



Mechanical properties and durability of ultra-high performance concrete containing steel fibers

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ABSTRACT

This study investigates the long-term mechanical, physical, and durability properties of ultra-high performance concrete (UHPC) with steel fiber addition. Tests included porosity, water absorption, density, compressive, tensile, and flexural strength, fracture energy, energy absorption, toughness indices, static and dynamic elastic moduli, ultrasonic pulse velocity (UPV), and frost resistance. Digital image correlation (DIC) was used to analyze cracking, damage progression, and failure modes. Steel fiber reinforcement significantly enhanced compressive strength at 730 days and flexural and splitting tensile strengths at 28, 56, and 730 days. Notable gains in fracture energy and energy absorption were observed at 28 days. Slight improvements in elastic moduli and slight reductions in UPV were recorded for fiber-reinforced mixes. After 180 freeze–thaw cycles, increased mass loss was noted with higher fiber content, indicating reduced frost resistance, likely due to higher porosity and water absorption compared to fiber-free UHPC. The results demonstrate that durable UHPC can be produced without heat treatment or high-pressure compaction, using coarse aggregate, natural sand, and standard-grade steel fibers. This approach offers a practical and economical alternative for UHPC production with enhanced long-term mechanical performance.

1. Introduction

Ultra-high performance fiber reinforced concrete (UHPFRC) is a new cement-based material characterized by a low water-to-binder ratio of 0.2 or less, an aggregate with a diameter of less than 1 mm, a compressive strength greater than 120–150 MPa, a tensile strength and a flexural strength exceeding 7 MPa, high toughness and excellent ductility in flexure and tensile [1–4]. Ultra-high performance concrete also has low water absorption and permeability, as well as great frost resistance, which results in its exceptional durability [5,6]. Furthermore, the mixture retains its pump ability and high workability despite the low water-to-binder ratio [7,8]. Ultra-high performance steel fibers reinforced concrete (UHPSFRC) is progressively used in high-rise buildings, long-span bridges and prestressed girders, and the demand for its excellent properties is growing with the development of the construction industry [9–11]. The outstanding strength of UHPSFRC reduces the weight of the structure, which can be reduced to up to 50 % of the weight of conventional reinforced concrete constructions functioning in the same load conditions [12]. UHPSFRC is considered a promising structural material exposed to impacts and explosions because of its excellent energy absorption capacity, strength and

deformability with multi-cracks [1].

The performance of UHPFRC depends primarily on the quality of the aggregate, the pore structure in the cement matrix, the quality of the aggregate as well as the bond strength between the matrix and aggregate in addition to the fiber and matrix. The weakest area of the composite is the contact surface, which can be strengthened, among others, by pressing, using aggregate with a diameter of less than 0.6 or reducing the water-to-binder ratio. UHPSFRC are not often used due to the high production costs in comparison with ordinary concrete and the requirement for large quantities of cement. Therefore, recently cement supplementary materials have been introduced into the UHPSFRC, such as microsilica, granulated ground blast furnace slag, fly ash, palm oil fuel ash, metakaolin, or even used foundry sand, which reduce the production cost, carbon footprint and at the same time improve some of its properties [2,4,13,14]. The addition of high-performance superplasticizers in an amount of up to 5 % by weight of cement is necessary to obtain appropriate workability. Researchers [1,3,15–17] report several ways to lower the costs of UHPSFRC without significantly impacting the quality of the material, namely eliminating or lowering:

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- the fraction of high-strength steel fibers up to 2.5 % with an aspect ratio in the range of 40–60,
- particles with dimensions smaller than 1 mm and their partial replacement with coarse aggregate,
- thermal hardening at 90 °C,
- expensive silica sands by substitution with natural sand.

Fiber performance depends on factors including the matrix properties, fiber volume content, geometry and orientation in the concrete [18]. Steel fibers with a high modulus of elasticity are commonly used. Several researchers have shown that steel fibers can effectively improve the bond condition of the cement paste with the aggregate, reduce the occurrence and development of cracks, and increase the continuity of the material [19–21]. Low porosity is associated with a fiber length of a minimum tenfold the maximum diameter of the aggregate. The proportions of the fiber have a major influence on its mix ability and the workability of the UHPSFRC. It has been found that workability decreases with increasing fiber aspect ratio [22,23].

There are still many problems that need to be overcome when designing and applying ultra-high performance steel fiber reinforced concrete structures. This is a consequence of inconsistent research conclusions regarding the durability of UHPSFRC [6,24]. Cracks in concrete cause a decrease in water absorption capacity and expose the material to destructive substances [18], therefore it is necessary to take actions aimed at improving the properties of hardened UHPSFRC [25]. Gao et al. [26] mentioned that to ensure good quality of steel fibers reinforced concrete, its surface should be additionally supplemented with a thin layer of mortar ensuring fiber coverage analogous to the coverage of steel bars in traditional reinforced concrete structures. The porosity of steel fiber reinforced concrete as well as the properties of the fibers and aggregate strongly influence the frost resistance of the concrete. Direct impacts of the external environment, among others, freeze–thaw cycling and harmful chemical attacks constitute sources of concrete degradation [27], and therefore in recent years, investigations have been undertaken in ultra-high performance concrete frost resistance [28].

As a result of numerous investigations [1,3] it was determined that the best ultra-high performance fiber reinforced concrete can be obtained by providing a water-to-binder ratio below 0.2 and 2–3 % steel fiber volume content. Mixing processes and the curing method at temperatures ≥ 90 °C are also important for its performance. It was found that a key aspect in the context of producing environmentally friendly UHPSFC for future applications in construction engineering is to reduce the amount of cement used [1].

In this study, only normal-strength steel fibers with a maximum content of 2 % were added to UHPC in order to curb the development of micro-cracks and ensure sufficiently high tensile and flexural strengths. A smaller amount of cement was achieved by using silica fume and coarse basalt aggregate. Moreover, expensive quartz sand was completely eliminated by replacing it with natural sand and heat treatment in the curing process was omitted. Anticipating the higher porosity of UHPSFRC, this work focused on assessing the effect of the normal-strength steel fiber volume content on the durability of UHPSFRC and on the long-term physical–mechanical properties.

2. Research program

2.1. Materials characteristics

Ultra-high performance concrete specimens containing steel fibers were made using low-alkaline, sulphate resistant Portland cement type I — CEM I 52.5 N-HSR/NA. Information about physical properties and chemical system of the cement is given in Table 1. So as to reduce the amount of cement to produce UHPSFRC, condensed silica fume was added in an amount of 11 % of the weight of cement, the detailed parameters of which are given in Table 1. The optimal addition of silica

Table 1

Physical and chemical properties of cement and silica fume [31].

Material characteristics	Cement	Silica fume
Specific surface area (m^2/kg)	443	17 000
Water demand (%)	30	—
Start of setting (min)	120	—
End of setting (min)	180	—
Volume stability acc. to Le Chatelier (mm)	2	—
Compressive strength at 2 days (N/mm^2)	27.7	—
Compressive strength at 28 days (N/mm^2)	57.1	—
Tensile strength at 2 days (N/mm^2)	5.3	—
Tensile strength at 28 days (N/mm^2)	8.2	—
Composition (%)		
SiO ₂	20.92	94.80
Al ₂ O ₃	3.50	1.30
Fe ₂ O ₃	4.38	0.83
CaO	64.69	0.56
MgO	1.20	0.71
SO ₃	3.07	—
K ₂ O	0.38	1.26
Na ₂ O	0.22	0.41
Cl	0.08	—
Loss on ignition	1.27	0.12
Insoluble matter	0.20	—

fume was also determined in previous investigations [29–31].

The fine aggregate consisted of natural sand, most of the particles of which passed through a 0.5 mm sieve. Ultra-high performance concrete with steel fibers was made of coarse-grained basalt aggregate with a maximal size of 16 mm. The specific gravity and water absorption of the sand were 1.12 % and 2.67 respectively, and those of basalt aggregate were 2.95 and 0.15 %. Aggregate grain size analyzes are given in Table 2.

Superplasticizers (SP) are known as efficient water reducers for the production of ultra-high performance steel fiber reinforced concrete. CX ISOFLEX 793, based on polycarboxylate ethers, was used as a superplasticizer to reduce water at the content of 3 % by weight of cement in the production of UHPSFRC.

The production of UHPC specimens with the content of fibers, as well as concrete curing, used tap water as a key ingredient of the mixtures.

BAUMIX® steel fibers were terminated with hooks at both ends as shown in Fig. 1. These steel fibers were employed to produce UHPSFRC. The physical properties of the used fibers are given in Table 3. The range of fibers employed to produce UHPSFRC was from 0 % to 2 % of the concrete volume.

2.2. Mixture Design and Sample production

Four mixtures were developed for the production of UHPC using steel fiber (SF) mixed with concrete at different volume contents of 0.5 %, 1 %, 1.5 % and 2 % and a reference mixture without fibers (REF) as shown in Table 4.

In order to calculate the various characteristics of hardened fiber reinforced UHPC, an experimental program was carried out using 100 mm cubes, 300 mm high cylinders 150 mm in diameter, and $50 \times 63 \times 350$ mm prisms.

Ultra-high performance concrete mixtures were produced by mixing dry fine aggregate (natural sand) and coarse aggregate (crushed basalt rock) for 3 min, and then adding half of the tap water specified in the recipe. The next phase of mixing the ingredients lasted 2 min. Next, cement, silica fume, the rest of the water and superplasticizer were added. This mixing phase lasted approximately 3 min. Finally, steel fibers were dosed manually to avoid fiber agglomeration. After 4 min of mixing the mixtures with the fibers, the molds were filled with the ready-made material, and then the concrete was compacted in layers by means of a vibrator. The specimens remained in the molds for 24 h and were protected against water loss. After demolding the specimens, they were transported to bath tank with clean water, where they matured for

Table 2

Sieve analyses of basalt aggregate and quartz sand.

Sieve size (mm)		16	8	4	2	1	0.5	0.25	0.125	< 0.125
Percentage passing	Basalt aggregate	100.0	67.0	26.3	4.1	–	–	–	–	–
	Quartz sand	–	–	–	100.0	88.2	74.8	11.6	–	–

**Fig. 1.** BAUMIX® steel fibers.**Table 3**

Physical characteristics of steel fiber.

Length (mm)	Diameter (mm)	Aspect ratio	Density (g/mm ³)	Tensile strength (MPa)
50	1	50	78.5	350

a 14-day period at the temperature of 20 °C. For the remaining time until all tests were conducted at 28, 56 and 730 days, the specimens were aged in laboratory air-conditions. At 28 days, the porosity, water absorption, density, compressive strength, toughness, flexural strength, splitting tensile strength, fracture energy, static and dynamic modulus of elasticity, ultrasonic pulse velocity (UPV), frost resistance were tested. However, at 56 and 730 days, the strengths and static modulus of elasticity of ultra-high performance concrete were determined. All the tests were performed on a set of three samples for each mixture and the average value of the results was used for their evaluation.

2.3. Research methodology

After hardening for 28 days, the density and porosity of ultra-high performance concrete specimens with steel fibers were measured on specimens intended to determine the compressive strength at 56 and 730 days in relation to PN-EN 12390-7 [32]. During the density test, the

Table 4Ultra-high performance concrete mix proportion per 1 m³.

Mix ID	Fiber		Aggregates		Cement (kg)	Water (l)	Silica Fume (kg)	SP (kg)
	Vol. content (%)	Steel (kg)	Sand (kg)	Basalt (kg)				
REF	0	–	500	990	670.5	178	74.5	20
SF0.5	0.5	39						
SF1.0	1.0	78						
SF1.5	1.5	117						
SF2.0	2.0	156						

mass and volume of specimens for each concrete were assessed. The ultra-high performance concrete reinforced with steel fibers was subjected to the water absorption test according to the PN-EN 13,755 standard [33] on cuboid specimens having a side of 100 mm after meeting the requirement of a 28-day curing period. Initially, 72-hour drying of the specimens was done in an electric oven at the temperature of 105 °C. After removing them from the oven, they were cooled in a dry environment for 24 h, then weighed and put in a tank with water at 20 °C for 30 min. After taking samples from the water, they were dried until the surface was saturated and weighed again. The increase in specimen mass after immersion in water was used in order to ascertain the water absorption of the specimen.

On the basis of the PN-EN 12390-3 [34] and PN-EN 12390-6 [35] standards, splitting tensile and compressive strength tests of ultra-high performance steel fiber reinforced concrete were carried out, respectively. Cuboid specimens having the dimensions 100 × 100 × 100 mm were assessed after 28, 56 and 730 days after curing them in water for 14 days.

According to the PN-EN 12390-5 standard [36], a three-point bend model was employed to determine the flexural strength of prismatic specimens made of ultra-high performance steel fiber reinforced concrete. The constant loading rate of 0.05 MPa/s was utilized to perform this test. In this experiment, the modulus of rupture (MOR) of ultra-high performance steel fiber reinforced concrete was evaluated. In order to evaluate the displacement, a linear displacement transducer (LVDT) installed in the center of prisms with dimensions of 50 × 63 × 350 mm was used. When performing the prism test, the data logger automatically recorded the displacement and applied load. The recorded results were relayed to a computer so as to examine the load–displacement curves.

Crack initiation and propagation were analyzed using a non-contact Digital Image Correlation (DIC) technique. This method allowed full-field strain measurements and visualization of crack patterns throughout the loading process, as also demonstrated in previous works [29,37,38]. Fig. 2

The DIC system used in this study enabled accurate assessment of displacement and strain changes at both peak load and post-cracking stages (see Fig. 3). Additionally, the energy absorption capacity and fracture energy were calculated from the area under the load–deflection curve according to previous study [29].

The static modulus of elasticity in compression was ascertained using three cylinders 150 mm in diameter and 300 mm in height by measuring the displacement of the specimen within the stress range starting from 0.5 MPa and ending at 30 % of the compressive strength for each UHPC. The examinations were carried out by using a device with an extensometer to measure the modulus, based on ASTM C469/C469M-14 [39].

The test method for the dynamic elastic modulus was performed on cylinders with dimensions as given above based on ASTM C666 [40] and ASTM C215 [41]. The dynamic elastic modulus of the specimens was

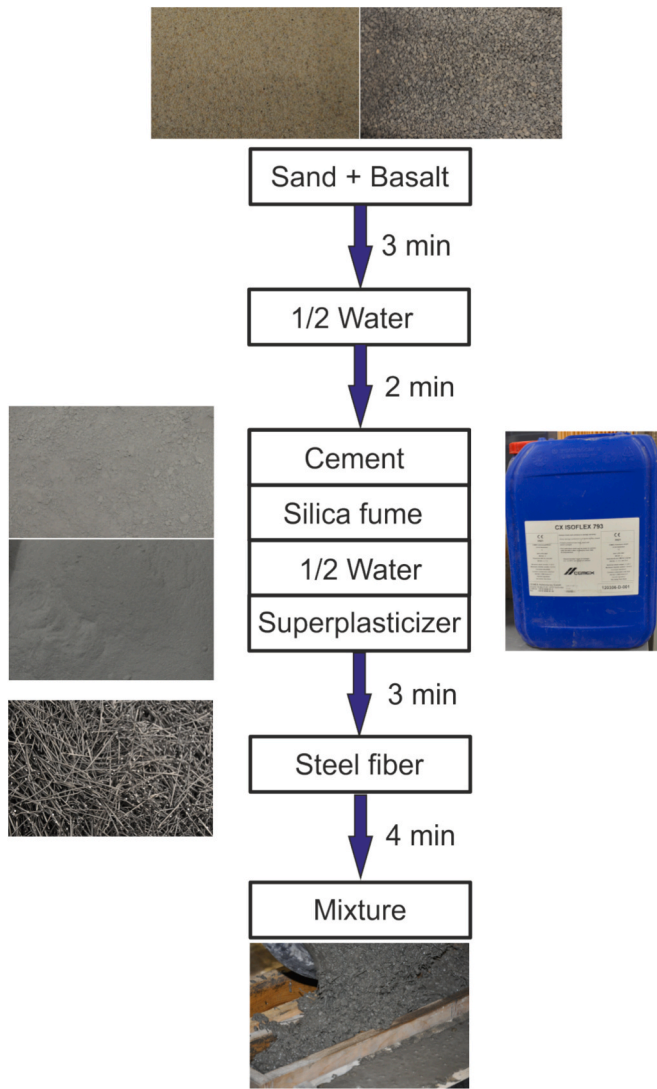


Fig. 2. Diagram of the UHPSFRC mixtures production process.

ascertained based on resonance frequency measurements performed by utilizing a frequency counter. A small diameter steel ball was employed as the impact source. The accelerometer measured the vertical motion when the top surface of the cylinder was struck by the ball. The results were obtained by a computer software. Examinations were conducted before and after frost resistance testing to assess internal damage to UHPC after freeze–thaw cycling. The dynamic modulus of elasticity of ultra-high performance concrete specimens was determined with the following formula [2,6,41]:

$$E_{DM} = 4L^2 n^2 \rho \quad (1)$$

where E_{DM} is the dynamic modulus of elasticity in GPa, L is the specimen length in m, n is the frequency in kHz, and ρ is the density in kg/m³.

The integrity and homogeneity of ultra-high performance concrete specimens reinforced with steel fibers was verified by means of an ultrasonic pulse velocity (UPV) test [42,43]. The test was conducted on cylinders 150 mm in diameter and 300 mm in height after 730 days of maturation in laboratory conditions, according to the PN-EN 13,791 standard [44].

The frost resistance was ascertained by means of the direct method in accordance with the guidelines given in the PN-EN 13,581 [45] standard. 180 freeze–thaw (F–T) cycles were performed on six 100 × 100 × 100 mm cubic specimens from each mixture. After placing the cubes in

the freezing chamber, they were subjected to F–T cycles according to the scheme shown in Fig. 4. In order to eliminate the difference in temperature between the cubic specimen and the chamber, the temperature of + 20 °C was maintained for 1 h. The freezing rate in water was set between + 20 °C and –20 °C for a duration of 6 h and the thawing rate in water was set between –20 °C and + 20 °C also for 6 h. Therefore, one F–T cycle lasted 12 h. Before the freeze–thaw cycles, the specimens were weighed and determination of their dynamic modulus of elasticity was conducted. After 90 days of testing, drying and weighing of the specimens were performed again to determine the mass loss, additionally their dynamic modulus of elasticity was determined.

3. Results and discussion

3.1. Porosity, absorbability and density

The basic characteristics of ultra-high performance fiber reinforced concrete are the pore structure, water absorption capacity, density and they play a fundamental role in its durability.

The amount of water absorbed while the specimen is immersed allows the total pore volume to be estimated. The water absorption capacity and porosity of the fiber reinforced ultra-high performance concrete were higher than the reference concrete and increased with increasing steel fiber content, as shown in Fig. 5. This is because when the bond between the fibers and the paste is formed, the micropores inside the concrete and, as a consequence, the porosity of the material as well as the water absorption capacity grow significantly with the increment in fiber content compared to the reference concrete. Despite this trend, ultra-high performance concrete strengthened containing steel fibers showed 4–5 times lower water absorption capacity than recommended for good quality concrete, i.e. less than 10 % by weight [46].

The ingredients used in the production of fiber reinforced concrete determine its density. The density of ultra-high performance concrete reinforced with steel fibers gradually grows with the increment in the addition of these fibers due to their high unit weight, as shown in Fig. 5.

These results show that an increase in the percentage of steel fibers effects in a gradual increase in the porosity, density and water absorption of ultra-high performance concrete. The porosity of the concrete was in the range of 4.3–5.7 % and was typical for such concretes. The 0.5 % steel fiber content gave rise to an increase in porosity of only 6.5 %, but as the fiber amount continued to increase, the porosity of the SF2.0 concrete increased by 21 % compared to the reference concrete. The water absorption rose with the steel fiber content from 67 % for SF0.5 to 76 % for SF2.0 in comparison to the specimens without fibers. Despite significant percentage increments between series, the absorbability of the specimens was low and ranged from 0.6 to 2.5 %. It was also revealed that ultra-high performance concrete had a density in the range of 2500–2600 kg/m³. It was observed that with an increase in the steel fiber content, the pore volume increases and a greater number of micro-defects are created in the cement matrix of ultra-high performance concrete, which could probably related to the high smoothness of the steel fiber surface and weaker adhesion of the fiber to the paste compared to other ingredients.

3.2. Compressive strength

The compressive strength was ascertained at 28, 56 and 730 days after the molding of ultra-high performance concrete prepared without and with the addition of steel fibers. Fig. 6 displays those results.

There was a marginal decline in the 28-day compressive strength of ultra-high performance concrete reinforced with the fibers and a marginal increase in the 56-day compressive strength with steel fiber content above 1.5 %. On the other hand, the increase in strength after 730 days of maturation with a volume addition of fibers from 1 % was significant. At 28 day, the control concrete REF (0 % SF) achieved a

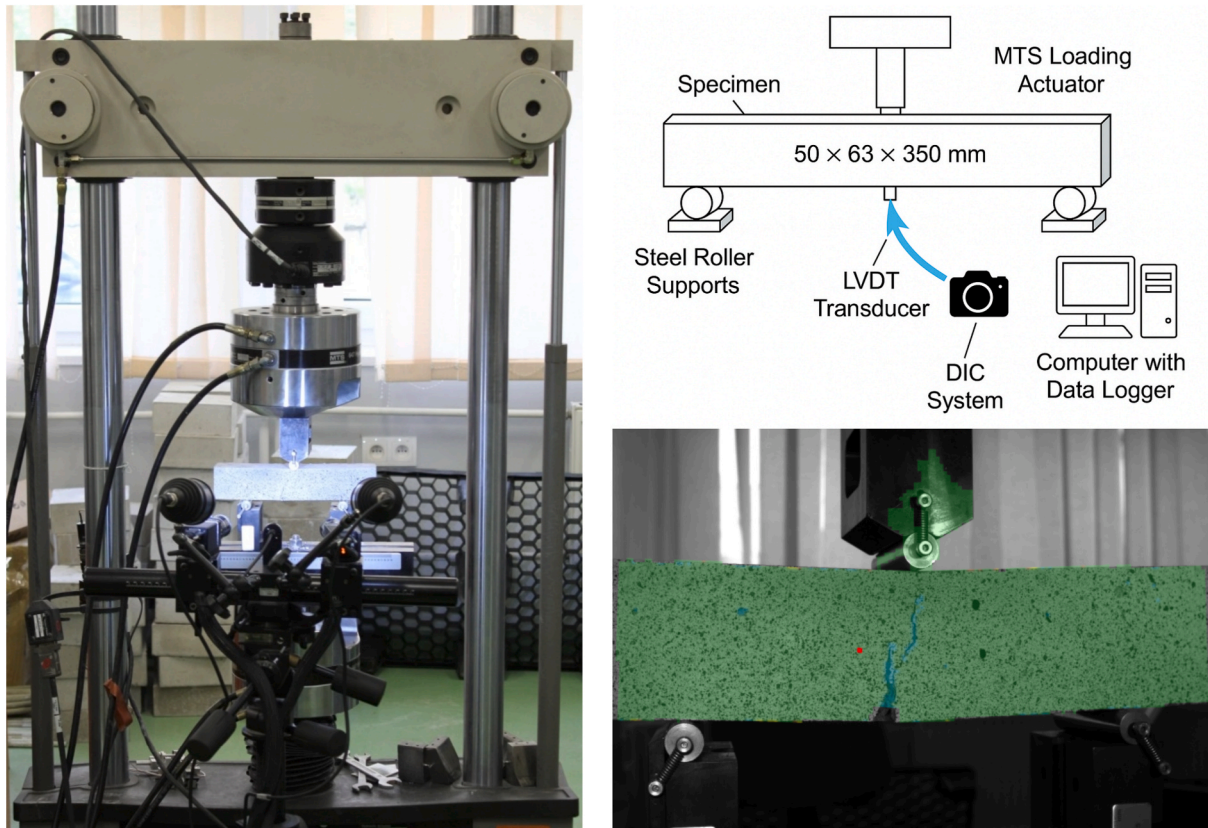


Fig. 3. Experimental setup: test photo and schematic diagram.

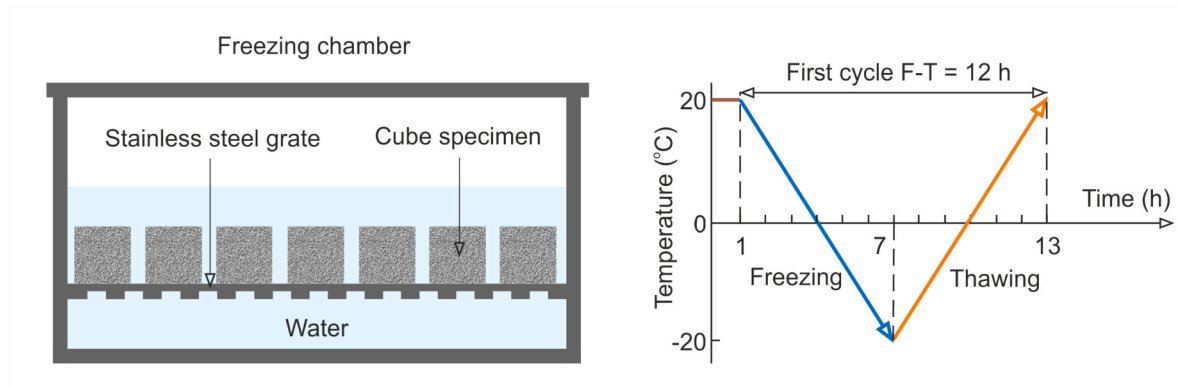


Fig. 4. Experimental set-up of UHPC frost resistance and cyclic temperature scheme for F-T test.

compressive strength of 139.8 MPa, while the concretes SF0.5 (0.5 % SF), SF1.0 (1 % SF), SF1.5 (1.5 % SF), SF2.0 (2 % SF) reached compressive strengths of 134.1, 135.1, 138.7 and 139.6 MPa, respectively. The decrease was 4.1 %, 3.4 %, 0.8 % and 0.1 % compared to the strength of the reference concrete REF. In turn, the REF control concrete achieved a compressive strength of 142.3 MPa at 56 days of aging, and the fiber concretes attained compressive strengths of 135.1, 141.8, 146.0 and 150.0 MPa, respectively. The decrease was 5.1 % and 0.3 % with 0.5 % and 1 % fiber additions and the increases were 2.5 % and 5.1 % with 1.5 % and 2 % fiber additions compared to the 56-day strength of REF concrete. It can be noted that steel fibers had virtually no impact on the compressive strength on day 28 and 56 of curing of the ultra-high performance concrete. However, at day 730, REF concrete samples achieved a strength of 146.3 MPa. Concretes with the addition of fibers achieved strengths of 139.3, 168.6, 176.2 and 179.0 in the order of the

percentage increase in their content. A 4.8 % reduction was recorded with only 0.5 % steel fiber content. The increases were 15.2 %, 20.4 % and 22.3 % with fiber additions of 1 %, 1.5 % and 2 %, respectively.

It was also found that the compressive strength of ultra-high performance concrete having a 1–2 % fiber content increased significantly between 56 and 730 days. The percentage increase in strength for SF1.0, SF1.5 and SF2.0 was 18.9 %, 20.7 % and 19.3 %, respectively, during this time period. A significant increase in the compressive strength of concrete containing 1–2 % steel fibers over an extended curing age proves that 50 mm lengthy hook-ended steel fibers can be successfully used in the production of ultra-high performance concrete.

3.3. Splitting tensile strength

The variation in splitting tensile strength in relation to the addition

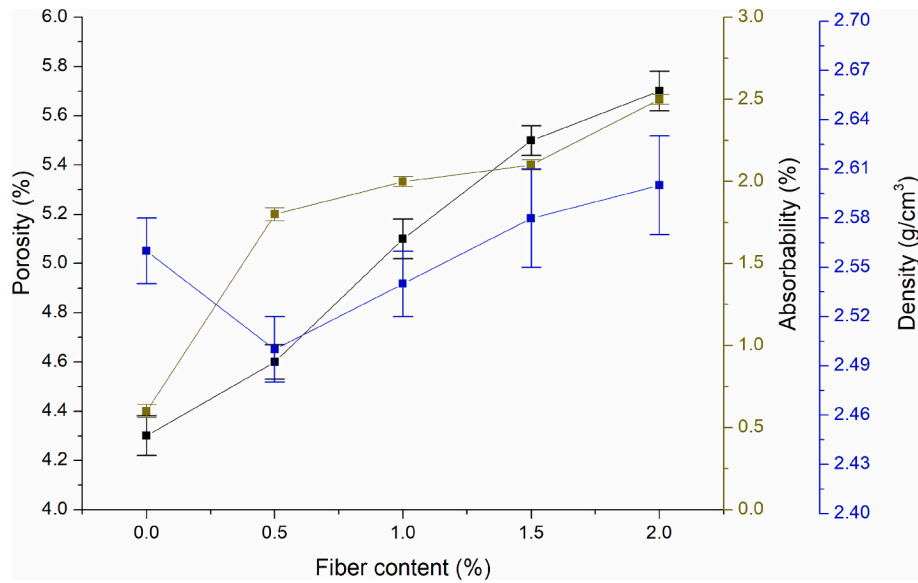


Fig. 5. Porosity, water absorption and density of ultra-high performance concrete depending on addition of steel fibers.

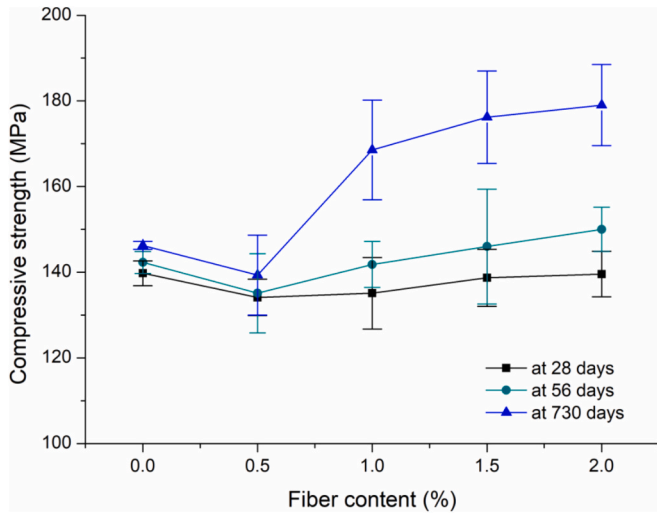


Fig. 6. Compressive strength of ultra-high performance concrete depending on steel fiber content and age of concrete.

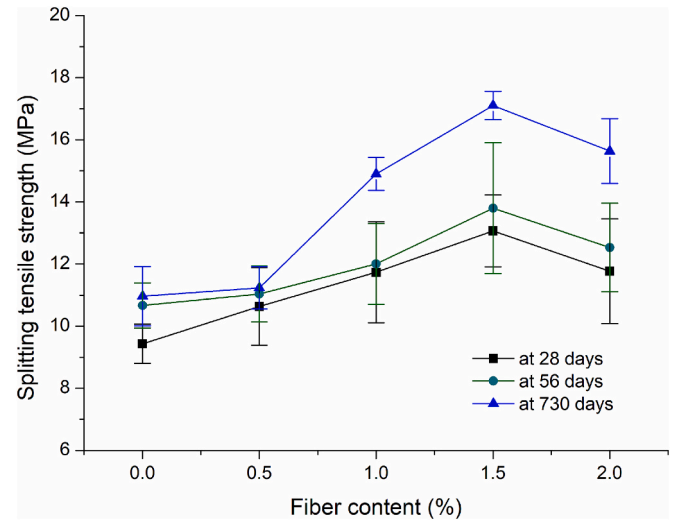


Fig. 7. Splitting tensile strength of ultra-high performance concrete depending on steel fiber content and age of concrete.

of steel fibers was alike to that seen for the compressive strength. There was a rise in the splitting tensile strength of the ultra-high performance concrete with the addition of fibers, as illustrated in Fig. 7.

The splitting tensile strength of REF (0 % SF) concrete at 28 days was 9.43 MPa, and that of SF0.5 (0.5 % SF), SF1.0 (1 % SF), SF1.5 (1.5 % SF) and SF2.0 (2 % SF) reached the levels of 10.63, 11.73, 13.07 and 11.77 MPa, respectively, which provided significant strength increases of 12.7 %, 24.4 %, 38.6 % and 24.8 % compared to that of the REF control concrete. The splitting tensile strength of the concrete was found to grow with age. At 56 days, REF, SF0.5, SF1.0, SF1.5 and SF2.0 reached strengths of 10.67, 11.03, 12.0, 13.80 and 12.53 MPa, respectively. Fiber concretes achieved strength increases of 3.4 %, 12.5 %, 29.3 % and 17.4 % compared to the 56-day REF strength. An analogous trend could also be seen for the splitting tensile strength results after 730 days. With age from 56 to 730 days, the growth in the split tensile strength of the concrete relative to the reference mixture (with no fibers) was between 2.4 and 3.4 % for SF0.5, 12.5–35.8 % for SF1.0, 29.3–55.9 % for SF1.5 and 17.4–42.5 % for SF2.0.

3.4. Flexural strength

The flexural strength of ultra-high performance concrete, without and with steel fibers, was ascertained at 28, 56 and 730 days of aging. The results of these tests are shown in Fig. 8.

Similar to the splitting tensile and compressive strength of the concrete, the flexural strength grew significantly along with the steel fiber content. On the 28th day, the flexural strength of the REF mixture (0 % SF) was 7.73 MPa, while for SF0.5, SF1.0, SF1.5 and SF2.0 it reached 8.33, 9.37, 11.10 and 9.60 MPa, respectively, and increases of 7.8 %, 21.2 %, 43.6 % and 24.2 % comparing to the strength of REF concrete. The flexural strength of the concrete was additionally found to increase with age. At 56 and 270 days, REF, SF0.5, SF1.0, SF1.5 and SF2.0 achieved flexural strengths of 8.10 and 8.40 MPa, 8.90 and 9.23 MPa, 9.83 and 11.9 MPa, 13.27 and 16.37 MPa, 11.73 and 15.10 MPa, respectively. The ultra-high performance steel fiber concretes at 56 and 270 days attained significant increments in the flexural strength of 9.9 % and 9.9 %, 21.4 % and 41.7 %, 63.8 % and 94.9 %, 44.8 % and 79.8 %, respectively, compared with 56- and 730-day strength of REF. The

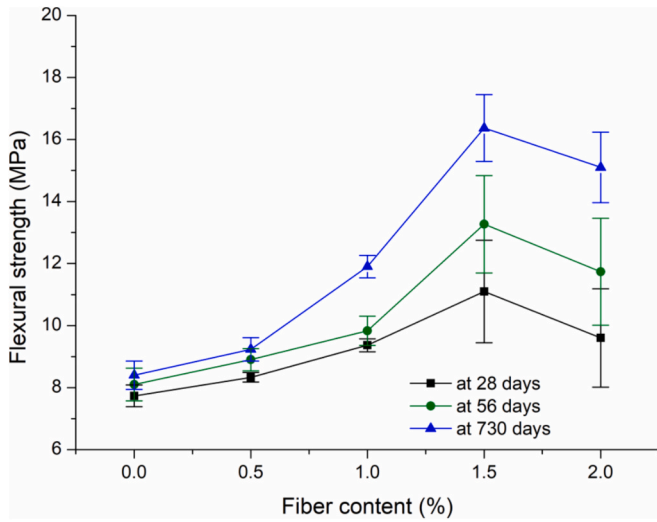


Fig. 8. Flexural strength of ultra-high performance concrete depending on steel fiber content and age of concrete.

obtained increases in flexural strength were the highest among all the tested strengths of ultra-high performance concrete.

Fig. 9 illustrates the average bending performance of ultra-high performance concrete (UHPC) reinforced with steel fibers. The initial peak in the bending curve represents the first cracking load marking the moment when microcracks begin to form within the UHPC matrix. This first peak is notably influenced by the inclusion of steel hook-end fibers, which enhance the matrix's tensile resistance and delay the initiation of cracking.

Following the first peak, the response curve demonstrates a second, more gradual increase. This second peak highlights the post-cracking behavior of the composite, where the steel fibers bridge the cracks and continue to bear the tensile loads. This fiber-bridging effect contributes to the material's enhanced ductility and toughness, allowing it to sustain and redistribute stress even after the onset of cracking. Overall, the two-peak response emphasizes the dual role of steel fibers in UHPC: enhancing initial cracking resistance and sustaining load-bearing capacity during crack propagation, resulting in a more resilient and durable composite material under flexural loading.

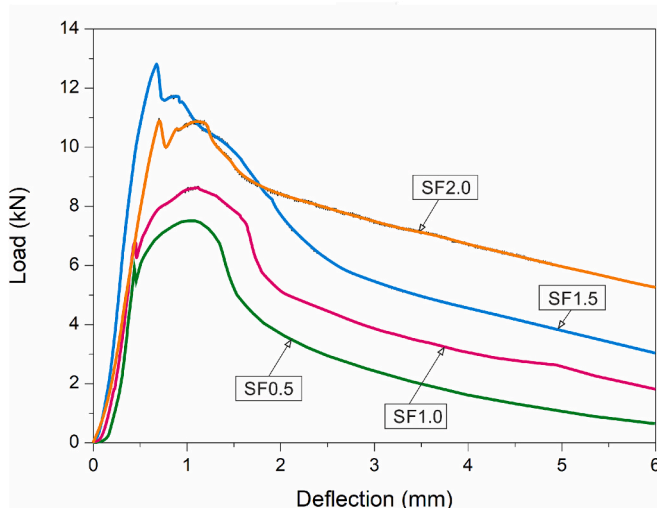


Fig. 9. Load-deflection response of steel fiber UHPC.

3.5. Energy absorption capacity and fracture energy

Fracture parameters of SF reinforced UHPC are shown in Table 5. The evolution of fracture parameters in UHPC reinforced with 50 mm long and 1 mm diameter hooked-end steel fibers clearly demonstrates the synergistic impact of increasing fiber content on both energy dissipation and fracture energy. As the fiber content increased from 0.5 % to 2 % by volume, significant changes in both peak load and fracture parameters are also observed by Yoo et al. [47].

The area under the load-deflection curve, particularly at the 10.56 point, represents the total energy dissipation capacity of the composite. This metric encompasses all forms of mechanical energy absorption, including microcracking, matrix friction, pull-out and bridging of steel fibers. The energy dissipation increases from 16.8 kN × mm at 0.5 % to 49.2 kN × mm at 2 %, showing a near-linear upward trend. While both parameters increase with fiber content, energy dissipation rises more rapidly, indicating that additional fibers not only improve toughness but also contribute to plastic deformation mechanisms and fiber-matrix interactions that go beyond pure crack resistance. The fracture energy, often considered a direct indicator of a material's toughness, increases significantly from 5.33 N/mm at 0.5 % fiber volume to 15.62 N/mm at 2 %. This parameter reflects the ability of the UHPC matrix to resist crack initiation and propagation. The steep increase between 1 % and 1.5 % suggests a threshold effect, beyond which steel fibers start to act effectively as bridges across the crack plane, providing resistance even after initial matrix failure [48].

The chart in Fig. 10 illustrates the evolution of energy dissipation at the highest deflection level (10.56) as a function of steel fiber volume content in UHPC reinforced with 50 mm long, 1 mm diameter hooked-end steel fibers.

A second-degree polynomial model was fitted to the experimental data to describe this relationship. The equation of the model is as follows

$$E(x) = 0.70x^2 + 21.67x + 4.42 \quad (2)$$

where $E(x)$ is the energy dissipation [kN × mm] and x is the steel fiber content [% by volume].

The fitted second-degree polynomial model reveals a strong correlation between fiber volume content and energy dissipation, suggesting increasing efficiency of fibers in absorbing mechanical energy beyond a threshold [49].

The fracture energy and energy absorption capacity as well as their improvement for prismatic specimens of ultra-high performance concrete reinforced with steel fibers are shown in Fig. 11. At 28 day, the REF control concrete obtained an energy absorption capacity of 0.075 kN × mm, while the concretes with 0.5 %, 1 %, 1.5 %, 2 % fiber content reached energy absorption capacities of 16.8, 22.7, 42.6 and 49.2 kN × mm, respectively. The fracture energy was determined by integration of the area under the load-deflection curve and dividing it by the cross-section of the prismatic specimen [29]. REF, SF0.5, SF1.0, SF1.5 and SF2.0 achieved 28-day fracture energies of 0.03, 5.33, 7.21, 13.52 and 15.62 N/mm, respectively. Bencardino et al. [50] determined the impact of 1 % and 2 % steel fiber contents on the fracture energy of high-performance concrete and obtained values of 5.2 and 6.8 N/mm, respectively. The higher fracture energies obtained in these tests are

Table 5
Fracture parameters of UHPC with steel fibers.

Designation	Peak load (kN)		Area under the curve (kN × mm) up to				Fracture energy (N/mm)
	1st peak	2nd peak	δ	3δ	5.5δ	10.5δ	
SF 0.5	5.8	7.5	0.7	6.1	11.5	16.8	5.33
SF 1.0	6.8	8.7	1.0	7.9	14.7	22.7	7.21
SF 1.5	12.8	11.7	4.3	17.8	31.2	42.6	13.52
SF 2.0	11	10.9	3.6	17.1	30.3	49.2	15.62

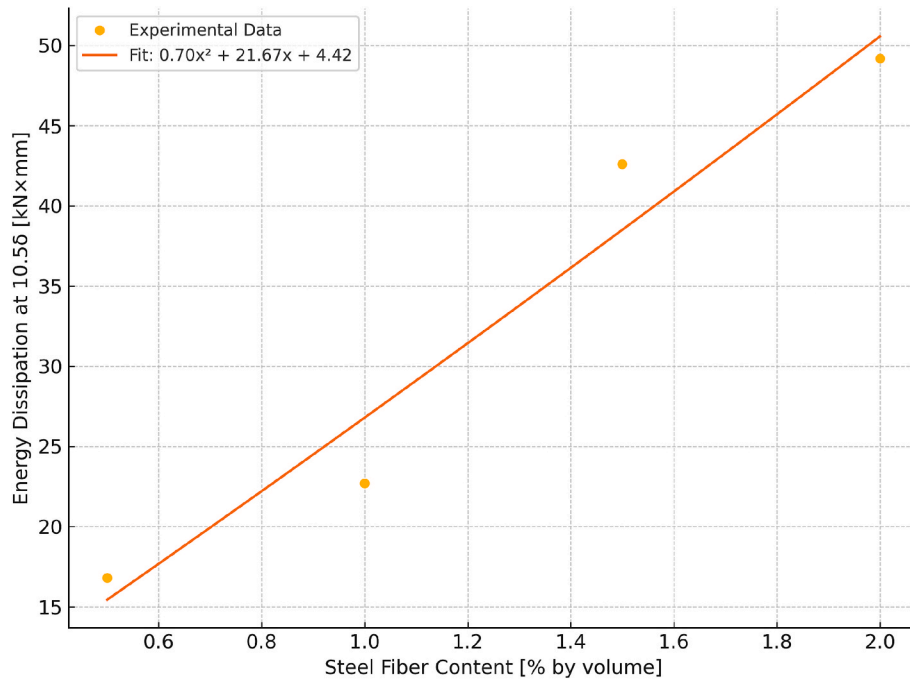


Fig. 10. Energy dissipation at 10.56 as a function of steel fiber volume content in UHPC.

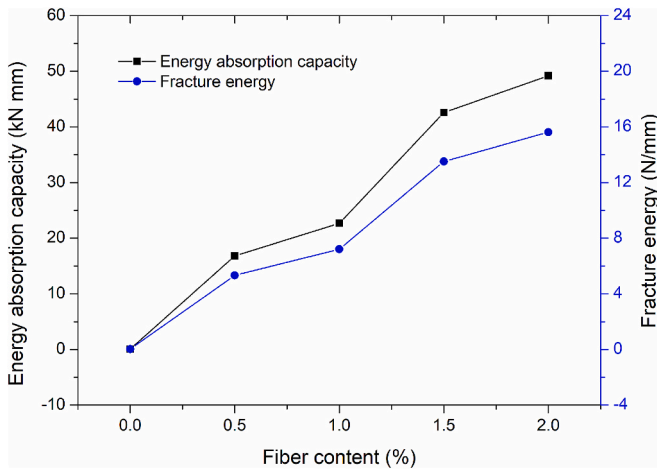


Fig. 11. Energy absorption capacity and fracture energy of ultra-high performance concrete depending on addition of steel fibers.

mainly owing to the higher tensile strength of the concrete matrix.

The I5, I10 and I20 toughness indexes were calculated from the areas under the experimental load–deflection curve limited to specific deflection values according to the recommendations of ASTM C1018 [51]. Fig. 12 presents the influence of the steel fiber content on the toughness indexes of ultra-high performance concrete.

The shape, type and fiber content are determinants of the toughness indexes. The indexes describe the effectiveness of fibers because they do not depend on the concrete's strength. The 28-day strength indexes I5, I10, and I20 were 8.7, 16.4, and 24.0, respectively, for SF0.5; 7.9, 14.7 and 22.7 for SF1.0; 4.1, 7.3 and 9.9 for SF1.5; 4.8, 8.4 and 13.7 for SF2.0. According to [51], the values of the indexes $I5 \geq 5$, $I10 \geq 10$ and $I20 \geq 20$ designate that the given fiber concrete behaves plastically. Such indexes were achieved by ultra-high performance concretes SF0.5 and SF1.0 with 0.5 % and 1 % steel fiber content. Lower values of indexes obtained by SF1.5 and SF2.0 concretes according to [52] may indicate lower effectiveness of fiber anchoring.

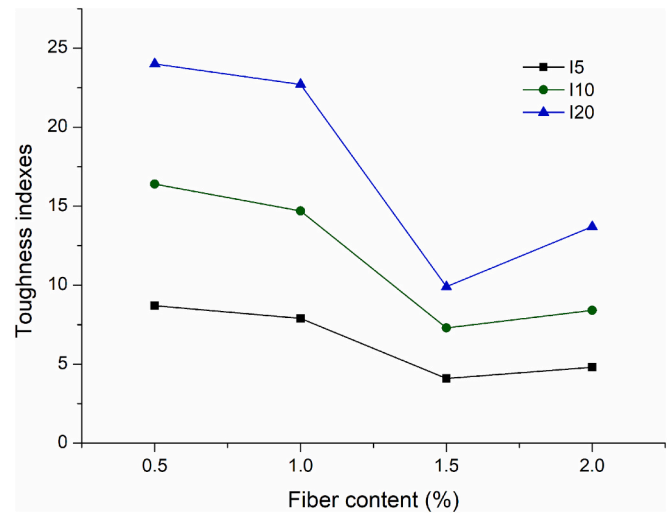


Fig. 12. Toughness indexes of ultra-high performance concrete in dependence with steel fiber content.

Using steel fibers resulted in an enormous improvement in energy absorption capacity and fracture energy compared to the reference concrete. The load-bearing capacity, fracture energy and energy absorption capacity gradually rose by incrementing the fraction of fiber reinforcement in concrete. Based on the failure assessment of the specimens, it was established that the steel fibers effectively bridged the cracks in the ultra-high performance concrete due to their high stiffness and favorable hook-ends allowing for good anchoring in the matrix.

3.6. Observation of crack propagation and curvature based on DIC technique

Fig. 13 illustrates the displacement and strain distributions for ultra-high performance concrete (UHPC) specimens reinforced with varying steel fiber contents (SF1.0, SF1.5, and SF2.0) under two loading stages: at the maximum applied force and subsequent to cracking (at $0.7 \times$

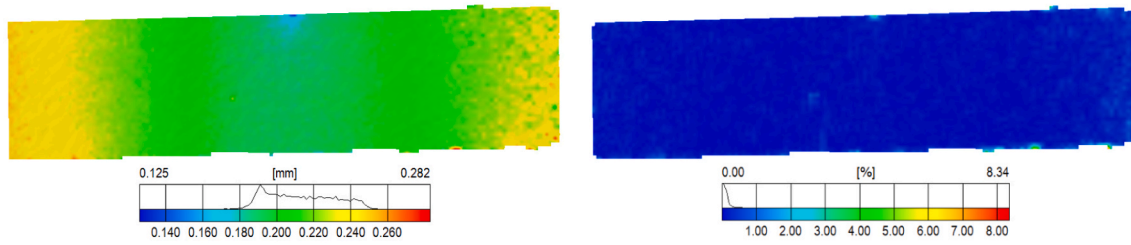
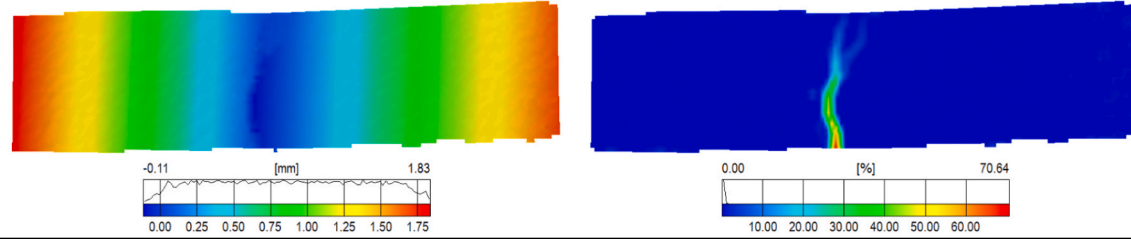
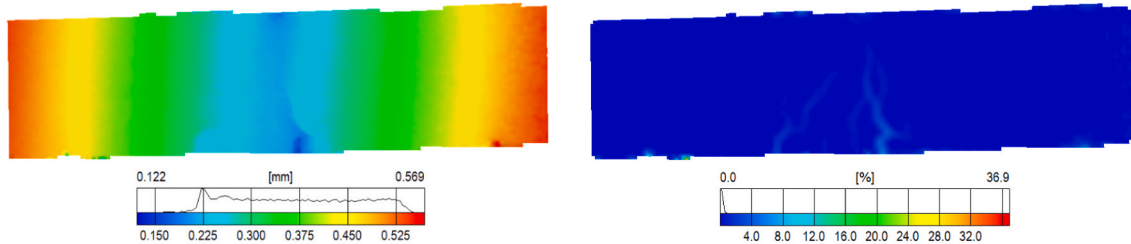
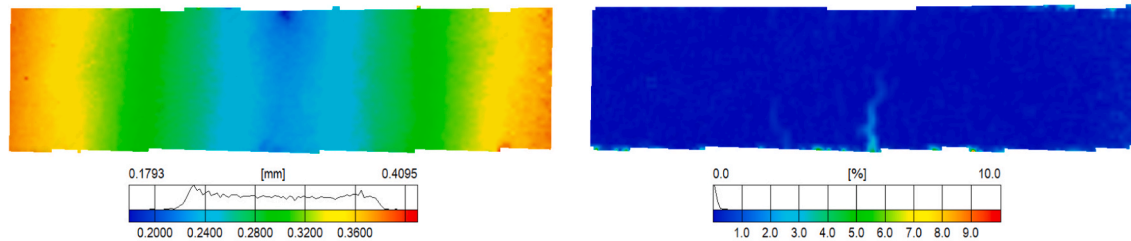
SF1.0**Displacements and strains at maximum force****Displacements and strains after cracking ($0.7F_{\max}$)****SF1.5****Displacements and strains at maximum force****Displacements and strains after cracking ($0.7F_{\max}$)****SF2.0****Displacements and strains at maximum force****Displacements and strains after cracking ($0.7F_{\max}$)**

Fig. 13. Typical displacement and strain fields of UHPC with different steel fibres content at different loading stages.



Fig. 13. (continued).

F_{max}). At peak load, specimens with lower fiber content exhibited localized zones of high displacement and strain, indicative of imminent crack initiation. Conversely, with increasing fiber content, particularly in the SF1.5 and SF2.0 specimens, the displacement fields expanded and the strain distributions became more diffused, reflecting the enhanced capacity of steel fibers to delay strain localization and inhibit catastrophic cracking [29]. Following the onset of cracking, all specimens demonstrated an expected increase in displacement and strain; however, specimens with higher fiber volume fractions displayed significantly more distributed deformation fields and evidence of multiple cracking events [47]. The SF2.0 specimens, in particular, exhibited superior ductility, characterized by extensive microcrack formation and strain delocalization [29,48]. These findings underscore the critical role of steel fibers in improving the post-cracking behavior of UHPC by facilitating stress redistribution across developing cracks and enhancing the material's energy absorption and fracture toughness [29,47]. The observed displacement and strain patterns are consistent with theoretical models of fiber-reinforced cementitious composites [1,3] and corroborate the mechanical behavior trends previously reported in the literature [29,48].

Fig. 14 presents the distributions of vertical displacements and material strains along the longitudinal axis of UHPC specimens reinforced with different contents of steel fibers (SF1.0, SF1.5, and SF2.0), captured after reaching the ultimate load (approximately $0.7 \times F_{max}$).

In Fig. 14a, the vertical displacement profiles illustrate the curvature of the specimens induced by flexural loading. For specimens with a lower fiber content (SF1.0), a pronounced concentration of displacements can be observed, suggesting the formation of a dominant crack that governs the failure mechanism. In contrast, specimens with higher fiber contents (SF1.5 and SF2.0) exhibit more distributed displacement fields, indicating multiple cracking zones and enhanced stress

redistribution across the length of the beam. Fig. 14b presents the strain profiles corresponding to the same loading stage. In specimens with lower fiber volume (SF1.0), the strain distributions show distinct and sharp peaks, confirming the localized nature of crack development. As the fiber content increases, particularly in SF2.0 specimens, the strain peaks become less pronounced and more evenly distributed, suggesting that the presence of a higher volume of steel fibers effectively bridges cracks and limits crack opening. The spread of smaller, distributed strain concentrations along the specimen length for SF1.5 and SF2.0 demonstrates an improvement in the post-cracking ductility and energy dissipation capacity of UHPC.

These results confirm that the incorporation of steel fibers contributes significantly to delaying crack localization, enhancing the formation of multiple microcracks rather than a single dominant macrocrack, and improving the overall mechanical integrity of the composite after cracking. The observed behavior aligns with previous research findings on fiber-reinforced UHPC, where increased fiber content is associated with improved toughness, higher energy absorption, and more stable post-peak mechanical performance [29,47]. These findings can also be contextualized by considering the concept of rotational capacity, as discussed by Foraboschi [53], who emphasized that the ability of a structure to develop sufficient plastic rotations in plastic hinges is essential to achieving a fully developed failure mode and avoiding premature failure [53]. In cases where rotational capacity is inadequate, failure can occur prematurely before all plastic hinges reach their maximum moment capacity, leading to a reduction in the overall load-carrying potential of the structure. In the present UHPC study, the observed strain and displacement distributions suggest that higher fiber contents (SF1.5 and SF2.0) effectively increase the local rotational capacity, allowing the specimens to sustain larger deformations post-cracking without catastrophic failure. Thus, the results support the

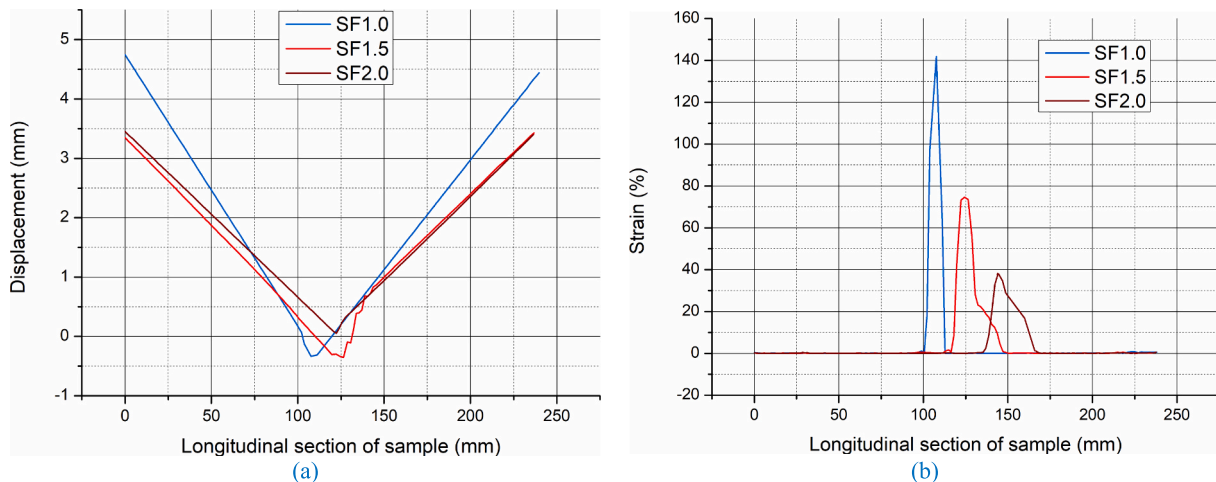


Fig. 14. Distributions of vertical displacements (a) and material strains (b) along the longitudinal axis of UHPC specimens reinforced with different contents of steel fibers.

conclusion that an increased steel fiber volume fraction enhances the rotational ductility of UHPC beams, a key parameter in promoting the realization of the material's full load-carrying potential.

The ductility indexes of ultra-high performance concrete (UHPC) specimens reinforced with varying steel fiber contents (SF1.0, SF1.5, and SF2.0) were determined based on the ratio of ultimate displacement (δ_u) to yield displacement (δ_y). The calculated ductility indexes are 7.90 for SF1.0, 4.14 for SF1.5, and 4.75 for SF2.0, respectively. These values were derived using the displacement at the first significant load drop (yield point) and the ultimate displacement measured after significant post-cracking deformation. The results indicate that the SF1.0 specimen, despite having a lower fiber content, exhibited the highest ductility index. This suggests that at lower fiber volumes, the material can sustain larger relative deformations post-cracking, although this may be associated with the formation of larger, localized cracks rather than distributed microcracking. For specimens with higher fiber contents (SF1.5 and SF2.0), slightly lower ductility indexes were observed, but these specimens demonstrated a more distributed crack pattern and a greater energy absorption capacity, as previously discussed. These findings align with the behavior reported in [53], where an increase in rotational capacity was associated with an improved ability to redistribute deformations without catastrophic failure, even when local ductility indices slightly decreased due to improved crack control. Overall, the addition of steel fibers not only enhances energy dissipation but also stabilizes the post-cracking response, improving the rotational ductility crucial for structural safety.

3.7. Static and dynamic modulus of elasticity

The static modulus of elasticity was calculated for 0.33 of the maximum load. The elastic modulus of ultra-high performance concrete was determined at 28, 56 and 730 days, and the results are revealed in Fig. 15.

The test results show that the addition of steel fibers raises the static elastic modulus of concrete. At 28 days, the elastic modulus of the REF control concrete amounted to 48.59 GPa, while the SF0.5, SF1.0, SF1.5 and SF2.0 concretes achieved elastic moduli of 50.19, 50.68, 51.09 and 51.63 GPa, respectively. The improvements ranged from 3.3 % to 6.2 % compared to the REF static module. On the other hand, the REF reference concrete attained a static modulus of 49.39 GPa at 56 day, and the ultra-high performance fiber concretes achieved static moduli of 50.5, 51.2, 52.0 and 52.2 GPa, respectively. The increases were slight and ranged from 2.2 % to 6.3 % compared to the 56-day static modulus of

REF concrete. It can be seen that the steel fibers had virtually no influence on the 28- and 56-day static modulus of elasticity of the ultra-high performance concrete. However, on 730 day, REF concrete samples obtained a modulus of 49.83 GPa and fiber concrete specimens reached moduli of 51.03, 54.37, 55.47 and 54.71 GPa in the order of adding steel fibers. Therefore, the increases were higher for concrete with at least 1 % fiber addition and amounted to 2.4 %, 9.1 %, 11.3 % and 9.8 %.

The dynamic modulus of elasticity of ultra-high performance concrete was determined at 28, 56 and 730 days of aging and the results obtained are plotted in Fig. 16. The measurements demonstrate that the greater the content of steel fibers, the greater the dynamic modulus of elasticity. The REF concrete exhibited a dynamic modulus of elasticity at 28 days of 51.71 GPa. Concretes SF0.5, SF1.0, SF1.5 and SF2.0 obtained dynamic moduli of 52.96, 54.53, 54.98 and 55.68 GPa. The modulus improvements ranged from 2.4 % to 7.7 % compared to REF. In turn, the 56- and 730-day dynamic moduli of the control concrete were 52.23 and 52.87 GPa, and the ultra-high performance fiber concretes achieved modulus increases of 2.3 %-7.6 % and 3.4 %-11.2 % at 56 and 730 days, respectively. It can be seen that, similar to the static modulus, the steel fibers also had a slight influence on the dynamic elastic modulus of the ultra-high performance concrete. We should note that the greatest impact on this parameter, an increase of approximately 10 %, was achieved during the long maturation time, at 730 days.

Fig. 17 presents the relationship between the dynamic and static modulus of elasticity for four types of ultra-high performance concretes with 0.5 %-2% additions of steel fibers.

A linear relationship of the form $ax + b$ seems to best fit the data, $R^2 = 0.82$. The literature states that the model can be considered correct when the R^2 coefficient is greater than or equal to 0.7 [54]. Consequently, the proposed equation can be employed successfully to project the relationship between the dynamic and static modulus of elasticity of ultra-high performance concrete containing steel fibers.

3.8. Ultrasonic pulse velocity

One of the most well-renowned non-destructive methods for assessing concrete properties is the ultrasonic pulse velocity (UPV) method [42,43]. The UPV method involves introducing an ultrasonic wave into the tested element and measuring the wave transit time between the transmitting transducer and the receiving transducer. Before starting the test, carefully measure the thickness of the test specimen. Knowing the time and distance travelled by the ultrasonic pulse, the speed of wave propagation can be calculated. Fig. 18 demonstrates the UPV of ultra-

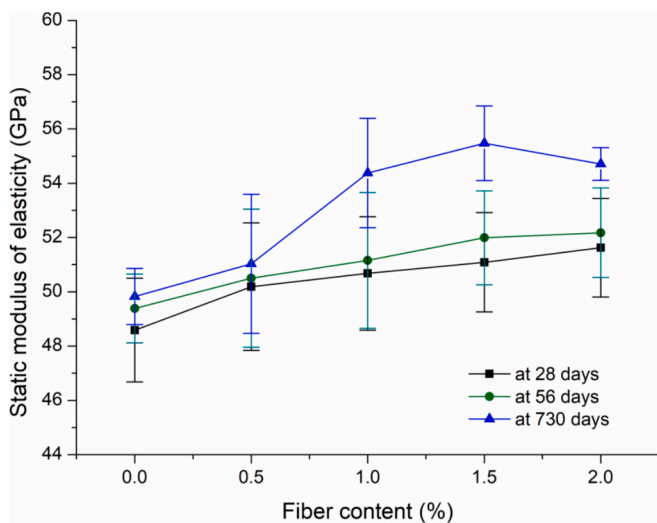


Fig. 15. Static modulus of elasticity of ultra-high performance concrete in dependence with steel fiber content and concrete age.

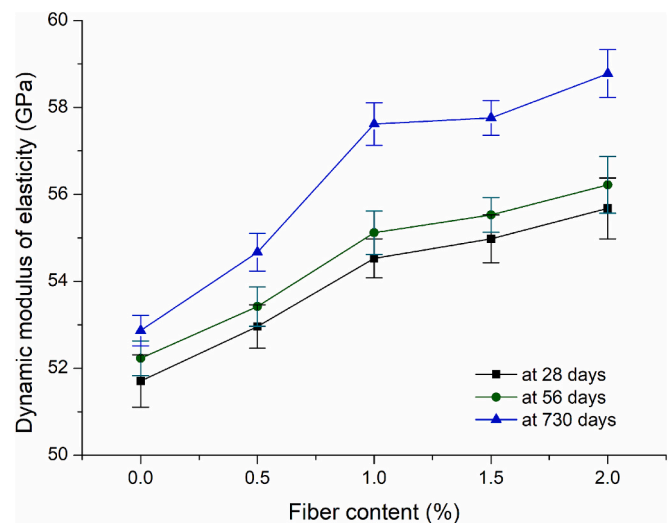


Fig. 16. Dynamic modulus of elasticity of ultra-high performance concrete in dependence with steel fiber content and concrete age.

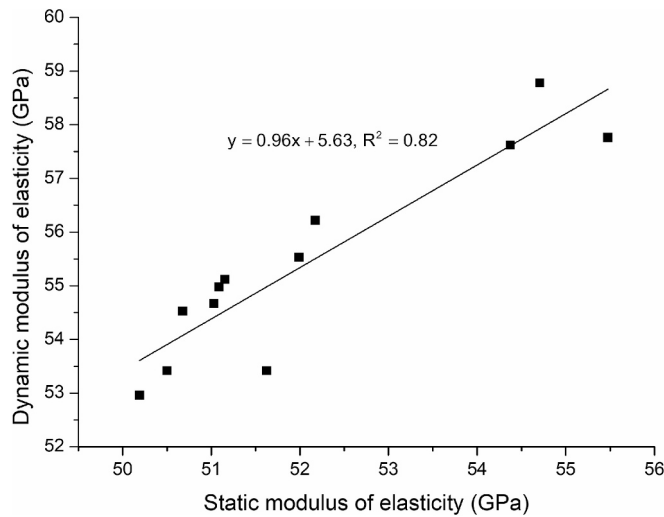


Fig. 17. Relationship between static and dynamic modulus of elasticity.

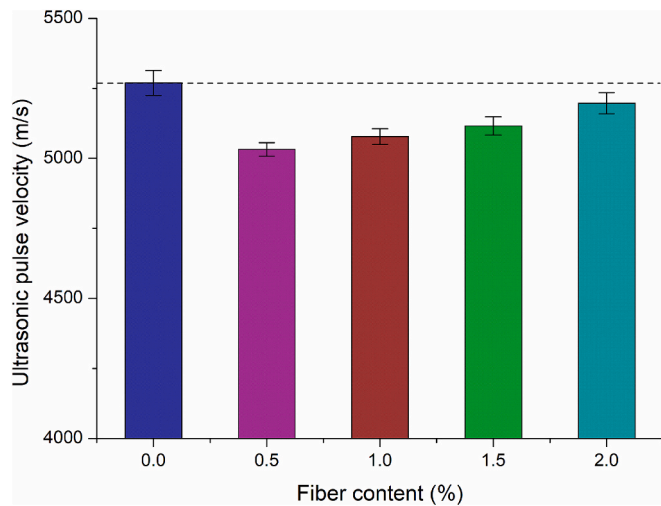


Fig. 18. UPV of ultra-high performance concrete depending on the steel fiber content.

high performance concrete containing steel fibers after two years of curing.

The greater the percentage of steel fibers, the greater the UPV. On the 730th day of maturation, the REF control concrete without fibers reached the highest UPV of 5269 m/s, while the SF0.5, SF1.0, SF1.5, SF2.0 concretes achieved UPV of 5032, 5078, 5116 and 5197 m/s, respectively. The UPV decreases were 4.5 %, 3.6 %, 2.9 % and 1.4 %, respectively, compared to the UPV of REF concrete. It can be inferred that the addition of steel fibers did not greatly affect the quality and homogeneity of UHPC. The optimally fitted curve on the basis of the compressive strength and UPV is displayed in Fig. 19.

It is seen that there is a very strong relationship between the ultrasonic pulse velocity and the compressive strength of UHPC with steel fibers. On the basis of the test results, the following exponential function between compressive strength and UPV with favorable correlation coefficient $R^2 = 0.99$ are found:

$$f_c = -1.87e^{(-UPV/34087)} + 179.51 \quad (3)$$

where f_c is the compressive strength of cubic specimens in MPa, and UPV is the ultrasonic pulse velocity in m/s.

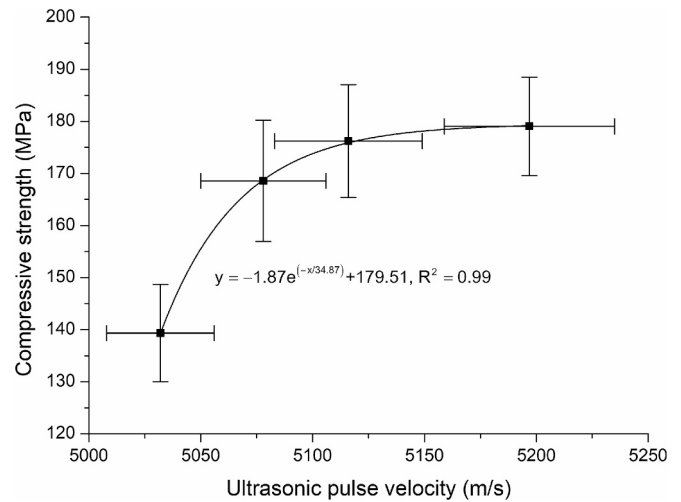


Fig. 19. Correlation between compressive strength and ultrasonic pulse velocity of steel fiber reinforced UHPC.

3.9. Frost resistance

The dynamic modulus is a crucial parameter for assessing the homogeneity, load-bearing capacity as well as the frost resistance of ultra-high performance concrete with added fibers [2,6]. The frequencies of UHPC specimens preceding and following the F-T cycles were determined based on the resonance theory, and the pre- and post-F-T dynamic modulus of elasticity of UHPC, calculated from formula 1, is shown in Fig. 20.

Similar to the strength of UHPC, the dynamic modulus of elasticity increased with the content of steel fibers. After 180F-T cycles for REF, SF0.5, SF1.0, SF1.5 and SF2.0, the following decreases in dynamic modulus were recorded: 3.6 %, 4.6 %, 5.3 %, 2.8 % and 2.6 %. In all cases, the relative dynamic modulus did not drop below 94 % of the initial value and hence it can be inferred that UHPC containing 0.5–2 % steel fibers is frost resistant.

The average mass losses of the cube specimens after 180F-T cycles with error bars are presented in Fig. 21. The weight loss increased with increasing steel fiber content. Ultra-high performance concretes with a steel fiber content of 0.5–2 % were characterized by a weight loss that was 4.4, 11.5, 17.9 and 27.7 times greater, respectively, than the REF concrete. This was directly related to the larger amount of pores with

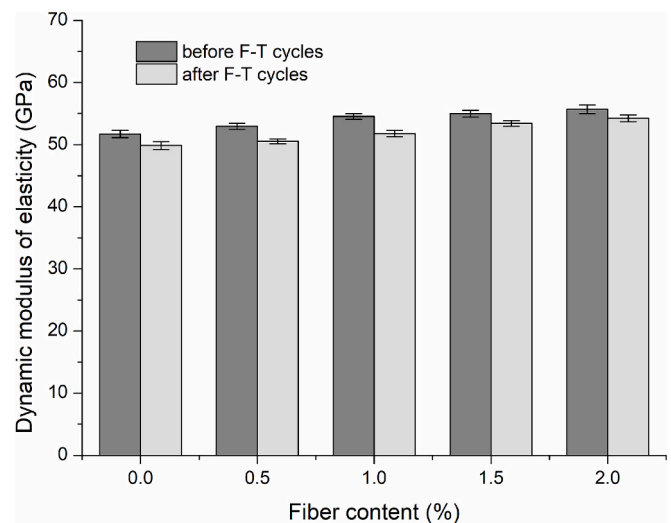


Fig. 20. Dynamic elastic modulus of UHPC before and after F-T cycles depending on steel fiber content.

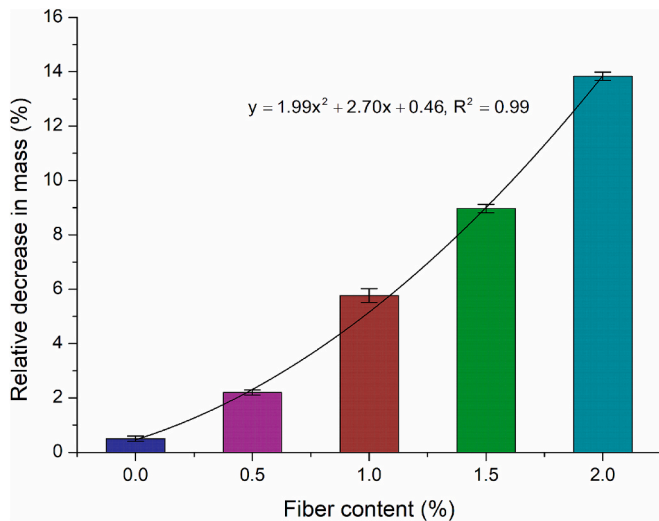


Fig. 21. Average mass loss of UHPC after 180F-T cycles depending on steel fiber content.

increasing addition of steel fibers (see Fig. 4). The ice swelling pressure was high enough to create microcracks, which transformed into macrocracks during the phase of cyclic freezing of water in the pores. Because of the fact that pores were also formed at the fiber–matrix interface, at a later stage the cracked pieces of concrete surrounding the fibers located near the edge surfaces of the specimens were chipped off. This process was observed in previous studies of ultra-high performance concretes containing a maximum percentage of steel fibers of 1 % [2]. On the other hand, Cwirzen et al. [5] noted that the fraction of steel fibers appeared to reduce the internal degradation of the material resulting from freeze-thaw cycles, which was probably owing to the use of short high-strength steel fibers in the UHPC production. The significantly smaller grain size of the applied aggregate compared to the present examinations also had an impact on the improvement in frost resistance.

The relation between the mass loss percentage following the frost resistance test and the steel fiber volume content was determined. This correlation can be described by the following equation: $y = 1.99x^2 + 2.70x + 0.46$. The polynomial trend was characterized by a strong correlation coefficient $R^2 = 0.99$ and very low intercept errors. The proposed equation can be successfully used to predict the relationship between the mass loss of ultra-high performance concrete after cyclic freezing-thawing and the volume content of steel fibers.

4. Conclusions

This research develops ultra-high performance concrete at a reduced costs. In the production of UHPC, only steel fibers of normal strength are used, the proportion of powders is reduced by using coarse basalt aggregate, eliminated quartz sand by using natural sand, and eliminated high-pressure compaction and heat treatment. In the experiments, very good mechanical and physical properties of UHPC containing steel fibers are obtained at various maturation ages.

On the basis of discussions put forward in this paper, the following conclusions have been drawn:

- The porosity, water absorption and density of ultra-high performance concrete containing steel fibers increases with increasing steel fiber content. These characteristics increase by 21 %, 76 % and 1.6 %, respectively, in comparison to the reference concrete for UHPC with a maximum fiber content of 2 %.
- There is a marginal decrease in the 28-day and a slight increase in the 56-day compressive strength of ultra-high performance concrete

having a fiber content above 1.5 %. Conversely, a considerable increase in the 730-day strength is achieved, which is 15.2 %, 20.4 % and 22.3 %, respectively, with the addition of 1 %, 1.5 % and 2 % fibers. The greatest increase in strength occurs between the 56th and 730th day of maturation of the UHPC specimens.

- The splitting tensile strength of UHPC grows along with the fiber additions up to 1.5 % and then decreases slightly at a fiber content of 2 %. There are significant strength gains of up to 38.6 %, 29.3 % and 55.9 % after 28, 56 and 730 days, respectively, compared to the strength of the REF control concrete. The splitting tensile strength of concrete rises with age, and the greatest increases in strength are obtained between 56 and 730 days of maturation.
- The trend of increasing flexural strength is analogous to that of splitting tensile strength, both with regard to the number of fibers and the age of the concrete. The obtained maximum strength gains are 43.6 %, 63.8 % and 94.9 % higher in comparison with the strength of UHPC without fibers after 28, 56 and 720 days of curing.
- The growth of steel fibers in ultra-high performance concrete shows enormous improvements in the energy absorption capacity (220–650 times) and fracture energy (175–520 times) compared to fiber-free concrete. It is worth emphasizing that the fracture parameters refer to 28 days.
- The modulus of elasticity of ultra-high performance concrete grows with age and with the steel fiber additions. The highest increases in the static and dynamic modulus, equal to 11 % in both cases, are obtained after two years of curing for SF1.5 and SF2.0, respectively.
- The steel fiber additions to ultra-high performance concrete shows a reduction in UPV from 1.5 % for SF2.0 to 4.5 % for SF0.5 relative to REF. The UPV decreases are marginal, so the steel fiber additions do not have an impact on the uniformity of the UHPC.
- The dynamic modulus of UHPC reinforced with steel fibers does not decrease by more than 6 % following 180F-T cycles. On the other hand, these concretes lose mass from 4.5 to 28 times greater than the control concrete, which is closely related to their greater porosity with the addition of fibers.
- Strong relationships are proposed between the dynamic and static modulus of elasticity, the compressive strength and the ultrasonic pulse velocity, in addition to the percentage of mass loss following the frost resistance test, as well as the volume content of steel fibers for ultra-high performance concretes reinforced with fibers at a content of 0.5 %-2%.
- The results obtained for concrete containing 0.5–2 % steel fibers over a long curing age indicate that 50 mm long hook-ended steel fibers can be successfully used in the production of durable ultra-high performance concrete.
- Further research on ultra-high performance concrete reinforced with different types of fibers and the assessment of their microstructure are planned.

Data availability Statement

The data that support the findings of this study are available from the corresponding author, P.S., upon reasonable request.

CRediT authorship contribution statement

Piotr Smarzewski: Conceptualization, Funding acquisition, Methodology, Resources, Validation, Writing – review & editing, Formal analysis, Software, Writing – original draft, Data curation, Investigation, Project administration, Supervision, Visualization.

Declaration of competing interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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