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Durability assessment of high-performance concrete reinforced with waste steel fibres

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Research Paper

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Durability assessment of high-performance concrete reinforced with waste steel fibres

Durability and sustainability are critical objectives in modern concrete research due to the increasing demand for cost-effective and environmentally friendly construction materials. While incorporating waste steel fibers into concrete has shown promise in enhancing mechanical properties, their impact on durability requires further investigation. This study evaluates the durability performance of high-performance concrete (HPC) reinforced with waste steel fibers sourced from building waste and recycled tires. Key durability parameters, including sorptivity, chloride penetration, and carbonation resistance, were analyzed under aggressive environmental conditions. Advanced characterization techniques, such as Fourier-transform infrared spectroscopy (FTIR) and thermogravimetric analysis (TGA), were employed to assess mass loss and provide insights into material behavior. The findings contribute to a deeper understanding of how waste steel fibers influence the long-term performance of sustainable concrete materials.

Key words:
high-performance concrete, waste steel fibers, sorptivity, chloride penetration, durability

Prethodno priopćenje

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Procjena trajnosti visokoučinkovitog betona s dodatkom otpadnih čeličnih vlakana

Trajnost i održivost ključni su ciljevi u suvremenim istraživanjima betona zbog sve veće potražnje za ekonomičnim i ekološki prihvatljivim građevinskim materijalima. Iako je ugradnja otpadnih čeličnih vlakana u beton pokazala potencijal u poboljšanju mehaničkih svojstava, njihov utjecaj na trajnost zahtijeva dodatna istraživanja. Ovo istraživanje procjenjuje svojstva trajnosti betona visokih uporabnih svojstava (engl. *high-performance concrete* - HPC) ojačanog otpadnim čeličnim vlaknima dobivenim iz građevinskog otpada i recikliranih guma. Ključni parametri trajnosti, uključujući vodoupojnost, prodor klorida i otpornost na karbonaciju, analizirani su pod agresivnim uvjetima okoliša. Napredne tehnike karakterizacije, poput Fourierove transformacijske infracrvene spektroskopije (FTIR) i termogravimetrijske analize (TGA), korištene su za procjenu gubitka mase i pružanje uvida u ponašanje materijala. Dobiveni rezultati doprinose dubljem razumijevanju kako otpadna čelična vlakna utječu na dugoročne performanse održivih betonskih materijala.

Ključne riječi:
beton visokih performansi, otpadna čelična vlakna, vodoupojnost, prodor klorida, trajnost

1. Introduction

The construction industry continually seeks efficient and sustainable solutions to enhance material performance. Concrete is one of the most fundamental construction materials owing to its favourable mechanical properties, particularly compressive strength; however, it is inherently brittle and exhibits limited tensile strength, in addition to being susceptible to environmental stresses. To address these limitations, researchers have explored the use of different types of fibres to improve the ductility and durability of concrete. The incorporation of fibres into concrete enhances its mechanical resistance. High-performance concrete (HPC) is specifically designed to achieve superior durability in conjunction with improved mechanical properties.

The primary role of fibres in concrete is to increase energy absorption capacity and to maintain load-bearing capability after initial cracking. Fibres act as bridges across cracks, inhibiting crack propagation and enhancing overall structural integrity, as reported in [1, 2]. In ultra-high-performance fibre-reinforced concrete (UHPFRC), steel fibres control crack development, reduce stress concentration, and improve energy absorption prior to failure [3]. Numerous studies have investigated the influence of fibres on concrete durability. Durability assessment involves consideration of factors such as permeability. Capillary suction is therefore a key parameter influencing the durability of reinforced concrete structures. Notably, the application of water-repellent treatments has been shown to substantially reduce capillary suction [4]. Driven by pressure differentials, represents another pathway for chloride ingress, while absorption remains a common transport mechanism [5].

One of the most critical factors affecting concrete durability is the ingress of aggressive agents that lead to the degradation of cementitious bonds; consequently, chloride diffusivity is a key parameter governing the durability of such structures [6]. Protective formulations are commonly incorporated into concrete to safeguard reinforcing bars against the ingress of corrosive substances, such as chlorides or sulfates, particularly in marine environments. Improving the quality of the concrete cover, for example, by reducing the water-to-binder ratio or incorporating supplementary cementitious materials, not only enhances mechanical performance but also significantly improves overall durability [7]. The porosity of concrete and the presence of stress-induced cracks play a major role in facilitating the transport of aggressive substances within the material. Accordingly, the chloride transport properties of concrete, including permeability and diffusion, are influenced by several factors, such as concrete quality, environmental exposure conditions, and the presence of stress or cracking [8].

The chloride diffusion coefficient increases with the expansion of crack areas as damage intensifies [9]. Crack characteristics, including tortuosity, depth, and width, have been shown to significantly influence chloride ion penetration, with crack width having a particularly pronounced effect [7]. It has also been reported that steel fibres embedded in cracked ultra-high-performance concrete (UHPC) undergo corrosion during prolonged immersion in NaCl solutions, with the extent of corrosion increasing proportionally with immersion duration [10]. Chloride diffusivity in concrete can be assessed through exposure to salt solutions using immersion or ponding tests [6]. A standard testing procedure involves soaking for 8 h followed by drying in an oven at 65 °C for 8 h, yielding a total cycle duration of 32 h. In freeze–thaw testing, the soaking medium is typically a 5 % sodium sulfate solution, with the solution depth maintained at 5 mm between the frozen surface and the liquid surface of the specimen [11]. When the surface of a porous material comes into contact with a wetting liquid, the liquid is absorbed through capillary action.

Numerous studies have been conducted to evaluate chloride absorption in concrete. Accelerated laboratory tests, including electrical resistivity, migration coefficient, charge flow rate, and diffusion coefficient obtained from immersion tests, indicate that ultra-high-performance fibre-reinforced concretes exhibit lower resistance to chloride penetration than fibre-free reference concretes [12]. Moreover, Augustino *et al.* observed that increasing fibre content, particularly through the use of recycled steel fibres, tends to increase the sorptivity coefficient, likely due to enhanced microvoid formation and reduced matrix compactness [13]. Hwang *et al.* reported that chemical degradation may occur in concrete containing steel fibres, as their presence can significantly increase the number of air voids and/or overall porosity [14].

The duration of immersion significantly influences the absorption of aggressive solutions and, consequently, concrete degradation. Prolonged exposure to corrosive environments, particularly when combined with higher fibre contents, accelerates strength reduction in UHPFRC. This loss of strength is attributed to fibre dissolution, cracking, and damage to the concrete matrix, especially under severe exposure conditions [3].

From a durability perspective, studies have shown that incorporating an optimal amount of steel fibres enhances concrete resistance to carbonation; however, it can adversely affect permeability resistance in composites reinforced with nano-SiO_2 [15]. At the microstructural level, Zhang *et al.*, based on scanning electron microscopy (SEM) analysis, reported that steel fibres improve the interfacial transition zone (ITZ) between aggregates and mortar, leading to enhanced compaction and overall microstructural refinement of concrete [16].

Although previous studies have reported improvements in durability, such as reduced permeability and enhanced carbonation resistance, resulting from fibre incorporation, few have integrated durability indicators with detailed microstructural and chemical characterisation techniques, including SEM, Fourier-transform infrared spectroscopy (FTIR), and thermogravimetric analysis/differential thermal analysis (TGA/DTA), when investigating waste steel fibres. Moreover, the influence of fibre type (waste tyre fibres and building waste fibres) on the internal structure, particularly with respect to the morphology of hydration phases and carbonation resistance, remains insufficiently explored.

This study aims to evaluate the effects of recycled waste steel fibres derived from construction debris and used tyres on the durability of HPC under aggressive environmental conditions. Durability was assessed using sorptivity and carbonation tests, complemented by TGA, DTA, and FTIR. The findings provide insight into the potential of recycled steel fibres as a sustainable alternative for advanced concrete applications.

Table 1. Chemical composition of Portland cement (%)

Al_2O_3	SO_3	SiO_2	CaO	MgO	Fe_2O_3	K_2O	LOI
6.40	1.80 – 3.00	20.05	61.23	1.20- 3.00	3.45	0.01 – 0.05	0.50 – 3.00

Table 2. Fibre properties

Type	**L** [mm]	**D** [mm]	**Volume** [%]	**Elasticity modulus** [GPa]	**Tensile strength** [MPa]
Steel fibres from waste tyres	30	1.36	2	220	850.33
Steel fibres from building waste	30	1.34	2	215	675.73

2. Materials and methods

Portland cement Type II was used as the primary binder. The chemical composition of the cement is presented in Table 1. Locally sourced sand (0/4 mm) and gravel (3/8 mm) were used as fine and coarse aggregates, respectively, in accordance with the European standard EN 12620. The particle size distribution of the aggregates is shown in Figure 1.

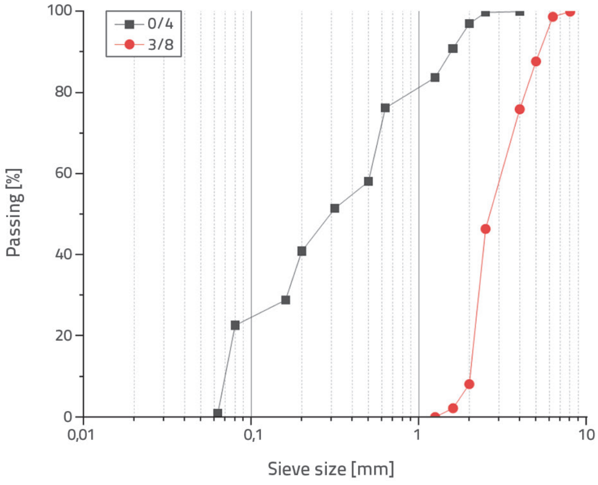

Figure 1. Particle size distribution of fine and coarse aggregates

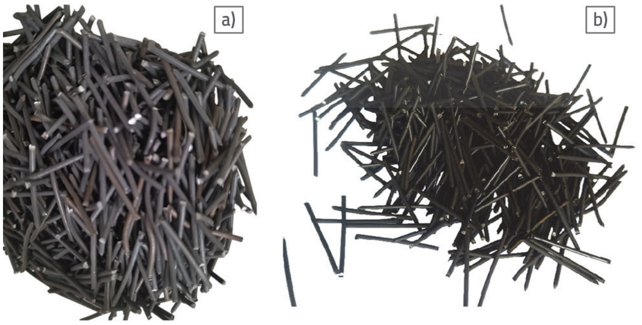

Figure 2. Waste steel fibres: a) waste tires fibres, b) building waste fibres

A key focus of civil engineering research is to address material inadequacies, and promoting the use of locally sourced construction materials represents an effective strategy [17]. Accordingly, recycled steel fibres with a length of 30 mm and a diameter of 1 mm, obtained from discarded automobile tyres and construction steel residues, were used in this study. The physical properties of both fibre types are summarised in Table 2. Figure 2 shows the physical appearance of the fibres, while Figure 3 presents SEM images illustrating their surface morphology and texture.

Prior to use, the fibres were manually cleaned and cut to an approximate length of 30 mm. It should be noted that the extraction of steel fibres from waste car tyres involves burning the tyres to remove rubber and recover the embedded steel wires. The recovered fibres are subsequently cleaned to remove residual contaminants before incorporation into the concrete mixtures. The fibre content was fixed at 2 % by volume of concrete. A superplasticiser dosage of 1 % by weight of binder was added to ensure adequate workability of the concrete.

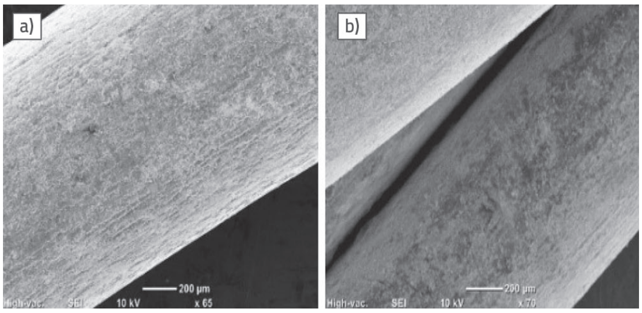

Figure 3. SEM analysis of steel fibres: a) Waste tire fibres; b) Building waste fibres

The dry materials were mixed for 2 min, after which water and superplasticiser were added and mixed for an additional 2 min at medium speed. Fibres were then gradually incorporated and mixed for 3 min to ensure uniform distribution.

Three concrete mixtures were prepared: one with waste tyre fibres, one waste building with steel fibres, and a reference mix without fibres for comparison. The ingredients were thoroughly combined and cast into 4 × 4 × 16 cm molds. After 24 h, the molds were removed, and the specimens were cured by immersion in water for 90 days at 20 °C in the EMIA/LFGM Research Laboratory, Bechar, Algeria. The concrete mix compositions are presented in Table 3.

Table 3. Concrete mix composition

Composition	(D1)	(D2)	(D3)
Cement [kg/m³]	400	400	400
Sand [kg/m³]	665	665	665
Gravel [kg/m³]	1111	1075	1075
Water [kg/m³]	148	148	148
Superplasticizer [%]	1.75	1.75	1.75
Fiber volume [%]	-	2	2
W/C ratio	0.37		

*D1: Concrete reference without fibres
D2: Concrete with waste tyre fibres
D3: Concrete with building with fibres

2.1. Sorptivity test

The sorptivity test conducted on concrete specimens provides valuable insight into the pore structure of concrete. Low sorptivity values indicate high-quality concrete with enhanced resistance to water absorption [18]. This test is essential for evaluating concrete durability and permeability, as excessive water absorption can lead to freeze–thaw damage, corrosion of reinforcing steel, and overall material deterioration. The sorptivity test, performed in accordance with ASTM C1585 [14], measures the rate at which water is absorbed by porous materials such as concrete.

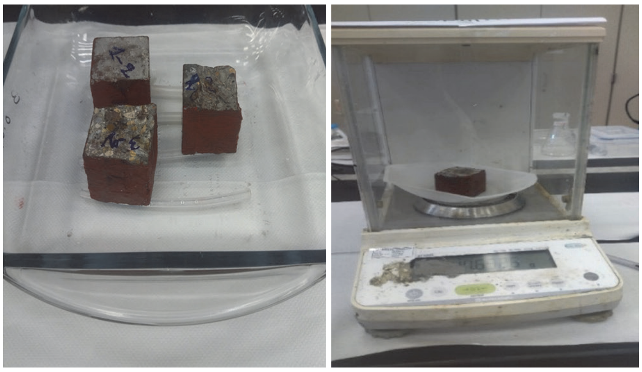

Figure 4. Sorptivity test setup

Figure 4 illustrates the experimental setup for the sorptivity test. Initially, concrete cubes with dimensions of 40 × 40 × 40 mm were dried in an oven at 105 °C for 24 h. Four surfaces of each cube were sealed with wax [4]. The initial mass was recorded, after which three specimens were immersed in water and three specimens in a 5 % NaCl solution to a depth of 5–10 mm. The specimens were removed at predetermined intervals, and the amount of absorbed liquid was measured over exposure times ranging from 5 min to 3 days. This procedure provides quantitative information on the absorption behaviour of concrete and supports the assessment of its overall quality. The symbols and references used in the text correspond to those defined in Equation (1):

$$S = \Delta W / (A \cdot \sqrt{t}) \qquad (1)$$

where:
S - sorptivity coefficient $[g/(cm^2.\sqrt{min})]$
ΔW - the weight gain [g]
A - the cross-sectional area of the exposed surface (cm^2),
T - the time of exposure [min].

2.2. Carbonation test

The carbonation test involved removing specimens from the solutions, followed by thorough drying. Each specimen was then precisely cut into two sections. Carbonation testing was conducted on one section after 1 day and repeated on the second section after 20 days. At each testing stage, the freshly exposed internal concrete surface was sprayed with a phenolphthalein solution. This procedure enabled the assessment and monitoring of carbonation behaviour at different exposure periods, providing insight into the chemical changes and progression of carbonation within the concrete.

2.3. SEM analysis

For SEM analysis, six specimens were prepared. Three concrete mixtures, reference concrete, concrete incorporating building waste steel fibres, and concrete incorporating recycled tyre steel fibres, were exposed to water and sodium chloride (NaCl) solution.

For SEM examination, the specimens were cut into small cubes with approximate dimensions of 1 × 1 × 1 cm. In addition, isolated steel fibres were analysed to enable fibre-specific observations. The analysis focused on microstructural features, including matrix–fibre bonding, porosity, and signs of degradation. SEM observations of both concrete specimens and fibres were carried out at the Centre for Advanced Materials (CAM), Qatar University, Doha, Qatar, using a versatile benchtop SEM. The operational configuration of the SEM system is shown in Figure 5.

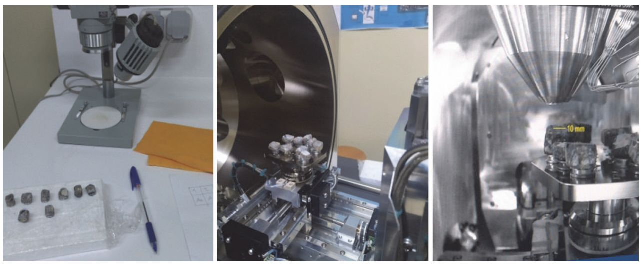

Figure 5. SEM analysis of specimens

2.4. TGA and FTIR analysis

TGA and FTIR analyses were performed at the Centre for Advanced Materials (CAM), Qatar University, Doha, Qatar, using a combined TGA–FTIR analyser (PerkinElmer). For TGA, 20 mg of powdered samples were heated from 25 °C to 650 °C under a nitrogen atmosphere at a heating rate of 20 °C/min. Sample and instrument preparation required approximately 1 h, and the analysis of each specimen took 32 min. FTIR spectra were recorded over a wavenumber range of 450–4000 cm^{-1}.

3. Results and discussion

3.1. Sorptivity

Figure 6 presents the sorptivity coefficients of specimens immersed in water. The results indicate that water absorption decreased progressively over time for all samples. Among the mixtures, concrete containing tyre steel fibres (D2) exhibited the highest sorptivity, absorbing the greatest amount of water over the test period, followed by concrete reinforced with building waste steel fibres (D3), and finally the reference concrete (D1), which showed the lowest absorption. This trend highlights the influence of fibre type on the water absorption characteristics of the concrete during submersion.

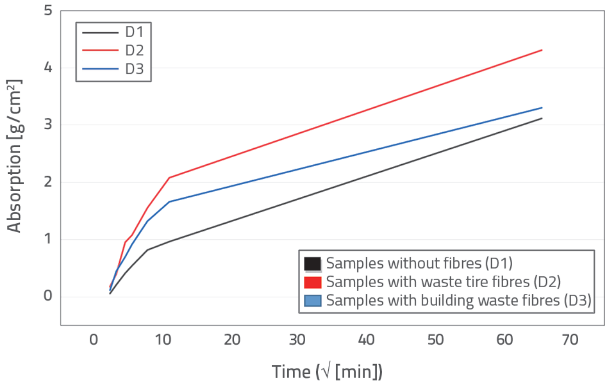

Figure 6. Sorptivity coefficients of samples immersed in water

For samples submerged in sodium chloride (NaCl), as shown in Figure 7, a pronounced absorption spike is observed at 5 min, which gradually decreases over time. This behaviour is attributed to the accelerating effect of sodium chloride on water absorption, resulting in increased concrete permeability. Concrete containing tyre fibres (D2) exhibited the highest absorption compared with samples reinforced with building waste fibres (D3). This trend is evident in the microstructure of tyre fibre-reinforced concrete (Figure 8), which shows pores around the fibres that facilitate solution diffusion into the concrete matrix.

In contrast, concrete containing building waste fibres (D3) displayed good adhesion between the fibres and the cement paste, as illustrated in Figure 9. High porosity of steel fibres may reduce the bond strength between the fibres and the surrounding concrete, potentially causing the fibres to behave independently from the concrete matrix under external loading [14]. Notably, after 3 days, absorption rates reached their minimum values in both water- and NaCl-submerged specimens. This decrease is likely due to the saturation of the concrete pores with the solution, which moderates further absorption over time.

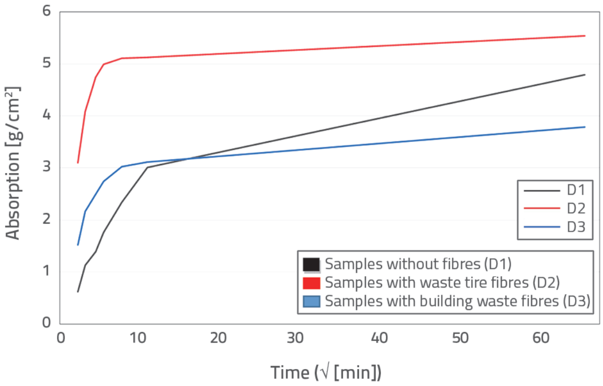

Figure 7. Sorptivity coefficients of samples immersed in NaCl solution

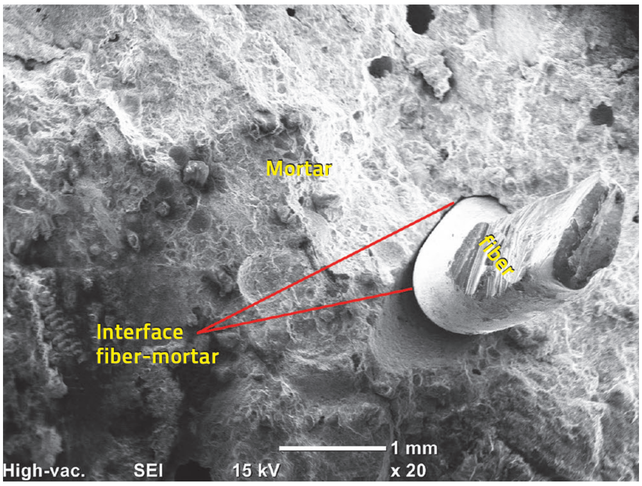

Figure 8. SEM analysis of concrete containing waste tyre fibres (D2) showing fibre–matrix adhesion

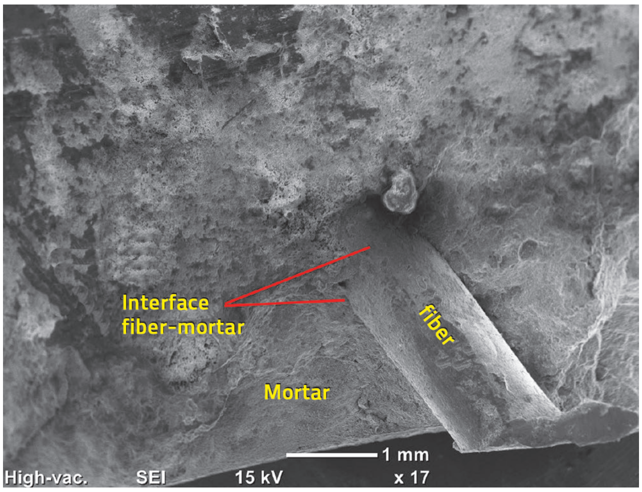

Figure 9. SEM analysis of concrete containing building waste fibres (D3) showing fibre–matrix adhesion

3.2. Carbonation

Carbonatation test after 1 day

Based on the visual assessment of the carbonation test images captured one day after the experiment (Figure 10), no violet coloration was observed upon the application of phenolphthalein solution in either the water-submerged or sodium chloride (NaCl)-submerged samples. The absence of violet colour indicates that carbonate formation had not occurred in the concrete samples under either condition within the first day.

Figure 10. Carbonation test 1 day after extraction from NaCl

Carbonatation after 20 days from sorptivity test

After 20 days, the carbonation test was performed on the remaining sections of the concrete samples, as shown in Figure 11. The samples submerged in water still showed no signs of carbonation. In contrast, the samples immersed in the sodium chloride solution exhibited complete carbonation. These findings confirm that chloride exposure accelerates carbonation, likely due to chloride-induced modifications of the pore structure and pH reduction. Additionally, the presence of steel fibres may influence carbonation susceptibility by affecting internal moisture retention and ionic diffusion.

Figure 11. Carbonation test 20 days after extraction from NaCl solution

3.3. TGA–DTA

Figure 12 presents the TGA of concrete samples with and without fibres (D1, D2, and D3) following exposure to sodium chloride (NaCl). The TGA curves show a gradual weight loss across the temperature range of 26–450 °C. This trend is further illustrated in Figures 13, 14, and 15, which display the DTA of the same samples. The weight loss observed between 25 and 170 °C is attributed to a combination of water evaporation and ettringite decomposition, with initial changes corresponding to ettringite dehydration at temperatures up to 90 °C. The calcium silicate hydrate (C–S–H) phase exhibits a minor reduction above 100 °C [20]. Beyond 450 °C, a marked increase in weight loss is observed, particularly in the D2 samples, exceeding that of D1 and D3. This behaviour indicates the decomposition of portlandite in these specimens, a phenomenon that is further highlighted in the DTA analysis shown in Figure 14, especially for the D2 samples.

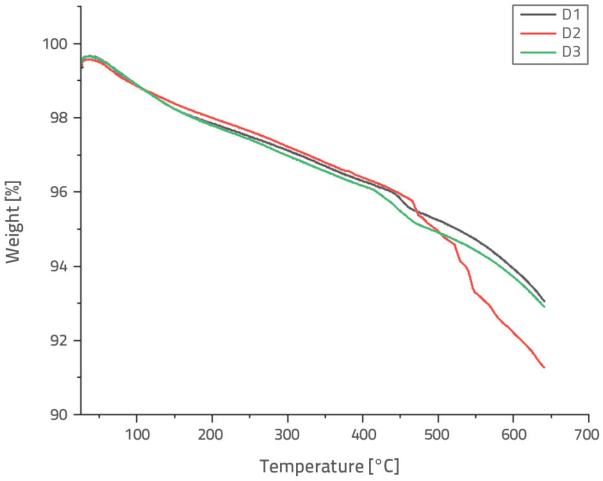

Figure 12. TGA analysis of D1, D2, and D3 following NaCl immersion

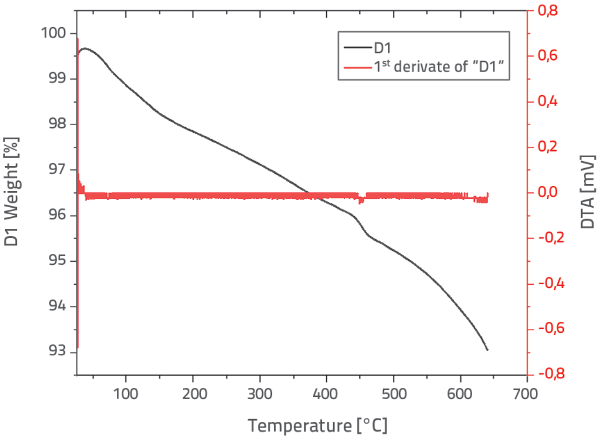

Figure 13. DTA analysis of D1 following NaCl immersion

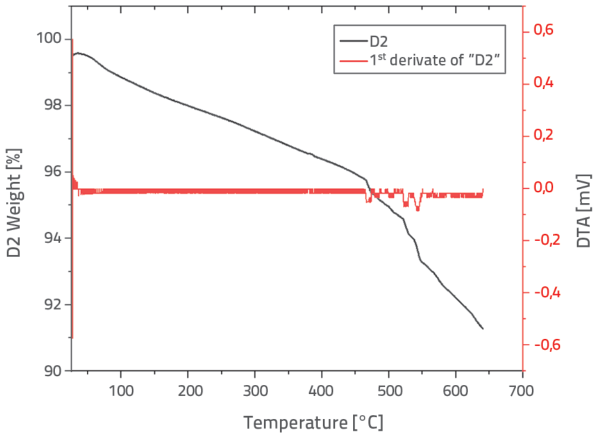

Figure 14. DTA analysis of D2 following NaCl immersion

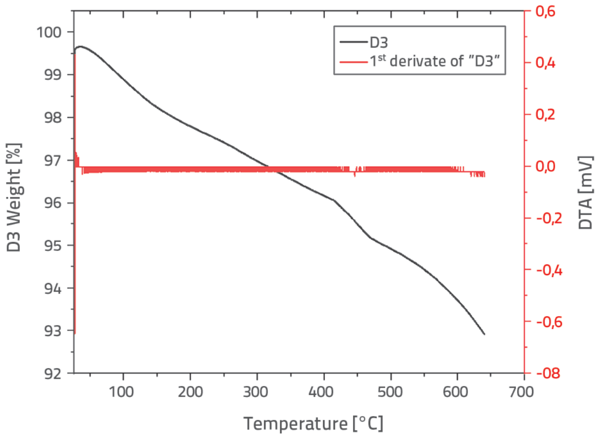

Figure 15. DTA analysis of D3 following NaCl immersion

3.4. Fourier transform infrared spectroscopy (FTIR) analysis

Figure 16 presents the FTIR analysis of concrete samples with and without recycled waste fibres after immersion in sodium chloride (NaCl). Distinct differences are observed in the wavenumber range of 2800–3400 cm^{-1}, corresponding to hydroxyl groups in water or mineral hydrates. In particular, the peak in the D3 samples is smaller but more pronounced than in D2 and D1 samples, indicating variations in composition. A similar trend is observed in the 1800–2500 cm^{-1} range. In contrast, in the 700–1600 cm^{-1} range, the D3 samples exhibit deeper absorption bands than D2 and D1. This region corresponds to silicate minerals in the concrete, with characteristic absorption bands, especially at 900–1000 cm^{-1}, confirming the presence of silica phases in the cementitious matrix [21].

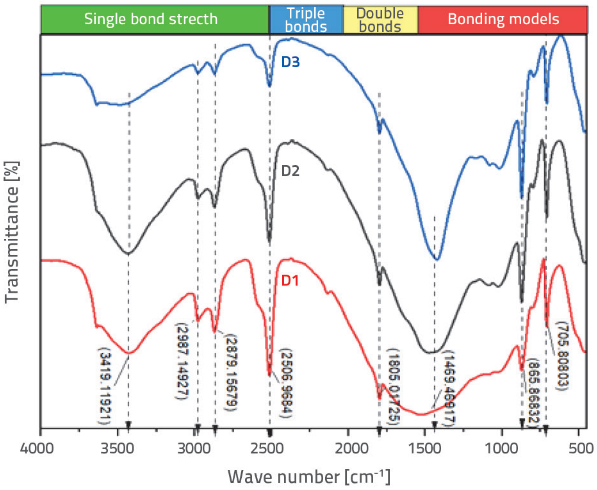

Figure 16. FTIR spectra of D1, D2, and D3 following NaCl immersion

4. Conclusion

This study investigated the effect of waste steel fibres and building waste fibres on the durability of concrete. The results show that fibre incorporation influences water absorption by creating pores that facilitate the diffusion of aggressive solutions. Concrete containing tyre fibres exhibited higher absorption than that with building waste fibres, highlighting the significant effect of fibre type on concrete properties.

Microstructural analysis using SEM revealed that concrete with building waste fibres developed a stronger fibre–matrix bond, effectively limiting chemical ingress. In contrast, concrete incorporating waste tyre fibres exhibited weaker interfacial bonding, increased porosity, and enhanced penetration of the sodium chloride solution. This chemical ingress led to degradation of the material due to the breakdown of cementitious compounds through reactions between hydration products and aggressive ions.

FTIR and TGA confirmed changes in hydration products and thermal stability. TGA revealed mass loss at higher temperatures, likely due to the decomposition of concrete paste components, while FTIR confirmed the presence of silicate minerals, providing additional insight into the concrete composition. Concrete samples exposed to sodium chloride solution were fully carbonated, indicating that the solution accelerates carbonation.

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