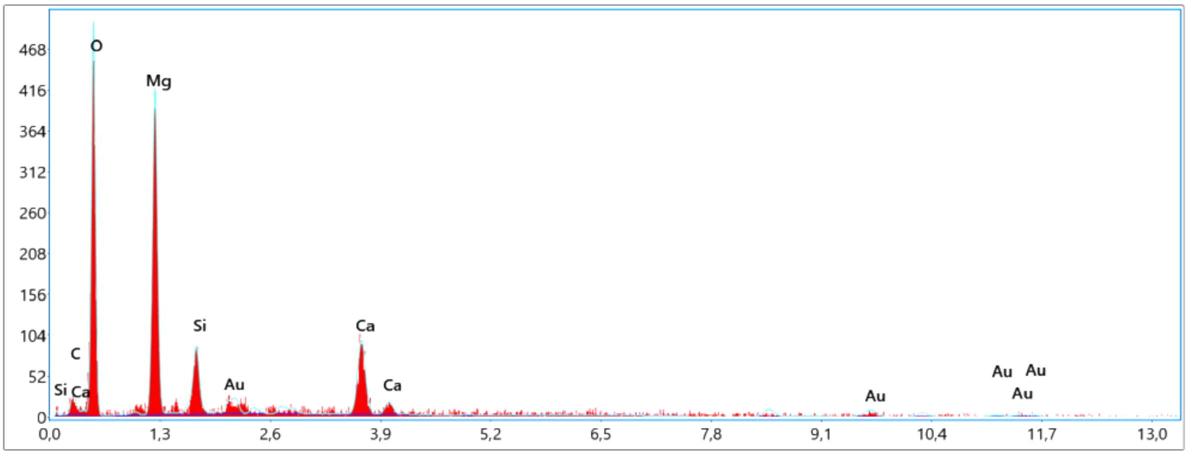


Fig. 21. CRS concrete with water repellent - aggressive environment

6. Conclusions

The objective of this research is to assess and evaluate the significance and effectiveness of various concrete protection methods in high-salinity environments. Identifying effective and durable solutions in this field contributes to enhancing infrastructure quality and extending their lifespan, benefiting societies and economies at large. The use of water-repellent and epoxy-based products as protective coatings for concrete made with CPJ (Portland Composite Cement) and CRS (Sulfate-

Resistant Cement) has demonstrated very satisfactory results in terms of improving the mechanical strength of concrete submerged in aggressive environments.

Water repellent admixture significantly decreases capillary water absorption capacity of concrete and greatly reduces its porosity. Its effectiveness is further enhanced when combined with CPJ cement. As the CPJ + HF system demonstrated, better in terms of coefficient of absorption than CRS + HF concrete. This could be due to a more favorable condition of the water repellent and CPJ concrete matrix interaction. Thus, yielding better long-term durability.

Epoxy protection should be reserved for aggressive exposure and not applied too early in normal curing conditions. However, epoxy coatings offer external protection, their application should be carefully timed to avoid compromising strength development, particularly in CPJ-based concretes.

The results for concrete based on CPJ cement, when protected with epoxy and mixed with water-repellent, yield acceptable values, suggesting the suitability of this product and cement type even in the most unfavorable conditions. Moreover, using CPJ cement protected by an epoxy-based and water repellent product in concrete offers numerous advantages; this cement can be more cost-effective than CRS cement, thereby reducing the overall financial burden in production. Additionally, it can enhance the durability of concrete structures in aggressive environments. In this way, CPJ cement can be considered as making “friendship with the environmental", not just for its moderate clinker reduction but also for enabling sustainable building design when used in a well-designed and well protected system. Its existing availability, affordability, and adaptability to green designs provide a further building block for transition to green concrete.

This study also opens new research perspectives regarding the effect of the concrete age at the time of application of epoxy resin. Moreover, other practical aspects regarding the durability of epoxy resin in environments with saline and sulfate solutions, the risk of blistering in immersion conditions, and the application of epoxy resin under real field conditions should be studied.

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