Journal of Applied Research and Technology

www.jart.icat.unam.mx

ICAT
Instituto de Ciencias Aplicadas y Tecnología

Journal of Applied Research and Technology 24 (2026) 147-154

Original

Aggressive Environments' Effect on HPC Reinforced with Building Waste Steel Fibers.

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Received: 23 08 2025; Accepted: 12 03 2025
Available: 02 28 2026

Abstract: Durability refers to concrete's ability to withstand deterioration from its surrounding environment. It is important to note that concrete durability encompasses not only its mechanical resistance but also its resistance to aggressive environments. This research paper investigates the chemical and mechanical durability of high-performance concrete reinforced with waste steel fibers. Concrete specimens were immersed in 5% HCl and $MgSO_4$ solutions for 90 days, while control samples were stored in water for comparison. The results show that specimens immersed in water exhibited very low mass loss, ranging between 0.1% and 0.8%, indicating minimal deterioration.

In contrast, fiber-reinforced specimens exposed to $MgSO_4$ and HCl showed slightly higher mass loss, ranging from 0.2% to 0.3%, especially in the fiber-reinforced specimens. Despite minor material loss, a corresponding reduction in compressive strength was observed after immersion. Overall, the findings demonstrate that incorporating waste steel fibers significantly enhances the durability and resistance of high-performance concrete in harsh chemical environments.

Keywords: **Aggressive environment, durability, mass loss, recycled fibers, strength loss**

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Peer Review under the responsibility of Universidad Nacional Autónoma de México.

1. Introduction

The durability of conventional concrete has become a significant concern in many countries and climates, as numerous concrete structures exhibit signs of extensive deterioration. It is important to note that this issue is not due to an insufficient understanding of the durability of conventional concrete (Aïtcin, 1998). Concrete is inherently a porous material, meaning it contains voids or pores. These pores significantly influence the concrete's strength and durability. It is widely recognized that low porosity serves as the most effective defense mechanism for concrete against various aggressive agents (Ployaert, 2009). Concrete's chemical system is relatively straightforward: it gradually reacts with the external environment, which is often more acidic, such as the atmosphere, water, salt solutions, and acids. Water is the common medium through which aggressive agents dissolve gaseous or solid compounds.

The transport of aggressive substances primarily occurs through permeation and diffusion, which are key indicators of durability and depend on the concrete's compactness (Escadeillas & Hornain, 2008). Achieving high resistance and low permeability to aggressive external and internal agents requires substantial reductions in porosity and the development of a dense, homogeneous matrix (Guiraud, 2018). External agents include chloride ions, carbon dioxide, sulfates, freeze-thaw cycles, microorganisms, and abrasives. While internal agents are chloride ions introduced through specific accelerators and cement alkalis when potentially reactive aggregates are employed (Aïtcin, 1998).

Chemical attacks on concrete primarily occur through dissolution and precipitation processes. When aggressive elements are exposed to the calcium hydrates present in cement, they either diffuse through ionic diffusion or through solution permeation. Magnesium sulfate, common in soil and groundwater, induces brucite formation and progressive destruction of C–S–H. At the same time, acids cause rapid dissolution of calcium hydroxide and destabilization of the cement matrix (Escadeillas & Hornain, 2008; Massaad et al., 2015).

Seawater contains relatively high sulfate concentrations, with $MgSO_4$ typically ranging from 2400 to 2900 mg/L, making it an aggressive medium for sulfate-related reactions. In groundwater, elevated sulfate levels commonly originate from dissolved magnesium sulfates ($MgSO_4$) or alkaline sulfates (K_2SO_4–Na_2SO_4) (Massaad et al., 2015).

$$Mg_2 + \quad + 2H_2O \rightarrow Mg(OH)_2 \tag{1}$$

Thus, where magnesium sulfate is present in higher concentrations, the main effect is a loss of strength (Dyer, 2014). Concrete must have chemical resistance when exposed to chemical attack, provided its composition is appropriate and it is properly consolidated (Soufiane, 2010) Concrete is likely to be attacked by various acids. Sulphuric acid is widely recognized as one of the most common causes of concrete degradation. Concrete structures buried in the ground can be vulnerable to attack by water in the soil, which may naturally contain mineral oxidation byproducts such as pyrite, or to the deposition of industrial chemical waste (Dieryck & Desmyter, 2004). When concrete is exposed to an acid solution, a lower solution pH is expected to result in a faster rate of deterioration. Therefore, an aggressive solution is characterized by a high concentration of strong acid. While this generalization holds, it is important to note that various other factors also influence the rate and mechanism of deterioration in concrete when exposed to acids.

When acid solutions are exposed to hardened concrete, various reactions will occur involving cement hydration products and aggregate minerals. In the case of calcium hydroxide, the general reaction is:

$$Ca(OH)_2 + 2HA \rightarrow CaA_2 + 2H_2O \tag{2}$$

Here, *HA* represents a monoprotic acid (Dyer, 2014).

On the other hand, concrete production generates a marginal amount of waste. On the other hand, inert waste from the demolition of buildings is not yet sufficiently recycled, although it can be used for filling. The main drawback of concrete is the use of non-renewable energy and non-energy resources. Its main quality is sustainability, which gives a very long life cycle and limits the impact of this use (Capmas, 2008), so using recycled fiber from waste buildings is an environmental and economic gain.

Chopped steel fibers have substituted traditional steel reinforcement in reinforced concrete for several uses, including airport runways, access roads, and parking lots. The incorporation of fibers into concrete mixtures markedly influences their mechanical and functional properties, altering the material's characteristics and broadening its potential applications. Fibers serve as reinforcement components that impede fracture initiation and progression, hence enhancing tensile strength, plasticity, and energy absorption capacity of concrete (Al-Rousan et al. 2023; Dziomdziora & Smarzewski, 2025).

Durability mainly depends on porosity, cracking, and compressive strength. The addition of fibers can limit crack development and improve durability (Fedaoui-Akmoussi et al., 2015). This enhancement typically leads to smaller crack widths in a concrete element, which benefits protection against the ingress of chemical substances that can damage either the concrete or its reinforcing steel (Capmas, 2008).

Numerous authors have emphasized that the inclusion of fibers in concrete diminishes penetration and cracking. Increasing the fiber volume can shift the failure mode from shear to bending, thereby delaying crack initiation. In general, fiber-reinforced concrete has significantly lower permeability than conventional concrete, even in a fractured state (Ojaghi et al., 2025).

Concrete can exhibit enhanced ductility when an appropriate volume of metal fibers is incorporated, allowing it to withstand deformation without sudden fracture. Increased ductility also contributes to improved post-cracking resistance.

2. Materials and Methods

2.1 Materials

The experimental procedure involved the utilization of various materials sourced from the Bechar region, each possessing specific characteristics as detailed below:

Cement: A high-quality Portland cement type II with a strength rating of 42.5 MPa was carefully selected for the experiment. This sulfate-resistant cement is produced by meticulously milling clinker containing low levels of calcium aluminate and gypsum. The chemical properties of the cement, which play a crucial role in the overall performance of concrete, are shown in Table 1.

Water: The water used for the concrete mix was subjected to stringent criteria to ensure its cleanliness and suitability for the experiment. Physically, it had to be free from solid, mineral, or organic waste. Chemically, the water was required to contain only a limited amount of dissolved salts, thereby excluding seawater, which could introduce impurities and compromise the concrete's integrity.

Superplasticizer: To optimize concrete workability, a high-performance SikaViscoCrete superplasticizer was used. This superplasticizer, with its 29% dry extract and density of 1.085, played a vital role in enhancing the fluidity and flow properties of the concrete mixture, ensuring better cohesion and easier handling during the experiment.

Aggregates: The experiment utilized locally sourced aggregates procured from the Bechar region. These aggregates included crushed sand-class limestone, with a fine particle size of 0.3 cm, and gravel crushed to 3/8 inch. The Particle Size Analysis of Aggregates, as depicted in Figure 1 [EN 933-1], allowed for a comprehensive understanding of the distribution and composition of the aggregates. Furthermore, the physical properties of the aggregates, crucial for determining the mechanical strength and durability of the concrete, were thoroughly examined and are reported in Table 2.

Fibers: To enhance the concrete's structural properties, recycled fibers derived from building waste were carefully incorporated into the experiment. These fibers, characterized by lengths of 2 and 3 cm and a diameter of 1 mm, provided reinforcement and improved crack resistance in the concrete. Their properties were meticulously monitored and controlled in accordance with EN 14889-1 within the university laboratory, ensuring consistency and reliability of the experiment. Fiber properties are presented in Table 3.

Table 1. The percentages of chemical compounds for the cement used (%).

Al_2O_3	SO_3	SiO_2	CaO	MgO	Fe_2O_3	K_2O	LOI
6.40	1.8	20.05	61.23	1.2	3.45	0.01	0.5
	-			-		–	–
	3			3		0.05	3

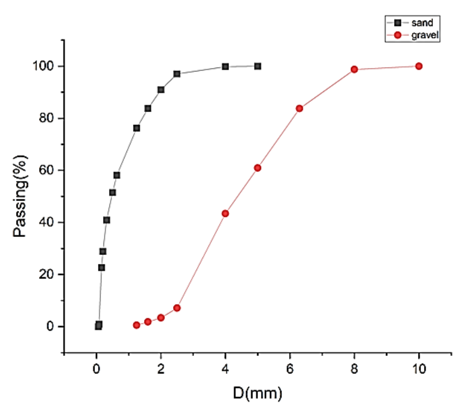

Figure 1. The coarse and fine aggregate gradients.

Table 2. Physical properties of the aggregate used.

Aggregate Type	Apparent density (kg/m^3)	Absolute density (kg/m^3)	Fineness Modulus
Gravel	2.60	1.25	-
Sand	2.54	1.53	2.78

Table 3. Waste building fibers properties.

Type	L (mm)	D (mm)	Volume (%)	Elasticity Modulus (GPa)	Tensile strength (MPa)
Steel fibers	30	1.34	2	215	675.73

2.2 Methods

Mixed proportions:

The concrete mix was prepared with a water/cement ratio of 0.37, ensuring an optimal balance between workability and strength. Specimens measuring 4 × 4 × 16 cm were meticulously cast in accordance with EN 196-1. Both plain concrete and concrete containing waste fibers were prepared in varying volume proportions. Four compositions with 2 and 3 cm of fiber lengths and 1 and 2 % of fiber volume, adding one composition without fibers as a reference, as specified in Table 4. Four specimens for every composition to immersed in solutions, and one is used as a reference for the mechanical properties and NDT for confirmation.

Curing and Testing: After casting, the specimens were cured to allow the concrete to develop strength over time. The curing duration was 28 days in water at 20 °C in the EMIA/LFGM Research Laboratory, Bechar, Algeria. At the end of the curing period, the concrete's physical and mechanical properties were measured, including compressive and flexural strengths, density, and porosity.

Durability Evaluation: To assess the concrete's durability under specific conditions, the specimens were subjected to prolonged exposure in different environments. For 90 days, the specimens were immersed in water, HCl (hydrochloric acid), and MgSO4 (magnesium sulfate) solutions. This immersion aimed to simulate concrete's performance in aggressive, corrosive environments.

Following the exposure period, the specimens' compressive strength and mass loss were measured and compared against the performance of the concrete samples before exposure. Additionally, the concrete's resistance to wet/dry cycles was evaluated by subjecting the specimens to alternating immersion in water and the aggressive environment solution, with a volume ratio of 5%. The resulting measurements provided valuable insights into the concrete's durability and ability to withstand harsh conditions.

Table 4. The composition of High-performance fiber-reinforced concrete.

Composition	RC	WB1L2	WB1L3	WB2L2	WB2L3
Cement (kg/m^3)	400	400	400	400	400
Sand (kg/m^3)	665	665	665	665	665
Gravel (kg/m^3)	1111	1093	1093	1075	1075
Water (kg/m^3)	148	148	148	148	148
Superplasticizer (%)	1.75	1.75	1.75	1.75	1.75
Fiber Volume (%)	-	1	1	2	2
Fiber length (mm)	-	20	30	20	30
W/C ratio			0.37		

3. Results and Discussion

Chemical resistance:

Mass loss: Figure 2 illustrates the mass loss of the concrete samples when exposed to different immersion solutions, with water serving as the reference. In water, all mixtures recorded minimal mass loss. In the $MgSO_4$ solution, a greater mass loss is observed due to sulfate attack, particularly for the reference concrete, while mixtures containing longer fibers and higher fiber contents. Retain more mass, suggesting that fibers help limit surface deterioration and material disintegration. While the samples immersed in hydrochloric acid (HCl) solution for 90 days exhibited the highest weight loss, reflecting the strong acidic dissolution of cementitious components, the largest mass reduction was recorded in waste building fibers reinforced concrete with 2% of volume and 3 cm of length (WB2L3).

The presence of fibers helps mitigate the formation and propagation of micro-cracks, leading to a more compact concrete structure. High-performance concrete exhibits minimal capillary porosity, resulting in low permeability and delayed penetration of aggressive ions. Consequently, the overall properties of the concrete remain highly intact. Overall, the data indicate that waste-building fibers enhance resistance to degradation and reduce mass loss under aggressive chemical environments, with the best performance achieved by longer fibers and higher fiber contents.

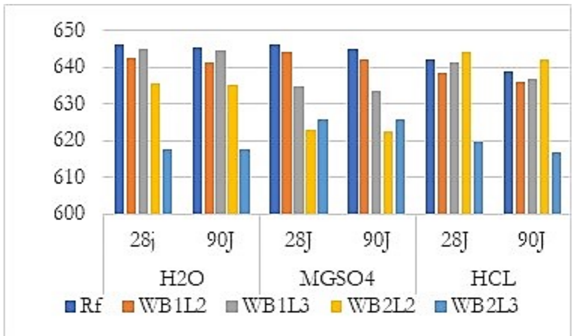

Figure 2. Weight degradation of concrete immersed in an aggressive solution.

The mechanism of acid attack involves the reaction between hydrochloric acid and calcium hydroxide present in the cement paste, as represented by the equation:

$$2HCl + \quad + \mathrm{Ca(OH)_2} \rightarrow CaCl + 2H_2O \tag{3}$$

This reaction results in the formation of soluble calcium chloride, which contributes to the observed weight loss. The composition of the degraded concrete, particularly the formation of calcium chloride, the main peaks are mostly made up of ettringite, portlandite, and calcite, but their strengths show important trends. The portlandite peaks, which are usually present in hydrated cement paste, look smaller and wider, which means that a lot of calcium hydroxide has dissolved because of acid attack, was analyzed using XRD (X-ray diffraction) techniques, as shown in Figures 3, the presence of the peak of Chloride as illustrated in EDS (energy-dispersive X-ray spectroscopy) analysis (Figure 4).

In the magnesium sulfate ($MgSO_4$) attack, weight loss was observed during immersion at various replacement percentages. However, this loss was less significant than that from acid degradation. The mass change was compared to a reference concrete sample immersed in water, which exhibited no weight loss. Overall, the pattern shows that HCl rapidly breaks down the original hydration products, especially portlandite, and promotes the formation of unstable secondary phases such as ettringite.

The degradation mechanism in the presence of $MgSO_4$ involves the reaction of the substance with portlandite, resulting in the formation of soluble calcium salts, as represented by the equation:

$$MgSO_4 + \mathrm{Ca(OH)_2} \rightarrow CaSO_4 + \mathrm{Mg}(OH)_2 \tag{4}$$

Furthermore, the interaction between calcium sulfate and aluminates leads to the expansion of ettringite and the depreciation of portlandite, as indicated in Figure 5 through DRX analysis, as represented by the equation:

$$Ca\mathrm{SO_4} + \mathrm{C3}A + 32\mathrm{H_2O} \rightarrow \mathrm{C3}A.3CaSO_{4.32}H_2 \tag{5}$$

Figure 6 shows a SEM (scanning electron microscopy) analysis of the secondary massive ettringite, identified by its characteristic needle-like, elongated crystalline morphology. These clustered crystals appear densely packed within the cement matrix, indicating significant sulfate-related deterioration. Overall, the SEM image confirms that ettringite accumulation played a major role in the deterioration mechanism of the concrete under the studied conditions.

Also, the Subs. These clustered crystals appear densely packed within the cement matrix, indicating significant sulfate-related deterioration. Titution of Ca++ ions by Mg++ ions in C-S-H results in a Loss of binding properties of C-S-H, the image of C-S-H gels was presented in Figure 6(a). As [3], see the dissolution and exchange reactions of the Ca++ ions of portlandite and CS-H with the Mg++ ions of seawater. These reactions lead to brucite precipitation ($Mg(OH)_2$), the gradual transformation of C-S-H into poorly structured compounds or mixtures such as C-M-S-H and M-S-H, lacking binding properties, and the formation of $CaSO_4 \cdot 2H_2O$ (gypsum).

The activity of the SO_4 ions of $MgSO_4$ solution is due to the reduction of the resistance, mainly related to the intensification of the $Ca(OH)_2$ resulting from the increase of the gypsum form following the ion substitution reaction between portlandite and sulfate.[7]

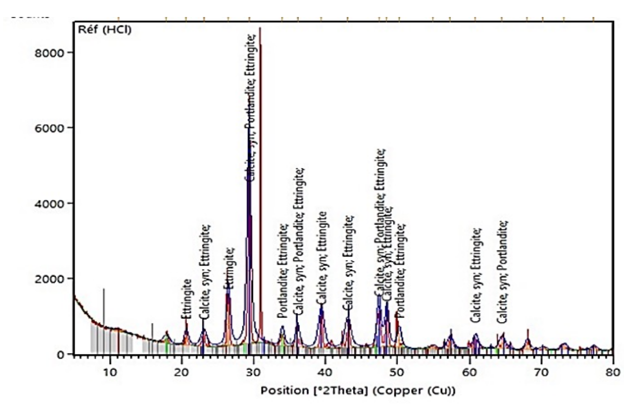

Figure 3. The X-ray diffraction (XRD) spectrum of concrete after immersion in HCl for 3 months.

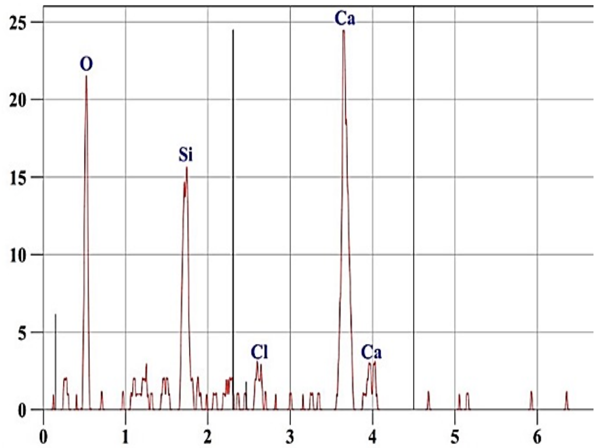

Figure 4. The spectrum of energy dispersive X-ray (EDS) of concrete after immersion in HCl for 3 months.

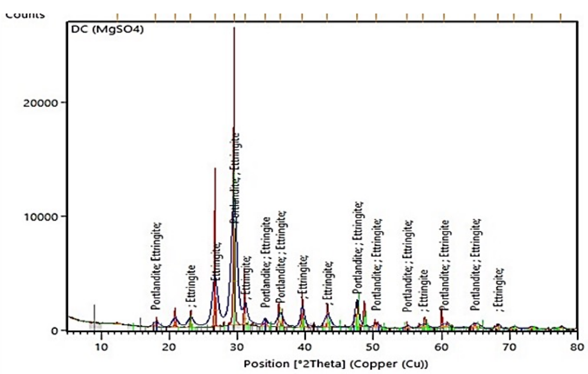

Figure 5. The XRD spectra of concrete after immersion in MgSO4 for 3 months.

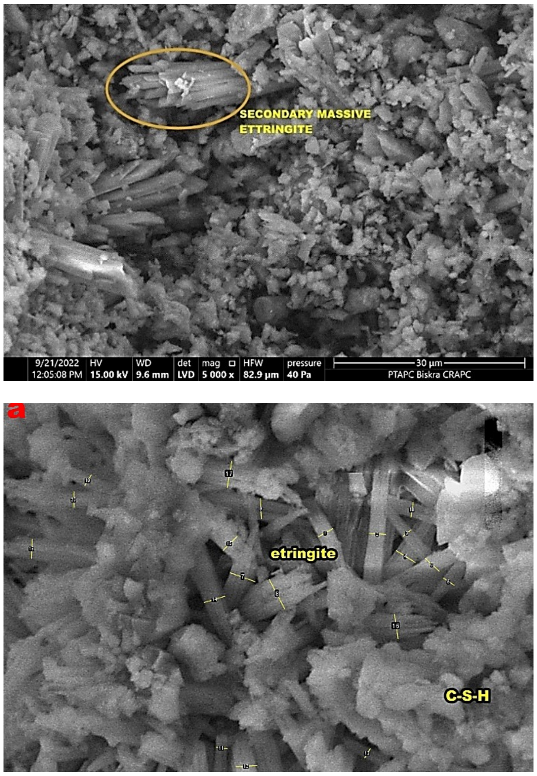

Figure 6. The SEM spectra of concrete after immersion in $MgSO_4$ for 3 months.

Strength loss: The high-performance fiber-reinforced concrete (HPRC) specimens underwent a 28-day water-curing period before being immersed in water, 5% hydrochloric acid (HCl), and magnesium sulfate (MgSO4) solutions for a total of 90 days. Figure 7 clearly illustrates the compressive strength loss observed in the specimens.

The results indicate a decrease in compressive strength for the concrete samples submerged in HCl and MgSO4 solutions. However, it is noteworthy that the strength loss in the MgSO4-submerged concrete was relatively lower than in the HCl-submerged concrete. Conversely, there was a relative increase in compressive strength after 90 days in water-immersed specimens. This can be attributed to further hydration of the remaining unhydrated cement particles in the concrete.

The strength loss increases with increasing mass loss, which is due to concrete's porosity. This increase can affect compressive strength (Saidat et al., 2021), as shown in Figure 8. However, this effect is related to the loss of C-S-H's binding properties, which can cause substantial damage to structural elements.

The percentage of the loss was calculated with:

$$\mathrm{Loss}(\%) = \left[\frac{\mathrm{Wi}-\mathrm{Ws}}{\mathrm{Wi}}\right] \times 100 \tag{6}$$

Where *Wi* is the initial weight, and *Ws* is the second weight

These findings highlight the importance of considering the impact of solution exposure on strength loss in HPRC and the relationship between mass loss and compressive strength.

Understanding these relationships enables a more comprehensive assessment of concrete durability and structural performance in aggressive environments. Notably, the presence of fibers prevents the formation of voids that allow acid penetration into the concrete, thereby mitigating rusting and further degradation. The addition of fibers reduced the loss of compressive strength after attack, even when weight loss was more significant (Dong et al., 2024; Flores-Medina et al., 2023;)

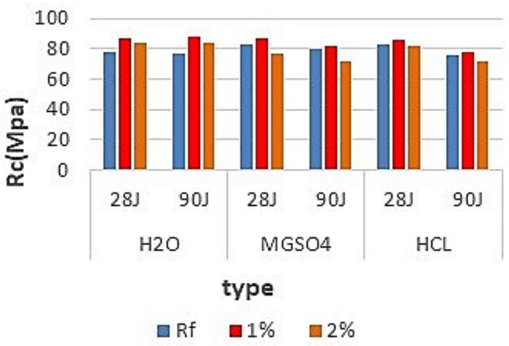

Figure 7. The compressive strength before and after immersion.

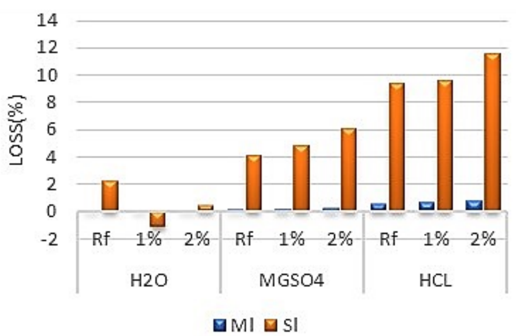

Figure 8. Mass loss with strength loss.

Conclusion

Based on the results obtained, the following conclusions can be drawn:

1. Durability in Aggressive Environments: The experimental findings reveal that high-performance concrete exposed to aggressive environments experiences a gradual loss in mass and strength. However, it is important to note that the careful selection of concrete composition plays a significant role in exhibiting resistance against such environments. It was observed that the degradation caused by acids was more pronounced than that caused by sulfates.
2. Mass Loss and Compressive Strength: The decrease in concrete mass directly correlates with reduced compressive strength. This can be attributed to the loss of the binding properties of calcium-silicate-hydrate (C-S-H), a crucial component responsible for concrete's strength.
3. Enhanced Durability with Fibers and Cement Type: The introduction of fibers in the concrete mixture, along with the selection of the appropriate cement type, contributes to the increased durability of the concrete. The presence of fibers enhances concrete's resistance to deterioration and cracking, while carefully selecting the cement type improves performance in challenging environments.

Overall, these findings highlight the importance of considering concrete composition, including the incorporation of fibers and appropriate cement types, to enhance the durability of concrete structures, particularly in aggressive environments.

Acknowledgements

The authors thank the Directorate General for Scientific Research and Technological Development (D.G.R.S.D.T., Algeria). Thanks to the professors and student members of the Laboratory of Eco-Materials: Innovations & Applications (EMIA ex. LFGM).

Funding

The authors received no specific funding for this work.

Conflict of Interest

The authors declare that they have no conflicts of interest to disclose.

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