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Research Article

Analyzing and examining the impact of various fiber types on the mechanical and functional characteristics of UHPC

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Abstract

In this research, we compared the performance and mechanical properties of (UHPC) produced with varying percentages of waste and recycled fibers, including polypropylene plastic (plastic sack fibers) (PP), polyethylene terephthalate (PET), date palm fibers (DP), Monterey pine tree fibers (MP), human hair (HH), and aluminum (from metal cans) (AF). This was done in relation to a control sample of UHPC (WC). The study investigated the effects of different percentages of these fibers (0, 0.5, 1, 1.5, and 2 percent by weight of cement) with a length of 3 cm in self-compacting concrete. We conducted tests on fresh concrete, including Slump Flow, J-Ring, V-Funnel, L-Box, and U-Box, as well as tests on hardened concrete, such as compressive strength, tensile strength, permeability, crack width control, thermal cracking, Schmidt hammer tests, and ultrasonic pulse velocity. The results indicated that increasing the percentage of fibers (PP, PET, DP, AF, MP, and HH) in UHPC enhances tensile strength, reduces permeability, and increases compressive strength. Additionally, under the influence of temperature, a decrease in both the depth and length of cracks was observed in the concrete slabs. Notably, the inclusion of 2% human hair fibers (HH) in UHPC resulted in superior tensile strength, reduced permeability, and minimized both the length and depth of cracks compared to other fiber types. Conversely, the addition of 2% aluminum fibers (AF) led to a reduction in tensile strength, an increase in permeability, and an increase in both the length and depth of cracks. This research demonstrated that, in terms of mechanical and functional properties, human hair fibers provided better results in UHPC across all tests conducted, significantly enhancing the longevity of the structure.

1. Introduction

Concrete is a composite material that is extensively utilized in the construction industry worldwide [1-3]. It possesses the ability to withstand applied loads without deformation [4-6]. One of the unique features of concrete is its efficiency and fluidity, allowing it to be easily molded into various shapes; thus, it is regarded as the most widely used material in construction [7]. In civil engineering, there has been a growing interest in self-compacting concrete [8]. This type of concrete is still under development and offers a wide range of applications and properties [9]. Self-compacting concrete is characterized by its ability to fill molds easily, even in the presence of reinforcement bars (rebars). Self-compacting concrete can be classified based on four key characteristics: flowability, viscosity, ability to pass through reinforcement, and resistance to segregation. Due to its high viscosity and ability to spread, it fills molds under its own weight and is widely employed [10-13]. The stability of self-compacting concrete encompasses two aspects: 1) Static stability, which

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refers to the ability to resist the separation of paste and aggregate, and 2) Dynamic stability, which pertains to the ability to maintain a uniform distribution of aggregates during the mixing process [14-16]. When combined with rebars, self-compacting concrete enhances the tensile strength and overall tensile properties of the material [17-19]. However, self-compacting concrete (SCC) generally exhibits low flexural strength, low tensile strength, and poor resistance to cracking and shrinkage. Research indicates that the addition of fibers to self-compacting concrete can significantly improve the properties of hardened concrete [20-22]. The incorporation of fibers in concrete offers numerous benefits, including the prevention of sudden failure, enhancement of fracture energy, reduction of crack width, minimization of shrinkage, and increases in flexural strength, tensile strength, and toughness [23-25]. Factors such as fiber type, length, mass, length-to-diameter ratio, shape, surface roughness, and the configuration of fiber ends can directly influence the properties of both fresh and hardened concrete. Fibers have been used to reinforce concrete since ancient times. The inclusion of waste or recycled fibers in concrete can reduce the demand for industrial fibers [26]. This practice contributes to the sustainability of the concrete industry by minimizing environmental pollution and the disposal of industrial waste. Consequently, it presents one of the most viable environmental solutions for the disposal and recycling of industrial waste [27]. Self-compacting concrete reinforced with artificial or natural fibers is effective in enhancing tensile strength, bending behavior, impact resistance, temperature stability, heat transfer, fire resistance, crack control, and overall durability [28]. The addition of fibers to concrete is an efficient method for improving its properties [25]. Fiber-reinforced concrete exhibits enhanced tensile strength, ductility, and resistance to cracking. The fibers act as crack arresters and also reduce the porosity and permeability of concrete, thereby improving its mechanical properties, impact resistance, and reducing brittleness [29]. Compaction of concrete is a crucial factor in maintaining the uniformity and integrity of a structure. Improper compaction can lead to the formation of honeycombs, trapped air, cold seams, and subsidence cracks, all of which contribute to permeability issues, corrosion of steel, and a reduction in the final load-bearing capacity. Research has shown that incorporating fibers into concrete can mitigate these problems [30-31]. Numerous studies have been conducted on the use of fibers to enhance the properties of concrete, and several examples are reviewed below:

Mirabi Moghadam [32] investigated the effect of the shape and quantity of date palm fibers on the tensile strength of concrete. Manjunat et al. [33] conducted an experimental study in 2021 on the use of human hair as fibers to enhance the performance of concrete. Patel et al. [34] reviewed the research on cement concrete reinforced with human hair in 2021. In 2022, Omar et al. [35] examined the impact of human hair fibers on the performance of concrete containing a high dosage of silica fume. Mustafa [36] also in 2022, explored the mechanical properties of high-performance self-compacting concrete reinforced with red pine needle fibers. Jaskowska et al. [39] investigated the properties of self-compacting concrete incorporating plastic waste as aggregate in 2022. Janata et al. [42] evaluated the addition of polypropylene (PP) fibers to self-compacting concrete in 2023 to mitigate cracking and plastic shrinkage. Derakhshan Nezhad et al. [46] in 2024 studied the use of date palm fibers to enhance tensile strength in self-compacting concrete with silica fume. Mirzaie Aliabadi et al. [47] conducted a laboratory investigation in 2024 on the effects of plastic packaging belt fibers and iron oxide on the mechanical properties of self-compacting concrete. Rashidi et al. [48] compared the effects of crushed cement blocks and construction waste on the fresh and hardened properties of self-compacting concrete in 2024. Asghari Pari et al. [49] investigated the influence of rust and iron shavings on the mechanical properties of self-compacting concrete in 2024. Shahidzade et al. [50] examined the effect of palm fibers on the mechanical properties of self-compacting concrete in 2024. Finally, Derakhshan Nezhad et al. [51] studied the impact of recycled polyethylene terephthalate fibers on the mechanical properties of self-compacting concrete in 2024. Reason: Improved clarity, readability, and technical accuracy by correcting grammatical errors, enhancing vocabulary, and ensuring consistent formatting.

This research is similar to the studies conducted by Mirabi Moghadam [32], Omar [35], Manjunat [33], Janata [42], and Mustafa [36]. However, it differs from these studies in that it incorporates ultrasonic testing, thermal cracking analysis, and the use of nano silica fume in the concrete slab samples. A key aspect of scientific advancement is the emphasis on sustainable development. Sustainable development involves utilizing existing resources and facilities while considering the needs of future generations, ensuring the optimal use of natural resources. Extensive research has been conducted on the potential of using natural or artificial fibers to enhance the tensile and compressive strength of concrete. Fibers serve as an effective solution for improving tensile strength, reducing permeability, enhancing compressive durability, mitigating thermal cracking, and controlling the width of concrete cracks. The innovative aspect of this project lies in the optimal utilization of recycled waste materials, which minimizes waste and environmental pollution. Additionally, nano silica gel was employed to enhance strength, reinforce the transition zone of concrete (the third phase), and utilize Viscosity Modifying Agents (VMA) to control the rheological properties in this mix design. These elements contribute to the innovative nature of this research. In this study, we investigate the mechanical and physical behavior, durability, compressive strength, and tensile strength of (UHPC) with various fibers, including plastic, wood, and metal. The specific fibers examined include polypropylene (PP), polyethylene terephthalate (PT), date palm (DP), Monterey pine (MP), human hair (HH), and aluminum (AF). The objective of this research is to compare the effects of different types of fibers on the properties of both fresh and hardened UHPC, focusing on their impact on tensile strength, concrete durability (as measured by permeability tests), crack width control in concrete slabs, ultrasonic pulse velocity, Schmidt hammer tests, thermal cracking, tensile strength, and compressive strength.

2. consumables

2.1. Materials utilized in the construction of UHPC

2.1.1. Cement

Choosing the appropriate type of cement for Ultra-High-Performance Concrete (UHPC) is crucial. Type II Portland cement was utilized in the mixture design, in accordance with the ASTM C150 standard [52] (as shown in Table 1).

Table 1. Type II Portland Cement

SO_3	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	Chemical analysis
0.68	2.08	65.40	3.88	4.82	21.68	Percent
C_3A	C_2S	C_3S	LOI	K_2O	Na_2O	Chemical analysis
6.21	14.46	60.63	0.20	0.88	0.25	Percent

2.1.2. Specifications of Types of Fibers (Plastic, Wood, Metal)

- Polypropylene Fibers (PP) (Plastic Sack Fibers)

Polypropylene fibers are utilized as a reinforcing material in concrete, offering several advantages, including: enhanced durability of fiber-reinforced concrete, reduced surface cracking, increased corrosion resistance, minimized shrinkage, improved flexibility, chemical resistance, and strengthened mechanical properties against hardness and impact. Additionally, they provide resistance to freezing and thawing, decreased corrosion and magnetism, and enhanced performance in wet environments, as well as increased bending and tensile strength while reducing both cracking and plastic shrinkage cracking. In general, polypropylene fibers are widely employed in various concrete applications to enhance performance and meet specific engineering requirements. Polypropylene is a semi-crystalline polymer composed of propylene monomers, and this semi-crystalline structure imparts flexibility and high mechanical strength to the fibers. The relatively low melting point of polypropylene makes it suitable for many low- to medium-temperature applications. Furthermore, polypropylene exhibits resistance to many acids, bases, organic solvents, and chemicals, a property attributed to its non-polar structure and long hydrocarbon chains. However, polypropylene has limited resistance to ultraviolet (UV) rays, which can cause it to degrade and become brittle when exposed to sunlight. This UV resistance can be improved by incorporating UV stabilizers. Due to its non-polar nature, polypropylene also has minimal water absorption, making it an ideal choice for use in humid environments.

- Polyethylene Terephthalate Fibers (PTF)

Polyethylene terephthalate (PET) is the primary and most common component in various types of plastic bottles that are discarded after use. One innovative application of polyethylene terephthalate is its use as thin fibers in construction, specifically as an additive in concrete. Incorporating polyethylene terephthalate fibers into concrete results in several benefits, including enhanced malleability, increased tensile strength, reduced permeability, and improved durability. Additionally, it offers heightened chemical and thermal resistance, impact resistance, and increased thermal stability at elevated temperatures. The use of PET fibers contributes to greater tensile durability and aesthetic appeal, while also reducing the overall weight of the concrete. It helps minimize surface cracks, enhances corrosion resistance, controls cracking, reduces plastic shrinkage cracking, improves impact resistance, and increases bending strength. PET is a thermoplastic polymer synthesized from terephthalic acid and ethylene glycol. Its crystalline structure endows PET with high mechanical strength and hardness. While PET is resistant to weak and strong acids, oils, and alcohols, it is susceptible to strong bases and concentrated acids. It exhibits very low water absorption, which helps maintain its mechanical properties in humid conditions. Although PET is stable against oxidation, it may decompose at extremely high temperatures, leading to a loss of its desirable properties.

Date Palm Fibers (DP)

The potential benefits of date palm fibers include increased tensile strength and flexibility, reduced weight, enhanced electrical insulation, improved heat resistance, greater corrosion resistance, and superior impact resistance. Additionally, they contribute to crack control, improved efficiency, reduced density, and sustainability, making them environmentally friendly. Generally, palm fiber is utilized in regions where palm trees are abundant, promoting the development of sustainable and eco-friendly construction methods. Date palm fibers possess a tubular structure with thick walls, composed of cellulose, hemicellulose, and lignin. This composition results in relatively high mechanical resistance. Cellulose provides high tensile strength, while lignin contributes to compression resistance and hardness. Due to their high lignin content, date palm fibers exhibit a degree of resistance to biodegradation; however, they may degrade in humid and hot environments. It is important to note that these fibers are not naturally resistant to insect and fungal attacks, necessitating protective treatments. Reason: Improved clarity, vocabulary, and technical accuracy while maintaining the original meaning.

- Monterey Pine Tree Fibers (MP)

The incorporation of pine tree fibers into concrete can enhance its various properties. Some potential benefits of using pine tree fibers in concrete include increased tensile strength, reduced surface cracking, improved impact resistance, decreased shrinkage, enhanced flexural and tensile strength, crack resistance, reduced permeability, lightweight characteristics, material stability, and increased efficiency. Pine tree fibers are particularly suitable for regions where pine trees are abundant, promoting the use of sustainable and locally sourced materials in construction. Their inclusion can significantly improve the mechanical performance of concrete and its resistance to external factors. While these fibers are resistant to humidity and typical environmental conditions, they are susceptible to strong solvents and concentrated acids. Due to their high lignin and hemicellulose content, pine tree fibers exhibit greater resistance to biodegradation compared to other plant fibers.

- Human Hair Fibers (HH)

Some potential effects of using human hair in various applications include increased tensile strength, improved crack control, environmental sustainability, lightweight properties, thermal insulation, enhanced flexibility, and reduced permeability. While human hair is commonly associated with beauty purposes, it also offers resistance to cracking. Human hair is composed of three main layers: the inner core (medulla), the middle layer (cortex), and the outer covering (cuticle). The cortex contains keratin fibers, which provide high tensile strength and elasticity. Keratin is a protein with a fibrous structure that includes sulfur-containing amino acids, such as cysteine. These amino acids form disulfide bridges that enhance tensile strength and flexibility. Hair is resistant to most acids and weak bases; however, it can be damaged by strong oxidizers and bases. Additionally, hair has the capacity to absorb moisture, allowing it to swell and shrink in response to changes in environmental humidity. Reason: The revised text improves clarity, enhances vocabulary, and corrects grammatical errors while maintaining the original meaning.

- Aluminum Fibers (AF)

Some potential effects include increased heat resistance, reduced weight, enhanced flexibility, corrosion resistance, improved tensile strength, better bending strength, improved conductivity, decreased density, and greater resistance to impact.


MP DP PP

PT AF HH

Fig. 1. Types of fibers (plastic, wood, metal)

Aluminum fibers are frequently utilized in specialized concrete applications where their unique properties are advantageous, such as in projects that demand conductivity or resilience against harsh environmental conditions.

Table 2. Specifications of types of fibers (plastic, wood, metal)

Diameter (mm)	Thermal bending temperature	Melting point (℃)	Elongation in submission	Elongation at failure	Tensile strength (MPa)	Tensile strength (MPa)	Water absorption (24 hours)	Special Weight (gr/cm^3)	Modulus of elasticity (GPa)	Type of fiber	No
0.7	67	207	3.6%	30%	0.08	341	8%	0.90	1.8	(PP)	1
0.6	54	177	1.2%	26%	0.06	725	27%	0.67	4	(PT)	2
0.5	86	277	0.8%	12%	0.07	70	57%	0.80	0.782	(DP)	3
0.9	88	286	0.7%	10%	0.07	61	62%	0.71	0.682	(MP)	4
0.4	80	300	0.9%	17%	0.08	526	52%	0.86	1	(HH)	5
0.8	130	670	5%	53%	0.003	9570	5%	2.7	10	(AF)	6

2.1.3. Aggregates

Almond sand that passed through a 1/2-inch sieve and sand that passed through an 8-inch sieve were used, in accordance with the ASTM C33 standard [53], as indicated in Table 3.

Table 3. detailed specifications of the aggregates

Aggregate type	SSD (gr/m^3)	Water absorption percentage	Bulk Density (kg/m^3)	Fineness Modulus
Coarse aggregate	2.571	1.3	1526	6.3
Sand	2.544	1.8	1489	2.5

2.1.4. Super Lubricant And Nano Silica Gel

Super Plast PC5000 carboxylate superlubricants are among the most widely utilized chemical additives in high-performance and self-compacting concretes. This research employed these additives, which are based on carboxylate chemistry. By reducing the water-to-cement ratio, the capillary pores within the cement matrix are minimized, enhancing the hydration process of the cement and significantly increasing the compressive strength of the concrete.

Table 4. Mechanical Characteristics of Nano Silica and Super Lubricants

Special Weight (kg/m^3)	Color	PH	Specific gravity (kg/liter)	physical condition	Characteristics
Super lubricant					
1.008	yellow	6	1.1	liquid	Specifications
Nano silica gel					
325	Black	8	1.6	thick liquid	Specifications

To achieve the mechanical properties characteristic of ultra-high-performance concrete (UHPC), nanosilica—derived from nanopolycarboxylate—was utilized as both a water-reducing agent and a reinforcement for exceptionally strong concrete, in accordance with ASTM C 494 standards [54] (refer to Table 4).

2.1.5. Water

Potable water was utilized in the formulation of the (UHPC) mix for producing and processing the samples, in compliance with the requirements outlined in ASTM C 94 [55] (refer to Table 5).

Table 5. Characteristics of Drinking Water

Chloride ion concentration	PH	Temperature (Celsius)	Characteristics
50	6	20	amount of

2.1.6. Limestone Powder

One essential material for achieving the proper viscosity in (UHPC) is stone powder. As a filler, stone powder possesses a very high specific surface area, which enhances the friction between the particles and consequently increases the viscosity of UHPC.

Table 6. Qom Limestone Powder

LOI	SO_3	Cao	MgO	Fe_2O_3	Al_2O_3	SiO_2	Chemical analysis
43.2	1.24	51.22	0.81	0.5	0.35	2.8	Percent

2.1.7. *Viscosity Modifying Admixtures (VMA)*

VMA powder admixture is designed to produce (UHPC) with enhanced viscosity and controlled rheological properties. VMA is crucial for regulating excess water in concrete, in accordance with the ASTM C 494/C 494M standard [54-56] (as illustrated in Figure 2).

1

2

3

4

5

6

7 8 9

Fig. 2. Materials: UHPC (1. Cement, 2. Stone powder, 3. Viscosity-modifying agent (VMA), 4. Coarse aggregate, 5. Nano silica gel, 6. Pea gravel, 7. Superplasticizer, 8. Sand, 9. Water)

2.2. Mixed Design

25 designs of Ultra-High-Performance Concrete (UHPC) mixes were investigated, focusing on the effects of various fibers on different bases (plastic, wood, metal). The fiber percentages were varied in different ratios: 0%, 0.5%, 1%, 1.5%, and 2% by cement weight. In all 25 mixed designs, the total amount of materials remained constant, while the percentages of the different types of fibers were adjusted (as shown in Table 7). The material units are expressed in kg/m^3, with a concrete grade of 400 and a water-to-cement ratio of 0.31.

Table 7. Mixing Plan for UHPC with and without fibers

Nano silica gel	fibers (plastic, wood, metal)	VMA	Stone powder	super lubricant	Water	sand	Almond sand	pea gravel	Cement
Self-compacting concrete without fibers (control)) 0%									
7	-	0.167	60	12	126	990	250	550	400
Self-compacting concrete with 0.5% fibers									
7	2	0.167	60	12	126	990	250	550	400
Self-compacting concrete with 1% fibers									
7	4	0.167	60	12	126	990	250	550	400
Self-compacting concrete with 1.5% fibers									
7	6	0.167	60	12	126	990	250	550	400
Self-compacting concrete with 2% fibers									
7	8	0.167	60	12	126	990	250	550	400

2.3. Conducting the Test

After mixing the materials in the mixer, it is essential to test the properties of fresh (UHPC) both with and without fibers. In this research, the average percentage of each UHPC variant with the respective fibers is detailed in the results and tests.

Table 8. Symbols for Each Fiber Used in the UHPC Mix Design

No	Fibers	Symbol	Percentage	L/D*	Symbol of total percentages
1	Polypropylene	PP	0.5, 1, 1.5, 2	42.85	PP 0.5 – 2%
2	polyethylene terephthalate	PT	0.5, 1, 1.5, 2	50	PT 0.5 – 2%
3	Date palm	DP	0.5, 1, 1.5, 2	60	DP 0.5 – 2%
4	Monterey pine tree	MP	0.5, 1, 1.5, 2	33.33	MP 0.5 – 2%
5	Human hair	HH	0.5, 1, 1.5, 2	75	HH 0.5 – 2%
6	Aluminum	AF	0.5, 1, 1.5, 2	37.5	AF 0.5 – 2%

*Fiber length to diameter ratio

2.3.1. Slump Flow Test

Slump flow testing is a widely used method for assessing the performance of (UHPC) due to its simplicity. The results of the slump flow test, presented in Figure 3, are based on the average measurements.

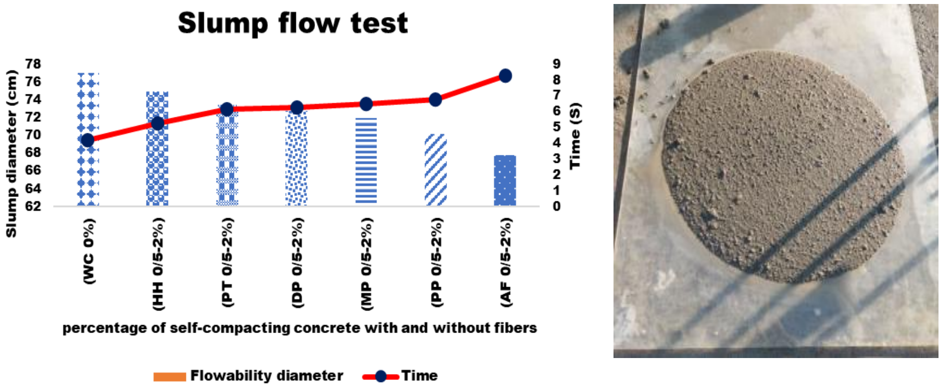

Fig. 3. Slump flow test

The average results of the slump flow test indicated that the water-cement ratio (WC) at 0%, hybrid fibers (HH) at 2-0.5%, polypropylene fibers (PT) at 2-0.5%, and other fibers such as diatomaceous earth (DP) at 2-0.5%, mineral powder (MP) at 2-0.5%, polyethylene fibers (PP) at 2-0.5%, and aramid fibers (AF) at 2-0.5% respectively. By increasing the percentage of fibers in (UHPC), the slump diameter (flowability) decreased by 2.59%, 4.54%, 5.45%, 6.49%, 8.83%, and 11.94% compared to the control UHPC. Additionally, the slump flow time increased by 1.1, 2.0, 2.2, 2.4, 2.8, and 4.1 seconds respectively compared to the control UHPC. This change is attributed to the diameter and water absorption characteristics of the fibers, which influenced the viscosity and flowability of the UHPC. This test adheres to the ASTM C1611 standard [57]. The order of the effect of fibers on the slump flow test is as follows:

- Slump diameter: (WC) > (HH) > (PT) > (DP) > (MP) > (PP) > (AF)
- Time: (WC) < (HH) < (PT) < (DP) < (MP) < (PP) < (AF)

2.3.2. V-Funnel Testing

The V-Funnel test is conducted to assess the ability of (UHPC) to change flow direction and flow characteristics. The results of the V-Funnel test are presented in Figure 4. The average results of the momentary V-Funnel test and the 5-minute V-Funnel test indicated that as the percentage of various types of fibers increased specifically, (WC 0%), (HH 0.5-2%), (PT 0.5-2%), (DP 2-0.5%), (MP 2-0.5%), (PP 2-0.5%), and (AF 2-0.5%)—the duration of the tests increased to 0.8, 1.7, 2.5, 3.2, 4.1, and 5.3 seconds for the momentary test, and 1.2, 2.1, 3.2, 4.3, 4.9, and 6.6 seconds for the 5-minute test, respectively. This increase in time compared to the UHPC (control) can be attributed to the type, diameter, and texture of the fibers used, in accordance with the ISISIR 3203-9 standard [58]. The order of influence of the fibers on the V-Funnel test is as follows:

- Time: (WC) < (HH) < (PT) < (DP) < (MP) < (PP) < (AF)

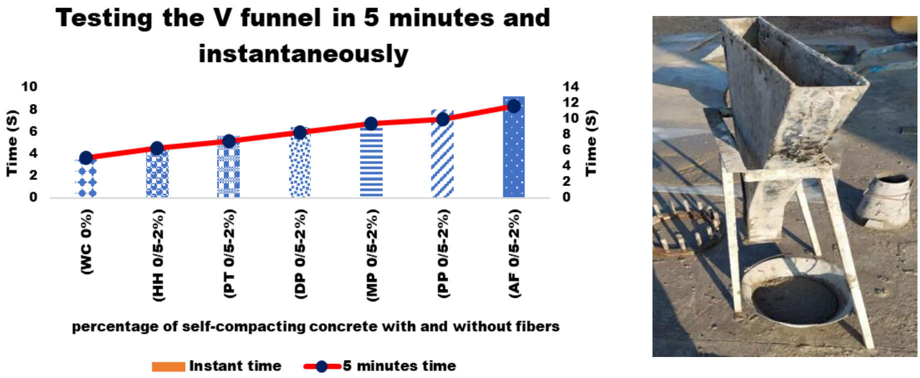

Fig. 4. V-Funnel test

2.3.3. L-Box Test

The L-Box test evaluates the flow of concrete between rebars, its stability against grain separation, and its fillability. The results of the L-Box test are presented in Figure 5.

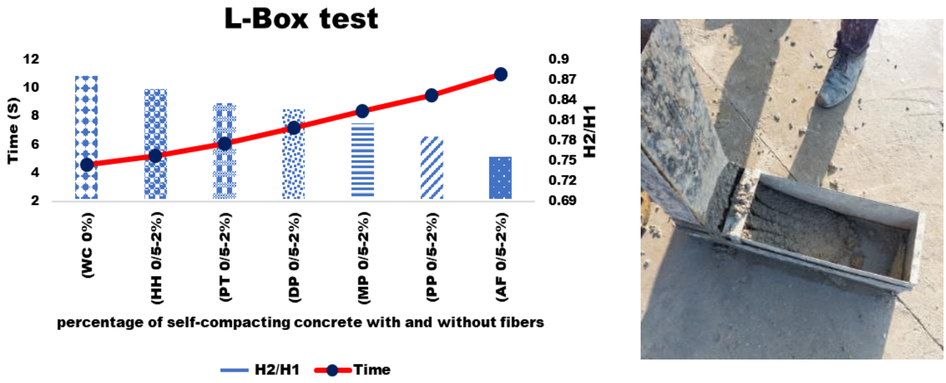

Fig. 5. L-Box test

The average results of the L-Box test indicated that as the percentage of various types of fibers increased—specifically (WC 0%), (HH 2-0.5%), (PT 2-0.5%), (DP 0.5%-2%), (MP 2-0.5%), (PP 2-0.5%), and (AF 2-0.5%)—the test duration also increased, with recorded times of 0.6, 1.5, 2.6, 2.8, 4.9, and 6.4 seconds, respectively. The heights of the concrete at the end of the horizontal section (H2) and the end of the vertical section (H1) were measured, and the ratio H2/H1, known as the document ratio, was calculated. As the percentage of different types of fibers increased, the document ratio decreased by 2.27%, 4.54%, 5.68%, 7.95%, 10.22%, and 13.63%, in accordance with the INSO 3203-10 standard [59].

- Proportion of documents: (WC) > (HH) > (PT) > (DP) > (MP) > (PP) > (AF)
- Time:(WC) < (HH) < (PT) < (DP) < (MP) < (PP) < (AF)

2.3.4. J-Ring Test

The J-Ring test simulates the flow of concrete through reinforcing bars (rebars) and is used to assess its passability. The results of the J-Ring test are presented in Figure 6.

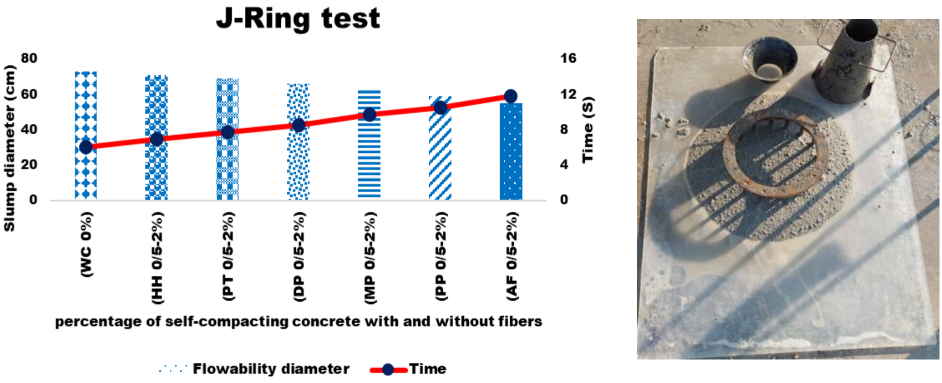

Fig 6. J-Ring test

The results of the J-Ring test indicated that as the percentage of various types of fibers increased—specifically, (WC 0%), (HH 0.5-2%), (PT 2-0.5%), (DP 0.5%-2%), (MP 0.5-2%), (PP 0.5-2%), and (AF 0.5-2%)—the slump diameter (flowability) decreased to 2.73%, 5.47%, 9.58%, 13.69%, 19.17%, and 24.65% compared to the (UHPC) control. Additionally, the time decreased by 0.9, 1.7, 2.5, 3.7, 4.5, and 5.7 seconds compared to the self-compacting concrete control. This effect can be attributed to the diameter of the fibers and their effective texture, as tested according to the INSO 11271 standard [60]. Order of influence of fibers on the J-Ring test:

- Slump diameter:(WC) > (HH) > (PT) > (DP) > (MP) > (PP) > (AF)
- Time:(WC) < (HH) < (PT) < (DP) < (MP) < (PP) < (AF)

2.3.5. U-Box Testing

U-box is utilized to assess the filling ability and flowability of concrete. The results of the U-box test are presented in Figure 7. The results of the U-Box test indicated that as the percentage of various types of fibers increased—specifically, (WC 0%), (HH 0.5-2%), (PT 2-0.5%), (DP 2-5.0%), (MP 0.5-2%), (PP 0.5-2%), and (AF 0.5-2%)—the time taken for the test increased to 1.1, 1.8, 2.5, 3.8, 5, and 6.6 seconds, respectively, compared to self-compacting concrete (control). Additionally, the difference in the height of concrete in the two ducts (H2-H1) increased to 1.5, 3, 4, 5.6, 7, and 11 millimeters, respectively, when compared to ultra-high-performance concrete (UHPC) (control). The difference in concrete height between the two ducts (H2-H1) was less than 30 mm, which was deemed acceptable. This test adheres to the UNI 11044 standard [61]. The order of influence of the fibers on the U-Box test is as follows:

- H2-H1: (WC) < (HH) < (PT) < (DP) < (MP) < (PP) < (AF)
- Time: (WC) < (HH) < (PT) < (DP) < (MP) < (PP) < (AF)

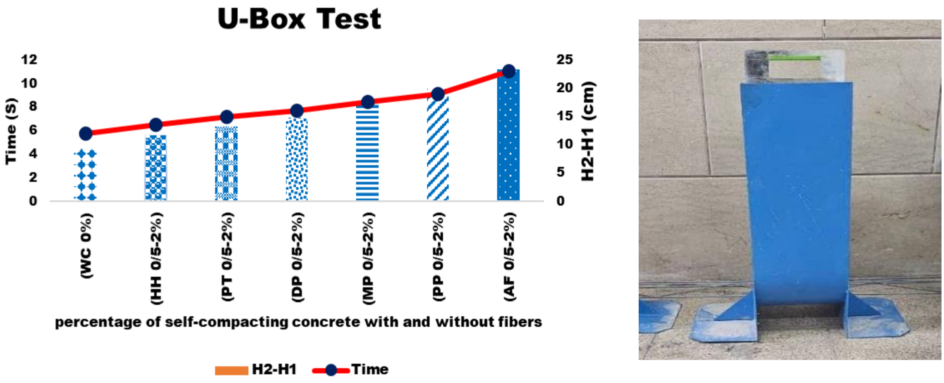

Fig 7. U-Box test

2.4. Sample Processing

Fresh concrete was cast in cubic molds measuring 15 cm x 15 cm x 15 cm and in cylindrical molds measuring 15 cm in diameter and 30 cm in height. After 24 hours, the samples were removed from the molds and submerged in water for curing over periods of 7 and 28 days. A total of 1,500 ultra-high-performance concrete (UHPC) samples were produced, both with and without fibers. Ultimately, the test results were compared to those of high-strength self-compacting concrete without fibers, which served as the control group.

2.5. Schmidt Hammer Test

The Schmidt Hammer (SH) test was employed to assess the compressive strength of both cubic and cylindrical samples. Schmidt's hammer is utilized to evaluate the properties of elastic materials, particularly for measuring the compressive strength of concrete. Today, the SH test is recognized as a non-destructive testing method and has recently become an effective tool for assessing the surface resistance of materials based on their hardness [51]. In this study, reliable readings and index values were recorded using the Schmidt Hammer on the samples, and the average results were documented in accordance with the ISO 1920-7 standard [67] (refer to Figures 8-9). The results of tests on cubic and cylindrical specimens showed that by adding different types of fibers (plastic, wood and metal) to UHPC, the compressive strength decreases with the Schmidt hammer test.

The reason for the decrease in the compressive strength test with the SH for cubic and cylindrical specimens is due to the amount of fibers, their shape and dispersion in concrete. Also, there is a decrease in the compressive strength of the samples with an increase in the percentage of non-adhesion fibers between cement and aggregates in concrete. The effect of different types of fibers in UHPC of cubic and cylindrical specimens with SH test

- Pushing Resistance: (WC)>(AF)> (DP)> (MP)> (HH)> (PT)> (PP)

Fig. 8. Hardness Testing on Cubic and Cylindrical Specimens

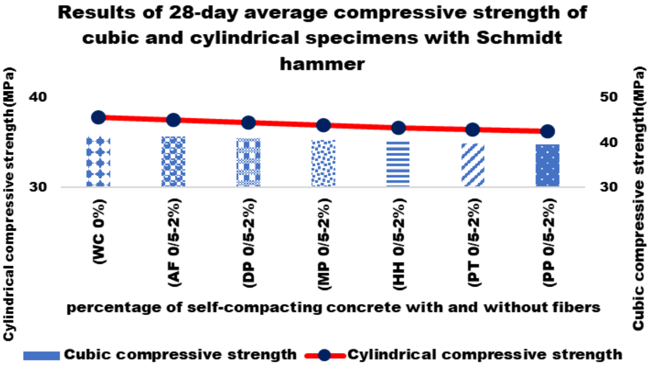

Fig. 9. The average results of the SH test for cubic and cylindrical samples after 28 days of processing

2.6. UPV Test

The UPV (Ultrasonic Pulse Velocity) test is a non-destructive testing method used to assess the homogeneity, uniformity, quality, wear, and the presence of defects, cavities, and internal voids in hardened concrete. The pulse frequency ranges from 20 to 170 kHz. The direct method was employed for this test, with the distance between the two ultrasonic transducers set at 15 cm for cubic samples and 30 cm for cylindrical samples, in accordance with the ISO 1920-7 standard [67] (see Figures 10-11).

Fig. 10. UPV Testing on Cubic and Cylindrical Specimens

The results of the tests conducted on cubic and cylindrical specimens indicated that the addition of various fibers to (UHPC) led to a gradual decrease in the speed of the ultrasonic pulse, which varied based on the type, material, and diameter of each fiber. The reduction in the (UPV) test results for UHPC can be attributed to the quantity, shape, and distribution of the fibers within the concrete. Furthermore, the decrease in pulse speed with an increasing percentage of fibers in the concrete samples is due to the effective water absorption by the fibers, which negatively impacted the results of the pulse speed test.

$$KM/S = \frac{CM}{MS} \times 10 \tag{1}$$

- Ultrasonic Pulse Speed: (WC)>(HH)> (PT)> (DP)> (MP)> (PP)> (AF)

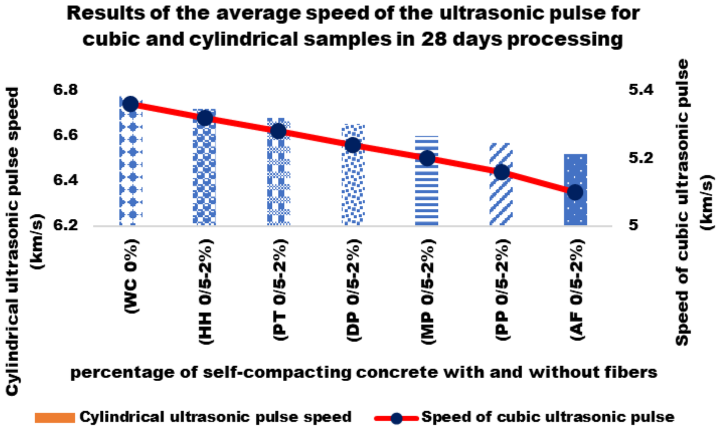

Fig. 11. UPV Test Results for Cubic and Cylindrical Samples After 28 Days of Processing

2.7. Penetration Testing of Cubic Specimens

The permeability test of (UHPC) was conducted on cubic and cylindrical samples, measuring 15 cm × 15 cm × 15 cm and 10 cm × 30 cm, respectively, to assess the durability of the samples. The performance and permeability of concrete are closely linked to its durability, particularly its resistance to gradual deterioration when exposed to extreme weather conditions, as well as compaction and settlement caused by water penetration.

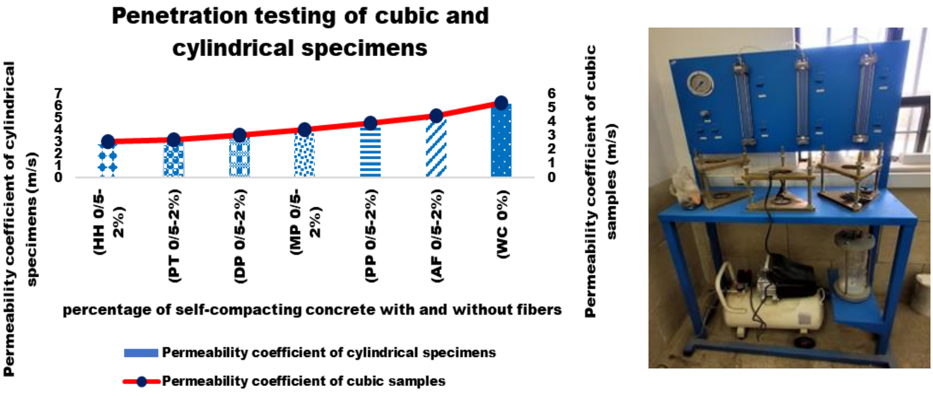

Fig. 12. Concrete Permeability Device and Its Test Results

Using various types of fibers with different textures and diameters in ultra-high-performance concrete (UHPC) can effectively reduce the permeability of the material. Each type of fiber possesses excellent mechanical properties, contributing to the overall strength and bond between the concrete and the fibers. These fibers can help control spalling and cracking while enhancing the concrete's strength as a reinforcing agent. By incorporating fibers into the concrete mix, both the mechanical and physical properties of the concrete are improved, leading to reduced permeability. Additionally, fibers can enhance the internal structure of concrete, including its strength, flexibility, and water resistance. Notably, human hair fibers demonstrated the lowest permeability in concrete tests, thereby increasing the durability of the concrete. This study examines the impact of different fiber types on the permeability of UHPC in both cubic and cylindrical samples.

- Permeability:(HH)<(PT)<(DP)<(MP)<(PP)<(AF)<(WC)

2.8. Thermal Cracking

2.8.1. Thermal Cracking Formula In UHPC

In (UHPC), thermal cracks develop when temperature fluctuations induce compressive stresses that exceed the concrete's compressive strength. Thermal cracking in concrete occurs due to non-uniform contraction or expansion resulting from temperature changes. This type of cracking is particularly prevalent in large concrete structures, such as dams, thick walls, and extensive foundations. In bulk concrete, the high rate of cement hydration can cause the internal temperature to rise significantly, while the outer surface, exposed to air, may remain cooler. This temperature gradient can generate tensile stresses on the outer surface, ultimately leading to cracking.

2.8.2. Factors affecting thermal cracking

- Temperature gradient (T):

When there is a significant temperature difference between the inner and outer sections of the concrete, it can result in tensile stresses in the cooler areas and compressive stresses in the warmer areas.

Modulus of elasticity (E):

Concrete with a high modulus of elasticity (harder) tends to resist deformation, which can lead to increased internal stresses within the material.

- Thermal expansion coefficient (Alpha):

Concrete with a high thermal expansion coefficient undergoes greater longitudinal changes in response to temperature fluctuations, which can lead to the development of thermal stresses.

- Mechanical properties of concrete:

The compressive strength of concrete and the modulus of rupture play a crucial role in its resistance to thermal cracking. Concrete with high compressive strength and a high modulus of rupture can better withstand the compressive stresses that develop.

2.8.3. Thermal Cracking Prediction Models

In this section, response surface methodology (RSM) analysis was employed to investigate the thermal cracking of self-compacting concrete, both with and without fibers. The use of various additives, the selection of different types of cement, the control of processing conditions, and the choice of fiber types can significantly reduce the risk of thermal cracking. For instance, utilizing low-heat cements or incorporating fibers can decrease the heat of hydration, thereby minimizing the occurrence of thermal cracking. The stress associated with thermal cracking can be calculated using the following Equation (2) [31]:

$$\sigma_{cr} = \frac{E \times \alpha \times T}{f} \tag{2}$$

In this formula, the cracking stress (MPa), the compressive strength of (UHPC) (MPa), Young's modulus of (UHPC) (MPa), the coefficient of linear thermal expansion of (UHPC) (1/°C), and temperature (°C) are all included.

Table 9. Results of Testing the Effect of Temperature on the Resistance of Cubic Samples and Thermal Cracking

		The minimum and maximum range of each value in terms of units				
No	Type of concrete	Cubic compressive strength (MPa)	Young's modulus (MPa)	Thermal expansion coefficient (1/°C)	Temperature (°C)	Cracking stress (MPa)
1	(WC 0%)	2.52 – 11.5	26 – 25.5	4 – 14	10 –160	0.02284 – 0.000097
2	(AF 0/5-2%)	3.31 – 11.94	26.5 – 25.7	3.9 – 13.8		0.017392 – 0.000093
3	(PP 0/5-2%)	3.80 – 12.38	27 – 26	3.8 – 13.6		0.015189 – 0.000090
4	(MP 0/5-2%)	4.15 – 12.81	27.3 – 26.5	3.6 – 13.3		0.013905 – 0.000087
5	(DP 0/5-2%)	4.37 – 13.68	27.7 – 27	3.4 – 13.1		0.013173 – 0.000081
6	(PT 0/5-2%)	4.95 – 14.6	28.2 – 27.9	3.2 – 13		0.011629 – 0.000076
7	(HH 0/5-2%)	5.92 – 15.25	28.6 – 28	3 – 12.9		0.009724 – 0.000073

- Thermal cracking in concrete: (HH)<(PT)<(DP)<(MP)<(PP)<(AF)<(WC)

Fig. 13. Cube testing in the drying oven and failure using the compressive strength device.

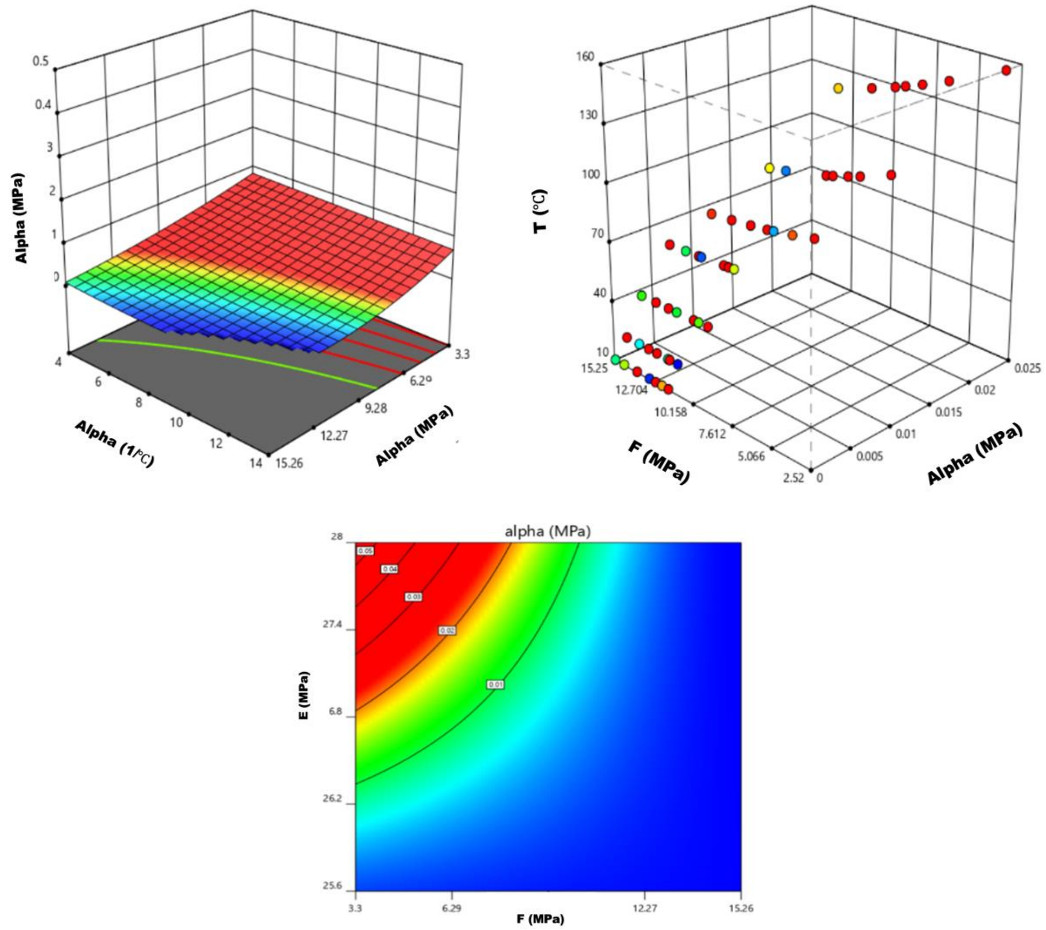

Fig. 14. Testing the Effects of Temperature on the Compressive and Tensile Strength of Cubic and Cylindrical Specimens

2.9. Crack Width Testing in Concrete Slabs with and without Various Types of Fibers

One of the primary factors threatening the durability of concrete is cracking in the concrete slab. Cracks in concrete serve as entry points for water, along with harmful chemical compounds, clay, and corrosive substances, which can lead to the corrosion of reinforcing bars and the deterioration of the concrete itself. Consequently, the durability and serviceability of the concrete decrease. Cracks in self-compacting concrete can facilitate the further growth and expansion of additional cracks, resulting in localized or widespread damage to both the surface and the interior of the concrete. The rate of evaporation from the concrete surface is influenced by various factors, including ambient temperature, relative humidity, and wind speed. When the rate of evaporation equals the rate of water loss from the surface of the concrete slab, the injected water layer is removed, creating negative pore water pressures (capillarity) on the surface. These negative pressures induce contraction in the concrete, and if the concrete is bonded, tensile stresses begin to develop on its surface. Bonding factors in concrete may include coarse aggregates, granular base surfaces or stabilizers, and reinforcing bars or fibers within the concrete slab, all of which can be affected by various conditions. Due to the low tensile strength of concrete in the early hours after construction, the tensile stress can exceed the material's tensile strength, leading to cracks caused by the shrinkage of the concrete paste. Fibers are one of the reinforcing elements that help resist the tensile stresses induced by various factors. They can enhance the tensile strength of self-compacting concrete and mitigate the expansion and growth of cracks. The high modulus of elasticity of plastic, wood, or metal fibers allows these reinforcing elements to effectively control cracking in concrete. The incorporation of fibers, due to their superior tensile properties in conjunction with reinforcing bars, significantly reduces cracking and strengthens the concrete, making it a critical consideration. In this research, a suitable template has been designed to investigate cracking by simulating practical constraints. Based on the geometric relationships of the mold and the degree of hardness and cracking, molds with dimensions of 60 cm by 90 cm by 5 cm were created. In this configuration, the adverbs are embedded in two perpendicular directions.

Fig 15. Concrete slab reinforced with fibers

During this experiment, environmental conditions such as temperature and humidity were maintained at constant levels. The area of the cracks was determined by multiplying the length by the width of each crack after a period of seven days. The length of the crack was measured using a measuring tape with an accuracy of 1 mm, while the width was assessed with a magnifying glass that had an accuracy of 0.1 mm. The samples were kept in molds for seven days within a controlled environment, which maintained a temperature of 18 ± 2 degrees Celsius, wind speeds of approximately 5 km/h, humidity at 21%, a low UV index, minimal dust, and a moderate Air Quality Index (AQI). From 91 concrete slabs, self-compacting concrete was produced in seven molds, incorporating various fibers in different percentages (0%, 0.5%, 1%, 1.5%, and 2% relative to the weight of the cement) for analysis. The cracking behavior in Ultra-High Performance Concrete (UHPC) mixtures, both with and without different fibers, was evaluated using the ASTM C1579 standard test method [68]. Reason: Improved clarity, vocabulary, and technical accuracy while correcting grammatical and punctuation errors.

- Cracking in concrete slab :(WC)>(AF)>(PP)>(MP)>(DP)> (PT)>(HH)

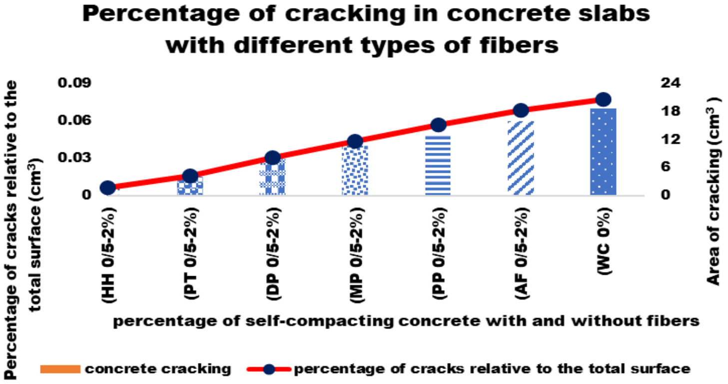

Fig. 16. Percentage of Cracking in Concrete Slabs with Various Types of Fibers

2.10. Testing the Compressive Strength of Cubic Specimens

The results of the compressive strength test on cubic samples measuring 150 mm × 150 mm × 150 mm, conducted in accordance with the ISIRI 3206 standard [65], indicated that the addition of various types of fibers in different percentages to (UHPC) resulted in a decrease in compressive strength (as shown in Figures 17 and 18).

- Pushing Resistance: (WC)>(AF)> (DP)>(MP)> (HH)> (PT)>(PP)

Like previous studies and research, including those by Mirabi Moghadam [32], Omar [35], Manjunat [33], Janata [42], and Mustafa [36], who have worked in the field of fibers, it was concluded that the use of fibers in concrete reduces compressive strength. This finding was also clearly stated in the current research.

Fig. 17. Testing the Failure of a Cubic Specimen Using a Concrete Breaker Jack

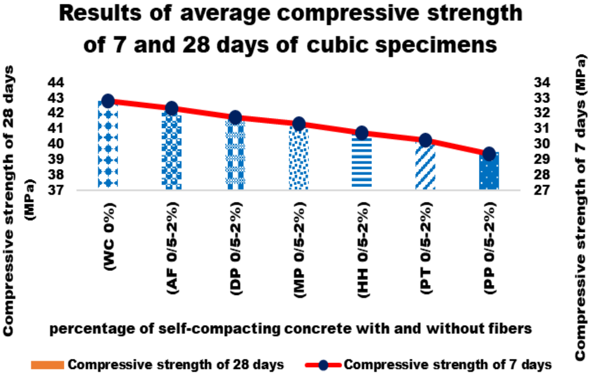

Fig. 18. Compressive Strength Test Results for Cube Specimens Cured for 7 and 28 Days

2.11. Testing the Tensile Strength of Cylindrical Samples (Brazilian Test)

The results of the tensile strength test on cylindrical samples measuring 150 mm by 300 mm, conducted in accordance with the ASTM C496 standard [66], indicated that the tensile strength increases with the addition of various fibers to (UHPC), as illustrated in Figures 19 and 20.

- Tensile strength : (HH)>(PT)>(DP)>(MP)>(PP)>(AF)>(WC)

Fig. 19. Cylindrical Specimen Failure Test Using a Concrete Breaker Jack

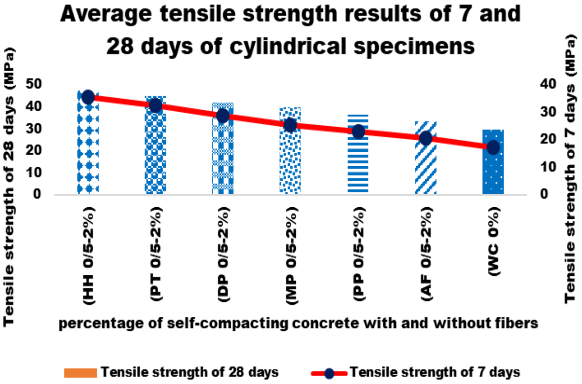

Fig. 20. Tensile Strength Test Results for Cylindrical Specimens at 7 and 28 Days of Curing

3. Conclusion

In this research, the use of various fibers in (UHPC) was examined. This study represents a significant contribution to sustainable development by potentially lowering the costs of structures and materials, mitigating the harmful effects of pollution on the environment, reducing brittleness and cracking in concrete, conserving natural resources, and enhancing both compressive and tensile strength. Based on the primary findings of this article, the following conclusions can be drawn:

- The average data from compressive strength tests of (UHPC) with varying fiber contents (0.5%, 1%, 1.5%, and 2% by weight of cement) revealed the following:
- In cubic specimens after 7 days, the addition of (AF), (DP), (MP), (HH), (PT), and (PP) resulted in reductions of compressive strength of 1.49%, 3.28%, 4.47%, 6.28%, 10.7%, and 14.76%, respectively, compared to the (UHPC) without fibers.
- In cubic specimens tested after 28 days, the addition of (AF), (DP), (MP), (HH), (PT), and (PP) fibers resulted in reductions in compressive strength of 1.60%, 2.51%, 3.89%, 5.03%, 6.17%, and 7.78%, respectively, compared to the (UHPC) without fibers.
-
- The average data from tensile strength tests on (UHPC) with varying fiber contents indicated that
- In cylindrical specimens, after 7 days, the inclusion of (HH), (PT), (DP), (MP), (PP), and (AF) fibers resulted in increases in tensile strength of 106.35%, 88.43%, 65.90%, 47.40%, 33.52%, and 19.65%, respectively, compared to the (UHPC) without fibers.
- In cylindrical specimens after 28 days, the inclusion of fibers (HH), (PT), (DP), (MP), (PP), and (AF) resulted in increases in tensile strength of 59.19%, 50.83%, 41.13%, 32.77%, 22.40%, and 11.70%, respectively, compared to the (UHPC) without fibers.

- The average data from rebound hammer compressive strength tests on (UHPC) with fibers indicated that:
- In cubic specimens after 28 days, the incorporation of (AF), (DP), (MP), (HH), (PT), and (PP) fibers resulted in reductions in compressive strength of 0.9%, 1.87%, 2.81%, 3.75%, 4.46%, and 4.92%, respectively, compared to the (UHPC) without fibers.
- In cylindrical specimens after 28 days, the incorporation of (AF), (DP), (MP), (HH), (PT), and (PP) fibers resulted in reductions in compressive strength of 1.03%, 1.55%, 2.33%, 3.10%, 4.14%, and 4.83%, respectively, compared to the u (UHPC) without fibers.
- The average data from ultrasonic pulse velocity tests on (UHPC) with fibers demonstrated that:
- In cubic specimens after 28 days, the addition of (HH), (PT), (DP), (MP), (PP), and (AF) fibers resulted in a decrease in pulse velocity of 0.7%, 1.49%, 2.23%, 3%, 3.73%, and 4.85%, respectively, compared to the (UHPC) without fibers.
- In cylindrical specimens after 28 days, the addition of (HH), (PT), (DP), (MP), (PP), and (AF) fibers resulted in a decrease in pulse velocity of 0.9%, 1.47%, 1.91%, 2.65%, 3.09%, and 3.83%, respectively, compared to the (UHPC) without fibers.
- The average data from permeability tests on (UHPC) with fibers indicated that:
- In cubic specimens observed over a 72-hour period, the incorporation of (HH), (PT), (DP), (MP), (PP), and (AF) fibers resulted in reductions in permeability of 54.71%, 47.16%, 41.50%, 33.96%, 26.41%, and 16.98%, respectively, compared to the (UHPC) without fibers.
- In cylindrical specimens over a period of 72 hours, the incorporation of (HH), (PT), (DP), (MP), (PP), and (AF) fibers resulted in reductions in permeability of 52.38%, 49.20%, 42.85%, 36.50%, 26.98%, and 17.46%, respectively, compared to the ultra-high-performance concrete (UHPC) without fibers.
- The average data from cracking tests on (UHPC) slabs containing fibers indicated that:
- In concrete slabs after 7 days, the addition of (HH), (PT), (DP), (MP), (PP), and (AF) fibers resulted in a reduction in cracking of 8.57%, 21.42%, 42.85%, 57.14%, 71.42%, and 85.71% relative to the total surface area, compared to slabs without fibers.

Table 9. Total Results of the functional properties of uhpc with and without fibers

Type of concrete	Type of test	Type of functional properties	level of quality compared to the control sample
(WC) > (HH) > (PT) > (DP) > (MP) > (PP) > (AF)	Slump flow test	Fresh properties	Slump diameter reduction
(WC) < (HH) < (PT) < (DP) < (MP) < (PP) < (AF)	V-Funnel test	Fresh properties	Increase flow time
(WC) > (HH) > (PT) > (DP) > (MP) > (PP) > (AF)	L-Box test	Fresh properties	Reducing the blockage ratio (H2/H1)
(WC) > (HH) > (PT) > (DP) > (MP) > (PP) > (AF)	J-Ring test	Fresh properties	Slump diameter reduction
(WC) < (HH) < (PT) < (DP) < (MP) < (PP) < (AF)	U-Box test	Fresh properties	Increasing height difference (H2-H1)

(WC)>(AF)> (DP)> (MP)> (HH)> (PT)> (PP)	Compressive strength with Schmidt hammer	hardened properties	Reducing compressive strength
(WC)>(HH)> (PT)> (DP)> (MP)> (PP)> (AF)	Ultrasonic pulse speed	hardened properties	Reducing the speed of the ultrasonic pulse
(WC)>(AF)>(PP)>(MP)>(DP)> (PT)>(HH)	Permeability	hardened properties	Reduced permeability
(WC)>(AF)>(PP)>(MP)>(DP)> (PT)>(HH)	Thermal cracking	hardened properties	Reduction of thermal cracking
(WC)>(AF)>(PP)>(MP)>(DP)> (PT)>(HH)	Cracking in concrete slab	hardened properties	Reducing cracking in concrete slabs
(WC)>(AF)>(DP)>(MP)>(HH)>(PT)>(PP)	Compressive strength	hardened properties	Reducing compressive strength
(WC)<(AF)<(PP)<(MP)<(DP)<(PT)<(HH)	Tensile strength	hardened properties	Increased tensile strength

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