# Impact of Wetting and Drying Cycles on the Performance of Fiber-Reinforced High-Strength Concrete

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## *Abstract*

*One of the important causes of structural deterioration in concrete structures subjected to a saline or maritime environment is chloride-induced reinforcement corrosion, which manifests as spalling, cracking, and delamination of the concrete cover. In addition, the loss of the link between the concrete and the reinforcement and the reduction in the cross-sectional area of the rebar may lead to additional damage to a corroded reinforced concrete element. Therefore, the samples were submerged in a solution of sodium chloride (NaCl), sodium sulfate (Na2SO4), and magnesium sulfate (MgSO4) to start the damaging process and achieve the anticipated chloride penetration. This study then examines wet-dry cycles (WDC) for 180-d. The volume fractions of date palm fibre (DF), polypropylene fibre (PF), and steel fibre (SF) of 0%, 0.2%, 0.6%, and 1.0%, respectively, were utilized for the fabrication of high-strength fibre-reinforced concrete (HSFRC). The crucial structural characteristics were assessed in this investigation, i.e., compressive strength, flexural strength, density, water absorption capacity, and load-displacement behaviour. The test results indicated that as the fibre contents increased under WDC exposure, the compressive strength of the high-strength concrete (HSC) with DF, PF, and SF increased by 25%, 27%, and 25%, respectively. Flexural strength increased by 37%, 28%, and 57%, respectively. The displaceability ductility, deformability, and energy ductility of the DF, PF, and SF-reinforced HSC were noticeably enhanced with the application of WDC. Hence, the natural DF fibres might be suitable to construct sustainable HSC and be applicable to protect against harsh weathering conditions compared to the PF and SF.*

***Keywords:*** fibre reinforced high-strength concrete; wet-dry cycles; ductility; deformability.

## 1. INTRODUCTION

The Arabian Gulf region has experienced rapid industrialization and extensive infrastructure development over the last 30 years (Williams, 2022). This growth has led to the widespread use of concrete in various structures. However, the region's harsh environmental conditions—high temperatures, extreme humidity, and challenging climates—greatly affect the durability of concrete (Ahmmad et al., 2016; Hosen, Jumaat & Islam, 2015). Durability, or the ability of concrete to resist environmental damage without major repairs, is essential in such conditions (Ma et al., 2017; Hakeem et al., 2022; Azad & Hakeem, 2016). A key challenge in the region is Sabkha soil, a highly saline soil found in coastal areas, which severely threatens concrete structures, particularly underground ones. Sabkha soil contains high levels of chloride and sulfate ions, which are highly corrosive (Hakeem et al., 2023). The salinity of Sabkha soil is much higher than seawater, causing physical and chemical damage to concrete. Sulfate attacks, in particular, accelerate the deterioration of concrete foundations (Hakeem et al., 2023). The fluctuating groundwater levels in Sabkha regions create an aggressive environment that leads to cracking and weakening of concrete structures over time (Ye et al., 2013).

Additionally, the Gulf region's extreme climatic conditions further exacerbate the problem. Summer temperatures can reach 50°C, while winter temperatures drop to as low as 2°C (Qaidi et al., 2023). Coastal areas experience high humidity, up to 80% at night, exposing concrete to repeated cycles of wetting and drying (WDC). These cycles worsen concrete degradation, particularly when combined with salt-laden groundwater (Qaidi et al., 2023). The evaporation during drying concentrates ions within the concrete, leading to expansion and cracking. In coastal and marine environments, concrete also faces sulfate attacks from sulfate-contaminated water, which forms compounds like gypsum and ettringite, causing cracks and weakening the structure (Gao et al., 2013; Ye et al., 2012). This process is accelerated in areas affected by WDC, where continuous wet-dry cycles increase ion penetration, speeding up corrosion. Research shows that WDC leads to faster deterioration of concrete than constant water submersion (Guo et al., 2019). In conclusion, the harsh environmental conditions and Sabkha soil in the Gulf region present serious challenges to concrete durability. Further research is needed to understand the effects of WDC and improve the longevity of concrete, especially when incorporating fibres like DF, PF, and SF.

## 2. MATERIALS AND METHODS

### 2.1. Materials

The high strength concrete (HSC) samples incorporating Date Fibre (DF), Polypropylene Fibre (PF), and Steel Fibre (SF) in this study were produced using standard Type-I Portland cement. The cement, certified by the manufacturer and in accordance with ASTM C 150, contained 59% C3S, 12.10% C2S, 10.60% C3A, and 10.40% C4AF (ASTM, 2022). Natural dune sand, used as a fine aggregate, had most of its particles pass through a 4.75 mm sieve, while crushed stone with a maximum size of 20 mm served as coarse aggregate for the fibrous concrete (Hakeem, Althoey & Hosen, 2022). Glenium® 110M, a polycarboxylate ether-based superplasticizer, was used to reduce water content, and filtered tap water played a critical role in mixing and curing the high-strength concrete, adhering to ASTM C1602/C1602M standards (ASTM International, 2018). DF fibres, Figure 1a, were sourced from 15 to 25-year-old trees in Najran, Saudi Arabia, which produce large amounts of agricultural waste. These fibres grow in two to three tightly packed layers around the trunk of the tree. To improve the compatibility of DF fibres with other concrete components, they were chemically treated with sodium hydroxide (NaOH) at different concentrations to remove impurities like lignin, wax, and oils. This process disrupts hydrogen bonding within the fibres' structure and increases surface roughness. DF fibres were soaked in NaOH solutions of 1.5%, 3.0%, and 6.0% for 24 hours at room temperature, with 3% NaOH yielding the highest tensile strength. Tensile strength testing of DF fibres, as per ASTM D3379-75, was conducted on 20 single-fibre samples using a Universal Testing Machine. The diameter of each fibre was measured along its gauge length with a Vernier caliper, and SEM analysis was used to examine the fibre morphology. The 3% NaOH treatment provided optimal tensile strength, as demonstrated in Figure 2.


Figure 1: Fibers utilized in the study: a) DF, b) PF, and c) SF

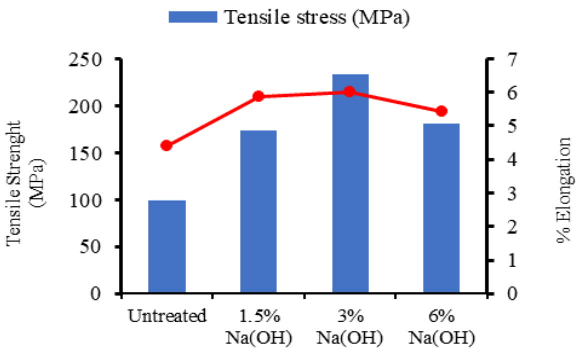



Figure 2: Tensile strength results of DF fibre before & after chemical treatment

The high-strength fibrous concrete was made using PF for comparison with DF and SF. The physical properties of PF and SF, provided by the manufacturer, are detailed in Table 1. PF fibres used in the experiment are shown in Figure 1b, while SF, hooked at both ends and bundled with adhesive, is depicted in Figure 1c.

Table 1: PF and SF's physical characteristics

| | Properties of Fibres | | | | | |
|---|---|---|---|---|---|---|
| Fibres | Length (cm) | Diameter (cm) | Density (g/cm$^3$) | Young Modulus (GPa) | Elongation at Breaking (%) | Tensile Strength (MPa) |
| PF | 1.2 | 0.0025 | 0.91 | 5.4 | 30 | 550 |
| SF | 6 | 0.075 | 7.85 | 205 | 1.95 | 625 |

### 2.2. Methodology

To evaluate the performance of DF, PF, and SF in high-strength concrete, various tests were conducted. Fibres were mixed with concrete at volumes of 0.2%, 0.6%, and 1.0% to produce ten mixtures of HSFRC, as shown in Table 2. The testing program included cubes (100 mm), cylinders (150 mm x 300 mm), and prisms (100 mm x 100 mm x 500 mm) to assess hardened properties over 180 days. After 28 days of water curing, samples were exposed to WDC conditions, including immersion in aggressive NaCl Sabkha soil, typical of the Gulf Region's tidal zones. This soil contains chlorides and sulfates, leading to concrete deterioration.

Table 2: Mix proportion for HSFRC (Source: Hakeem et al., 2023)

| Proportion (Kg/m$^3$) | | Mix ID | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | REF | DPF0.2 | DPF0.6 | DPF1.0 | PPF0.2 | PPF0.6 | PPF1.0 | SF0.2 | SF0.6 | SF1.0 |
| Fibres | DF | / | 8 | 24 | 40 | / | / | / | / | / | / |
| | PP | / | / | / | / | 8 | 24 | 400 | / | / | / |
| | Steel | / | / | / | / | / | / | / | 8 | 24 | 40 |
| Aggregates | Fine | 736.9 | 736.9 | 736.9 | 736.9 | 736.9 | 736.9 | 736.9 | 736.9 | 736.9 | 736.9 |
| | Coarse | 1105.4 | 1105.4 | 1105.4 | 1105.4 | 1105.4 | 1105.4 | 1105.4 | 1105.4 | 1105.4 | 1105.4 |
| Cement | | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 |
| Water | | 176.4 | 176.4 | 176.4 | 176.4 | 176.4 | 176.4 | 176.4 | 176.4 | 176.4 | 176.4 |
| SP | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

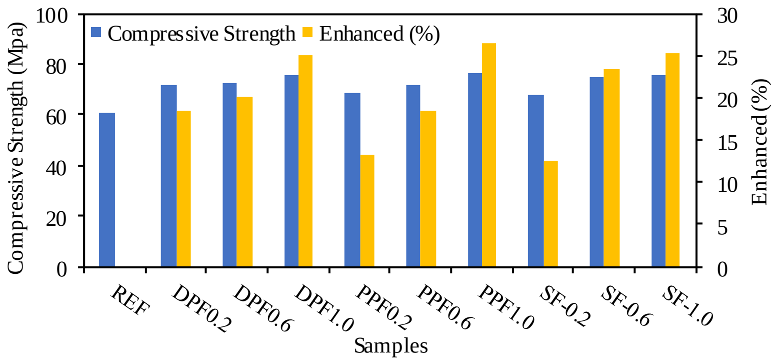
The first cycle involved immersing samples in a solution of NaCl, sodium sulfate (Na2SO4), and magnesium sulfate (MgSO4) with a concentration of 15.7% Cl- and 0.55% SO4- for two days. Samples were then dried for two days at 25 ± 5ºC. This wetting-drying cycle was repeated for approximately 45 cycles, with the soil being monitored and replaced every 30 days to maintain consistent concentration. The compressive strength, flexural strength, hardened density, water absorption, and load-displacement behavior of the samples were measured after this exposure cycles.

## 3. RESULTS AND DISCUSSIONS

### 3.1. Compressive strength

Figure 3 illustrates the impact of WDC on the compressive strength of HSC with varying fibre content (0% to 1%) of DF, PF, and SF. The HSC without fibres had a compressive strength of about 60 MPa. Adding these fibres increased the strength, with PF fibres showing the highest improvement due to better adhesion in the matrix. However, WDC had minimal influence on the compressive strength. Natural DF fibres may offer a more sustainable option for reinforcing concrete.

Figure 3: Influence of WDC on the compressive strength of fibres containing concrete




### 3.2. Flexural Strength

Figure 4 shows the impact of varying fibre content (0% to 1%) of DF, PF, and SF on the flexural strength of HSC under WDC. The flexural strength of HSC without fibres was 7.23 MPa, while DF, PF, and SF-reinforced samples exceeded 8.5 MPa, except for DPF1.0. SF-reinforced HSC exhibited the highest flexural strength, with a 57% increase. Overall, flexural strength improvements were significant, reaching up to 85% for DF, 79% for PF, and 165% for SF compared to the reference sample without implementing WDC (Althoey et al., 2022).

### 3.3. Density

Figure 5 demonstrates the relationship between density and compressive strength of HSC with DF, PF, and SF fibres (0%, 0.20%, 0.60%, and 1.0%) under WDC. While SF reinforced samples showed an increase in density, DF and PF-reinforced samples experienced a gradual density reduction as fibre content increased. However, compressive strength increased with higher fibre content under WDC. At 1.0% fibre content, DF slightly increased density, while PF reduced it by 1%. In contrast, SF increased the density by 1% compared to reference samples.

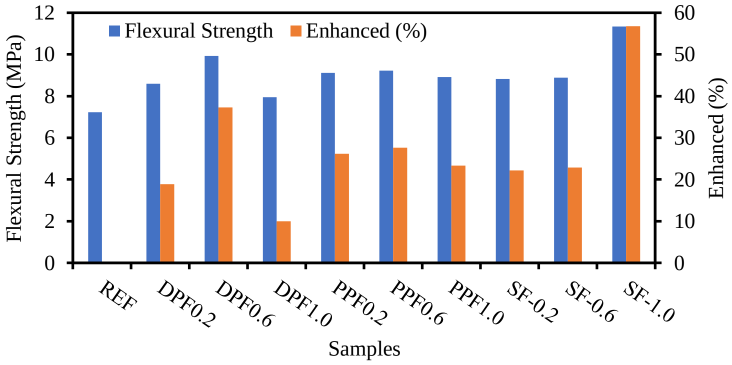



Figure 4: Impact of WDC on the flexural strength of different fibre-reinforced concrete

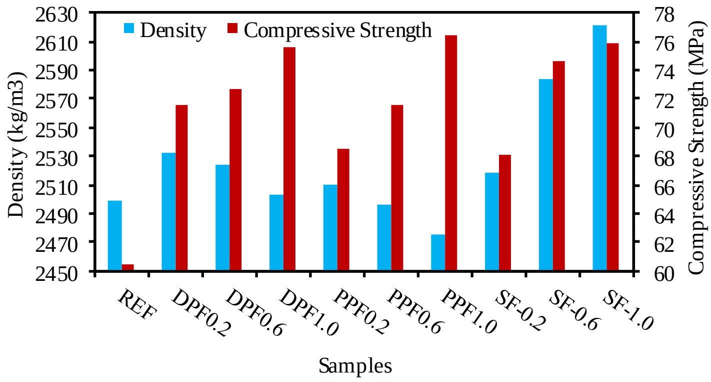



Figure 5: Influence of WDC on the density of fibrous HSC

## 3.4. Water Absorption Capacity

Concrete's serviceability largely depends on its durability (Azevedo et al., 2021), which is closely related to its permeability. Permeability refers to the ability of fluids to pass through concrete's microstructure, and high permeability allows harmful molecules to enter and compromise chemical stability. Low permeability improves concrete's resistance to water, sulfate, chloride, alkali ions, and other chemical attacks (Zhang & Zong, 2014). The total pore system volume of concrete can be measured by the amount of water absorbed during immersion (De Schutter & Audenaert, 2004). Under WDC, HSC with DF, PF, and SF fibres absorbed more water than reference samples. The fibres increased micro-pores around the paste, enhancing water absorption, particularly in DF-reinforced concrete, which saw up to a 36% increase, shown in Figure 6.

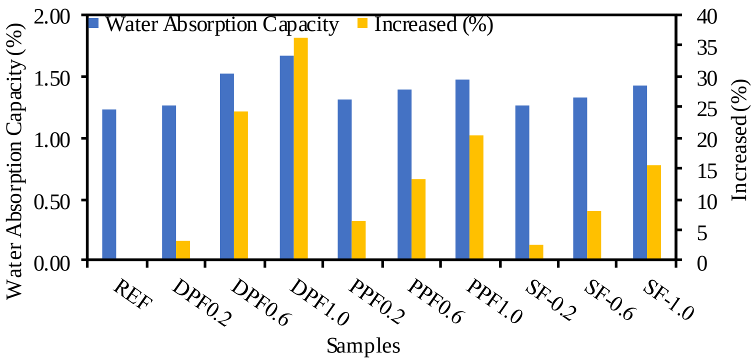



Figure 6: Water absorption capacity of fibre-reinforced concrete under WDC

## 3.5. Load-displacement Behaviour

Figure 7 illustrates the load-displacement behavior for DF, PF, and SF at the mid-span of prism samples. Under WDC, the load-displacement characteristics of the DF, PF, and SF-reinforced HSC samples were similar to the reference sample (REF), except for SF-1.0. The graphs initially rise linearly up to the yield point, followed by a steeper slope until the ultimate load. SF-1.0 showed distinct damage behavior in the plastic phase due to its higher tensile strength. Increased fibre content (0.2%, 0.6%, 1%) reduced displacement by improving flexural rigidity, effectively controlling cracks. These results support the use of fibre-reinforced samples for structural elements in harsh conditions.

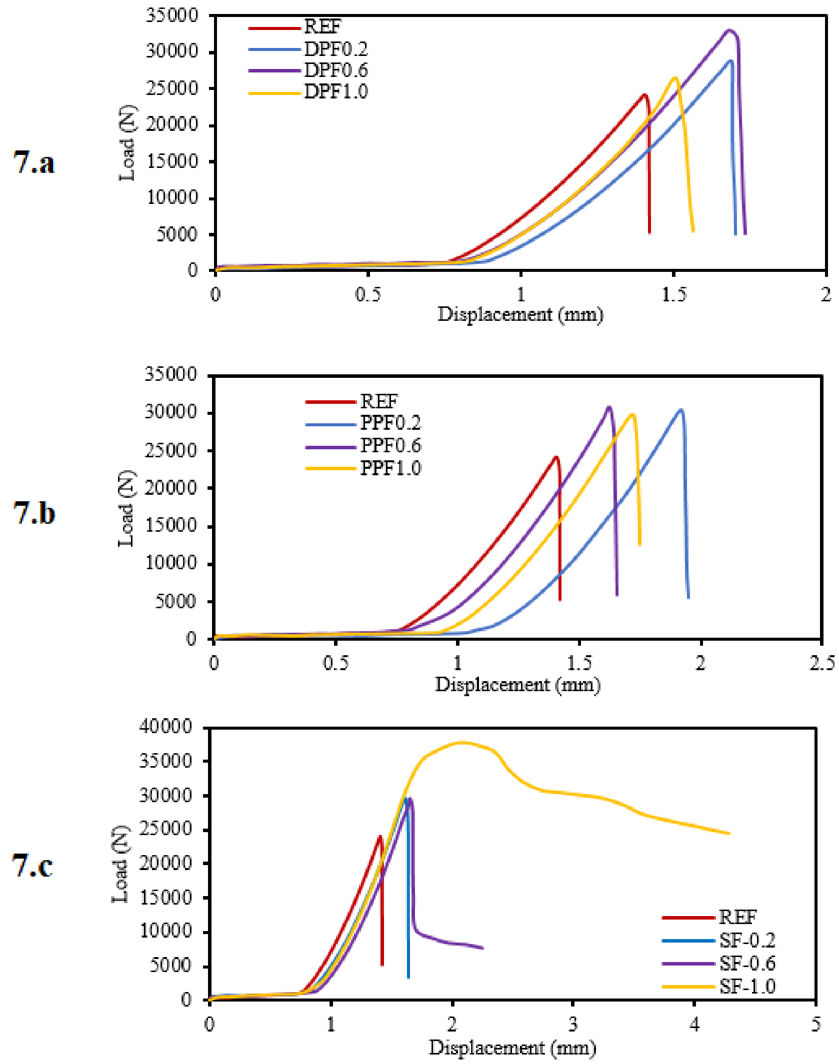



Figure 7: Load versus displacement behaviour of different fibres reinforced concrete: (a) DF fibres, (b) PF fibres, (c) SF

### 3.6 Ductility

The study examines three types of ductility in HSC reinforced with DF, PF, and SF: displacement, deformability, and energy ductility. Results show that HSC containing DF, PF, and SF improves displacement ductility, with SF showing the greatest resistance post-cracking. This enhancement allows structures to endure large deformations without failure. Deformability was also improved, particularly with SF, showing a 115% improvement compared to reference samples, while PF reduced deformability, except in certain concentrations. The study suggests that DF and SF fibers are more suitable for handling deformability challenges in harsh weather conditions than PF. Regarding energy ductility, the fibers improved performance, with SF showing the highest enhancement (up to 250%), due to better bonding and resistance under weathering conditions. DF and PF showed less improvement in energy ductility, as they lacked the homogeneity of SF. Overall, the study confirms that incorporating DF, PF, and SF into HSC enhances its ductility properties, especially SF, which performs the best across all categories.

## 4. CONCLUSIONS

The impact of WDC on HSC incorporating DF, PF, and SF, was explored to support sustainable construction practices. Fibre volume fractions of 0%, 0.2%, 0.6%, and 1.0% were applied to create HSFRC, with key structural properties such as compressive and flexural strength, density, water absorption, load-displacement behavior being examined. The study findings revealed that increasing fibre content, combined with WDC, led to significant improvements in compressive strength. When

DF, PF, and SF were increased to 1.0%, compressive strength rose by 25%, 27%, and 25%, respectively, over the standard sample. Flexural strength also improved significantly with the incorporation of WDC and fibres. At 1.0% fibre content, DF, PF, and SF enhanced flexural strength by 37%, 28%, and 57%, respectively, compared to the reference. While DF and PF fibres reduced density due to their lightweight nature, SF increased density due to its higher unit weight. Fibre inclusion also raised water absorption, attributed to micropore formation within the concrete. Regarding load-deflection behavior, increasing fibre content resulted in reduced deflection. These findings indicate that natural DF fibres offer significant potential for enhancing sustainable HSC, particularly in protecting against severe weather conditions, outperforming PF and SF fibres.

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