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ARTICLE

Experimental Study on the Compressive and Flexural Properties of the Ultrahigh-Performance Concrete Containing Fibers

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ABSTRACT

Ultrahigh-performance concrete (UHPC) is a groundbreaking kind of concrete that distinguishes itself from conventional concrete through its unique material properties. Understanding and managing the time-dependent characteristics of these materials is essential for their effective use in various construction applications. This study presents an experimental evaluation of the compressive and bending properties of the UHPC incorporating polypropylene, steel, and glass fibers. Based on ACI-211 guidelines, the UHPC mix was designed by using three types of aggregates: limestone, andesite, and quartzite, along with 5% fiber content (at varying percentages of 0, 5%, 10%, 15%, and 20%) relative to the cementitious materials, and three different water-to-cement (w/c) ratios (0.24, 0.3, and 0.4) were used. In this research, the compressive and flexural strength tests were conducted. The results show that increasing the values of the fibers significantly enhances the compressive strength of the studied samples. Furthermore, the utilization of fibers markedly improves the bending strength of the samples, demonstrating a strong correlation with the yield resistance of the material. Also, findings show that using steel fibers increases the compressive and bending strength of the tested samples more than polypropylene and

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glass fibers. For instance, in UHPC samples with 0.4 w/c, the average compressive strength values are 82.2 MPa, 70.3 MPa, and 67.1 MPa for steel, polypropylene, and glass fibers, respectively. Also, in the flexural strength test, the modulus of rupture is obtained as an average of 6.24 MPa, 5.24 MPa and 4.83 MPa for UHPC samples with steel, polypropylene and glass fibers, respectively.

Keywords: Experimental Study; Ultrahigh-Performance Concrete (UHPC); Polypropylene Fiber; Steel Fiber; Glass Fiber; Compressive Strength; Flexural Strength

1. Introduction

Ultrahigh-performance concrete (UHPC) represents a novel category of concrete that has emerged in a new era. In comparison to high-performance concrete, UHPC samples typically enhance mechanical and durability features. While there are distinctions between various types of this concrete, there are also numerous overarching likenesses [1–3]. The Interim Recommendations for Ultra High Performance Fibre-Reinforced Concretes issued by the Association Française de Génie Civil in 2002 define UHPC as a material exhibiting a compressive strength greater than 150 MPa. This concrete type is distinguished by its internal fiber reinforcement, which contributes to its non-brittle characteristics, as well as a significant binder content that includes specialized aggregates. Furthermore, UHPC is manufactured using a low water-to-cement (w/c) ratio, generally falling between 0.15 and 0.25. Due to the minimal water content, the incorporation of superplasticizers is essential to enhance the arrangement of the particles within the composite material, thereby improving the fluidity and workability of the mixture [4]. UHPC is an innovative construction material that is characterized by its remarkable mechanical attributes and resilience, particularly its ability to withstand frost damage and resist chloride ion penetration. To satisfy rigorous standards, UHPC must achieve the least values of compressive and tensile strength of 120 MPa and 6.9 MPa respectively after 28 days at the point of initial cracking. Although proprietary UHPC formulations, which utilize high-quality materials, are frequently transported over considerable distances, including international shipments, the sustainability of this practice raises concerns due to the significant production costs. These expenses can be 20 to 30 times greater than those associated with normal strength concrete, largely due to the costly aggregates, steel fibers, and premium cementitious materials necessary for UHPC, in addition to the shipping costs incurred [5, 6]. Fibers possess the ability to enhance strain-hardening characteristics of UHPC subjected to tensile stress, thereby converting what would typically be a brittle failure into a more ductile one [7]. A considerable amount of research has focused on enhancing the formulation of UHPC, improving its performance, lowering production costs, and minimizing energy consumption during its manufacturing procedure [8]. Kang et al. employed an analyzed image method to investigate the influence of fiber distribution characteristics on flexural strength through flexural tests. The mentioned study demonstrated that the developed image processing method could quantitatively assess fiber distribution properties by utilizing metrics. The parameters included the distribution index, the density of fibers, the packing density observed in the fiber image, and the orientation of the fibers. Additionally, it was observed that the characteristics of fiber distribution were influenced by the orientation of placement. The findings indicated that while fiber distribution characteristics had a significant impact on the ultimate flexural strength, they had minimal effect on the initial rupture strength. The outcomes of reliability were confirmed by comparing them with an analyzed prototype of bending strength [9]. Siba et al. conducted an experimental optimization program aimed at determining the ideal combination of steel fibers and cost-effective carbon nanofibers in UHPC. The mentioned study identified optimal volume fractions of 1.1% for steel fibers and 0.04% for carbon nanofibers, which collectively enhanced the bending strength, ductility, energy dissipation capacity, and the strength of impact and abrasion of this kind of concrete. This study revealed complementary and synergistic interactions between the nanofibers and steel fibers, which were linked to their reinforcing capabilities at various scales [10]. Iqbal et al. performed an investigation into the effects of integrating micro-steel fibers into high-performance concrete that is both lightweight and capable of self-compaction. Also, the findings demonstrated a reduction in compressive strength of about 12% when the steel fiber content was at or above 1%. In contrast, the research highlighted notable improvements in both splitting tensile and bending strength, which saw increases of approximately 37% and 110%, respectively, as the steel fiber content was elevated from 0% to 1.25%[11]. Krahl et al. conducted a study on the cyclic behavior of UHPC with fibers subjected to cyclic loading tests involving tension, compression, and bending, with varying steel fiber contents of 0%, 1%, and 2%. The findings indicated that increasing the volumetric content of fibers increases the residual strength and toughness of the material following cyclic loading[12]. Ryabova et al. explored the enduring flexural strength of GFRC that included silica fume and metakaolin. Their findings revealed that the addition of metakaolin, constituting 30% of the Portland cement, played a crucial role in maintaining the enduring strength of this concrete[13]. Madhkhan and Katirai explored the role of pozzolanic reactions in glass fiber reinforced concrete (GFRC) to mitigate damage to glass fibers over time. Various pozzolans were individually incorporated into the GFRC matrix, and the mechanical properties, including toughness and compressive strength, were evaluated at intervals of different days. The findings of this research demonstrated that the inclusion of nanosilica and metakaolin significantly mitigated the deterioration of the concrete's modulus of rupture and toughness as it aged[14]. Ali and Qureshi studied the influence of incorporating glass fibers into concrete matrices made up of reclaimed coarse aggregates. Their compressive strength tests indicated that glass fibers could partially mitigate the decrease in the values of compressive strength resulting from the replacement of natural aggregates with coarse aggregates. Specifically, the inclusion of glass fibers was found to enhance the compressive strength of the samples by approximately 4–5% and to significantly improve bending strength by around 50%. However, it was noted that the durability properties related to permeability were negatively influenced by the content of glass fibers[15]. Algburi, Sheikh and Hadi investigated the effects of different fibers like glass and steel, and the interplay of these factors on the mechanical characteristics of reactive powder concrete (RPC) is noteworthy. The findings of this study showed that using steel fibers enhanced the mechanical features of the mentioned concrete compared to RPC without fibers. Conversely, while glass and hybrid fibers enhanced tensile and shear strength[16]. Liu, Jia and Wang conducted an investigation into the mechanical features and durability of concrete with different fibers like glass and polypropylene over a period of 28 days. To evaluate durability, they performed chloride penetration tests. The findings indicated that the concrete reinforced with hybrid fibers exhibited superior properties compared to the other two types of concrete. The incorporation of polypropylene into the concrete matrix resulted in enhanced mechanical properties, surpassing those achieved with glass fibers[17]. Khan et al. investigated the effects of substituting a fraction of cement with waste glass powder within the concrete matrix, while evaluating different curing periods. They analyzed the mechanical properties of the altered concrete in relation to a control sample that exhibited a compressive strength of 20 MPa. The findings indicated a decrease in compressive strength of no less than 5% in comparison to conventional concrete; nevertheless, the modulus of rupture for the prismatic specimen showed a 2% enhancement following 58 days of water curing[18]. Madhkhah and Saeidian undertook a study examining the mechanical characteristics of UHPC that is reinforced with glass fibers subjected to three distinct curing methods: normal, autoclave, and a hybrid curing approach involving autoclave followed by a 50-day immersion in hot water to replicate accelerated aging conditions. Furthermore, the research investigated the impact of replacing silica fume with metakaolin in the mentioned concrete to assess its mechanical characteristics following the process of elevated temperature curing. The findings revealed that specimens exposed to accelerated aging demonstrated heightened brittleness, accompanied by a significant decrease in both the modulus of rupture and toughness indices across all prismatic samples[19]. Dang, Pham and Dinh conducted an experimental investigation aimed at examining the compressive and bending properties of cement-based composites designed for the production of thin, lightweight, and high-performance construction materials. The study utilized expanded hollow glass particles, ranging in size from 0.25 to 0.5 mm, as lightweight fillers[20]. Hosseinzadeh et al. performed research to evaluate the characteristics of high-strength concrete in comparison to normal concrete that has different fibers subjected to both standard and sulfate curing conditions. The mixture that achieved the highest compressive strength was found to contain 1% SF and 0.2% PF. Regarding tensile strength, the formulation with 0.5% high-performance polypropylene (HPP) fibers, in conjunction with 1% SF and 0.2% PF, exhibited the best results. Furthermore, the mixture with 0.5% HPP fibers and 1% SF recorded the greatest flexural strength. Importantly, the fiber-reinforced concrete samples demonstrated a lower water absorption rate after 30 minutes compared to those without fibers, with the lowest absorption observed in the sample containing 0.5% PF and 20% silica fume, which measured 0.53% [21]. Ghasemzadeh Mousavinejad, Radman and Ghorbani GilKalaye performed an extensive investigation into the mechanical characteristics of UHPC subjected to different thermal environments, employing a variety of both industrial and recycled fiber types. Their findings revealed that the heat strength of UHPC that incorporates recycled fibers is similar to that of UHPC that is reinforced with industrial materials. Additionally, a significant correlation was identified between the ultrasonic pulse velocity of the samples and their strength after being subjected to high temperatures, indicating a possible connection between these two characteristics [22]. Luo et al. explored the viability of utilizing defect-containing recycled aggregates (RA) in UHPC and assessed the synergistic effects of nanosilica (NS) and silica fume (SF) on its performance enhancement. Researchers evaluated how varying the RA substitution rate, along with different levels of SF and NS, influenced the flexural properties and microstructural characteristics of RA-UHPC through four-point bending tests. The results revealed that specimens without additional SF exhibited a linear elastic increase in the load-deflection curve, which was followed by a rapid decrease in load after reaching the maximum point, lacking a significant descending phase [23]. Haruna et al. performed an investigation into the bonding features of U-shaped normal strength concrete and reinforced UHPC samples by employing various methodologies [24]. Yingying et al. explored the integration of steel fibers and nanopalygorskite (NP) into UHPC with the aim of improving its durability. This research focused on evaluating the long-term mechanical properties and shrinkage behavior to assess the influence of fiber shape and NP on the performance of fiber-reinforced UHPC (FUHPC). The microstructural development of UHPC was examined using mercury intrusion porosimetry, X-ray diffraction, and scanning electron microscopy. The results indicated that the inclusion of steel fibers significantly improved the long-term performance of UHPC, with hooked fibers (HF) at a dosage of 1.5% demonstrating superior performance compared to straight fibers. Additionally, the introduction of NP further enhanced the long-term performance of FUHPC, achieving optimal results with a SF dosage of 1.0% and NP dosage of 0.2%. Notably, the nanopalygorskite-reinforced straight fiber UHPC (NPRSFUHPC) exhibited the highest 180-day compressive strength of 150.6 MPa, surpassing the control sample without NP (SFUHPC) by 10.7%. Furthermore, the nanopalygorskite-reinforced hooked steel fiber UHPC (NPRHFUHPC) achieved a maximum 180-day flexural strength of 26.1 MPa, which was 29.9% greater than the control (HFUHPC) [25]. Simanjuntak and Aslani established dependable correlations for forecasting the mechanical properties of UHPC under elevated temperatures. These properties encompass compressive, tensile, and flexural strengths, as well as the modulus of elasticity, peak strain, and the stress-strain curves associated with compression. The findings of this research indicated the necessity for additional testing to enhance the constitutive relationships, which include examining various specimen dimensions and configurations, altering heating durations, and assessing different curing techniques [26]. Wang et al. conducted a study on the residual characteristics of UHPC that incorporates a hybrid fiber blend of steel and polypropylene, particularly in the context of fire incidents occurring during construction. The researchers performed uniaxial compressive tests on UHPC that had been subjected to elevated temperatures at an early age. The findings revealed that, up to a temperature of 600 °C, the residual compressive strength of the UHPC tends to increase with age, attributed to enhanced resistance and accelerated hydration processes. However, at 800 °C, there is a slight reduction in strength with age, which can be linked to the effects of porosity and carbonation reactions [27].

2. Problem Statement

The increasing world population and the wave of migration to cities have caused the need for the expansion of urban infrastructure to increase, and this problem is directly related to the availability of suitable materials for construction. On the other hand, environmental conditions for living in urban areas are also deteriorating. Therefore, issues such as these have always caused the demand for new and high-safety methods for improving and strengthening structures to increase. Recently, the integration of several disciplines such as civil engineering and materials science has led to the emergence of a new type of concrete with extraordinary properties that has overcome many of the limitations of conventional concrete. This concrete has been introduced as reinforced concrete (RPC) and also UHPC. This concrete usually has a compressive strength of more than 1500 kg cm^{-2} and can also be said to be almost impenetrable, which has made it free from many of the weaknesses of conventional concrete, such as weakness against freeze-thaw cycles, corrosion of reinforcement, and attack by harmful ions. It has also largely eliminated the major weakness of concrete, namely low tensile strength, so that in a type of UHPC using steel fibers, there is no need to use reinforcement in the concrete [1–3].

3. Research Novelty

UHPC is a cement-based composite characterized by fine grain aggregates and a uniform matrix, offering remarkable compressive strength and outstanding strength to strict conditional environments. The incorporation of short steel fibers is a prevalent practice in UHPC, as these fibers significantly enhance the material's flexural ductility, durability, and energy absorption capacity. In this research, as an objective, UHPC samples are constructed and stored in a water pond and the compressive strength and bending strength of the samples are measured at 7, 28, and 91 days. As an innovation, the experimental study of the influence of the different fibers such as polypropylene, steel, and glass on the mechanical features of UHPC has been investigated and their effect has been compared with each other. Also, the histogram of the flexural strength of all samples with the studied fibers is compared. The course of the study is presented in **Table 1**.

Table 1. Scheme of experimental tests of UHPC.

Phase	Description of the Procedure
I	Preparing fibers such as polypropylene, steel, and glass.
II	Constructed UHPC samples with the proposed mix designs.
III	Curing the constructed samples.
IV	Performing a visual assessment.
V	Performing a compressive strength test.
VI	Performing a flexural strength test.
VII	Assessing the mechanical properties of the UHPC containing fibers.

4. Theoretical Fundamentals

4.1. UHPC

Today, based on the current concrete technology, it is possible to manufacture concrete with high and unexpected compressive strengths that can be used for the design of common operational structures. Although most concrete codes still limit the strength of concrete used in structures to 60 MPa, new codes have recently considered a higher limit of 105 MPa. The manufacture of high-strength concretes of up to 120 MPa and its use in tall buildings has become popular in developed countries of the world. This strength has been increased by adding fine and active materials to cement to such an extent that concretes with compressive strengths between 200 and 800 MPa and tensile strengths between 30 and 150 MPa have been obtained in laboratory samples. To achieve such strengths, it is necessary to make changes in the mixing design and use new materials and additives [28]. One of the important factors in achieving such strengths is the use of resistant aggregates and reducing the maximum aggregate size in the concrete mixture for greater homogeneity. Also, by using very fine-grained materials with sizes less than a tenth of a micron, a denser set with very low porosity that will have the highest specific gravity can be prepared. In high-strength concretes, the water-cement ratio (w/c) should be reduced as much as possible (today, even a ratio of 0.18 = w/c has been used), in which case some unhydrated cement grains in the form of fine-grained fillers increase the density and, as a result, increase the strength. Obviously, to ensure the efficiency of such mixtures with very little water, it is necessary to use lubricants, super-lubricants and fine particle dispersants in the concrete. To increase the softness of such concretes (as the brittleness and brittleness of the concrete increase), short fibers can be added to them. In the manufacture of such concretes (strength at the level of steel and higher), pressure and temperature hardening methods are used to cure the concrete and provide high initial strength [29].

UHPC has emerged as a serious option in the field of sustainable building materials, considering significant interest due to its exceptional mechanical properties and outstanding durability. The characteristics of UHPC—such as its high strength, versatility, resilience, and capacity to support a variety of aesthetic designs—make it a highly advanced and multifunctional material. Its durability is evaluated based on its resistance to water and chloride-ion penetration, carbonation, freeze-thaw cycles, chemical degradation, and susceptibility to alkali-silica reactions, wear, and fire. As a result, UHPC is well-positioned to be the preferred material for concrete structures across a range of applications and environments. Additionally, the integration of fibers into concrete has been proven to greatly improve the durability of concrete structures under various loading conditions, including impacts and fatigue stresses [28–30].

4.2. Fibers

The idea of adding fibers to brittle and brittle mixtures that have little tensile strength has existed since ancient times. Studies show that the idea of using fibers has existed since ancient times. The ancient Egyptians used straw to reinforce mud bricks. In addition, fireproof cotton fibers and horse hair have also been used for weapons. Today, in the world, there are many various kinds of fibers for different applications in this concrete, one of the most widely used of which is steel fibers. Steel fibers have a high modulus of elasticity and failure strain, which is considered the most suitable and economical type of fiber due to its good plasticity and high tensile strength. This type of fiber is made in different shapes (straight, hooked end, toothed, etc.) to improve the behavior of concrete. Also, mixing them with other concrete materials is done easily. Among the applications of these fibers can be mentioned in the construction of structures under impact and explosion, runways of airports, floors of industrial halls, pipes and thin shells, tunnels, street flooring, parts that are exposed to high temperature changes and even at very high temperatures. Considering the special advantages and applications of concrete reinforced with steel fibers, it is necessary to take necessary measures for its practical application while knowing more about this technology. Considering the nature of the conducted research, which includes the preparation of concrete samples and a series of compressive and flexural resistance tests [31].

4.3. Compressive Strength Test

The concrete cube test for assessing compressive strength provides essential information regarding the fundamental characteristics of concrete. This specific evaluation serves to determine the correctness of the concreting process undertaken. In standard construction situations, the compressive strength of concrete typically ranges from 15 MPa to 30 MPa, with even higher strengths observed in commercial and industrial applications. Various elements affect the compressive strength of concrete, such as the water-cement ratio, the quality of the cement, the standard of the concrete materials used, and the degree of quality control exercised during the concrete manufacturing process. The compressive strength assessment can be conducted using either a cube or a cylinder [32].

4.4. Flexural Strength Test

This test is considered a mechanical evaluation designed to assess the flexural characteristics of a material. There are three primary variations of this test: the three-point, four-point, and simple cantilever loading methods. Among these, the three-point flexural test is the most commonly employed for plastic materials. This method is utilized to analyze the flexural response of the material when subjected to a three-point loading scenario. It is particularly suitable for plastics, as the maximum bending stress occurs directly beneath the loading anvil, making it ideal for homogeneous materials like plastic. Through the flexural test, one can ascertain key features like flexural strength, bending strain, and the elasticity modulus in bending state. Flexural strength specifically refers to the maximum stress or force that a material can endure before experiencing bending failure [33].

5. Materials and Methods

In this experimental study, cement type II with grade 420, whose physical and chemical features are in based on the ASTM C150 standard[34], was used, and the technical and chemical characteristics of the elements and oxides used in cement type II are presented in **Table 2**. Also, the mechanical characteristics of steel fibers, polypropylene and glass are mentioned in **Table 3** that the steel fibers used in this research were obtained from Zanjan Wire Industry Company and the lubricant used was obtained from Khatam Chemical Concrete Company. The amount of lubricant for fibers of steel, polypropylene, and glass is 0.5%, 0.33%, and 0.1%, respectively. The used fibers in this study are presented based on **Figure 1**. The quality of these fibers is approved without any damages.

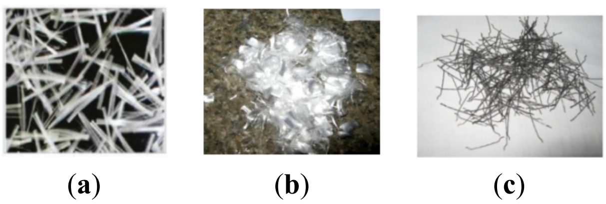


Figure 1. Used fibers in this study: (**a**) glass fiber, (**b**) polypropylene fiber, and (**c**) steel fiber.

The materials used to make concrete samples are as follows: Based on ASTM C150 standard, the researchers in the current study used cement type II. Glass fiber fibers (S-glass type) with a diameter of 17–19 microns and a length of 3–50 mm, steel fibers with a diameter of 0.6–1.2 mm and a length of 50 mm and polypropylene fibers with a diameter of 0.021 mm and a length of 6 mm. Melamine formaldehyde sulfonate superplasticizer in accordance with ASTM C494-Type F standard. Fine limestone with a purity percentage of more than 91% ($CaCO_3 \geq 91\%$) and a grain size within the permissible range of the ASTM standard with a softness modulus of 2.66, density of 2.478, water absorption percentage of 1.3% and natural humidity of 0.2%. Coarsely broken limestone, andesitic, and quartzite aggregates, with a grain size of 8 in ASTM C33, with a maximum diameter of 9.5 mm and other physical characteristics. Two mechanical properties of compressive strength and elastic modulus of limestone, andesitic, and quartzite rocks are determined by testing cylindrical samples with dimensions of 5×10 cm separated from the same rocks from which the aggregates were produced. The compressive strength of quartzite stone was significantly higher than that of limestone and andesitic stones, and the compressive strength of andesitic stone is between that of quartzite and limestone. On the other hand, the elastic modulus of quartzite stone is also significantly higher than that of limestone and andesitic stones, but the elastic modulus of andesitic stone is only slightly higher than that of limestone. In this study, a superplasticizer was used to increase the efficiency of the mixed concrete and it was mixed for two minutes.

To perform this test, 12 cubic samples with dimensions of 15 × 15 × 15 were used for the compressive strength test. The mix design of samples is presented based on **Table 4**. The purpose of mixing concrete with high strength and performance is to determine the mixing ratio between concrete components in order to obtain specific properties in fresh and hardened concrete (necessary efficiency, desired compressive strength and sufficient durability). Today, there are many different methods and regulations for ordinary concrete mix design, but a comprehensive mixing design for UHPC has not yet been developed. ACI 211-4R-93 regulation[35] is one of the regulations that partially refers to high strength concrete mixing design. Among the criticisms that can be made to the draft of the aforementioned regulations, the non-interference of the mechanical properties of coarse grains in determining the concrete mixing design in order to obtain the desired compressive strength. Extensive research by researchers shows that the mechanical properties of coarse grains play a significant role in the formation of the mechanical properties of UHPC. Another problem with the mixing plan of ACI 211-4R-93 regulation is the non-interference of fiber percentage in the formation of concrete compressive strength. It is clear that by replacing different percentages and while the total weight of cement materials is constant, different growths in compressive strength are observed. Sometimes, it can be seen that by replacing 10 to 15% of fibers, the compressive strength has increased by about 30% compared to the state where there are no fibers. In this research, by using the method of ordinary concrete mixing design according to the American Concrete Code according to ACI 21-89[36] and its appendices (regarding the percentage replacement of cement by fiber materials) and also the UHPC mixing design method of the American Concrete Code according to the ACI 211-4R-93 regulation, and considering the recommendations of Committee 363 of the American Concrete Society on the construction of UHPC, as well as by collecting and applying the opinions and research results of researchers who have conducted studies in the field of UHPC, and also based on

Table 2. Chemical properties of cement type II.

Combination	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	L.O.I	IR
Standard	MIN 20	MAX 6	MAX 6	MAX 5	MAX 4	MAX 4	MAX 0.75
Cement type II	22.5	4.48	5.52	4	1.4	1.0	0.4

Table 3. Specifications of used fibers in this study.

	Polypropylene	Glass	Steel
Shape	Smooth	Smooth	Hooked
Length (mm)	12	18	50
Diameter (µm)	20–30	15–30	10
Density (g cm^{-3})	0.9	2.6	7.8

the results of the present research, it has been tried to use a standard method for mixing concrete with high strength. In the following, the results of compressive strength tests are presented. The limitation of the force applied by the loading device caused standard samples with smaller dimensions to be used to test the compressive strength of concrete with high strengths. Therefore, according to the ASTM C39 standard [37], standard cylindrical samples with dimensions of 20 × 10 cm should be used for this research. Upon concluding the construction phase, the concrete mixture was poured into the molds, which were subsequently opened after a 24-hour period. The samples were then immersed in water for two hours prior to testing. In accordance with the ASTM C617 standard [38], the sides of the samples were coated with sulfur to ensure that the loading surfaces were entirely smooth and aligned perpendicularly to the length of the samples.

Figure 2. Constructed samples for compressive strength test.

6. Results and Discussion

This assessment was done to check the compressive strength of cubic concrete samples, in accordance with the ASTM C39 standard. Based on **Figure 2**, to perform this test, 20 cubic samples of 15 × 15 × 15 were constructed, according to the 15 available mixing designs, after 7, 28 and 91 days, the samples were taken out of the pond. First, their dimensions were measured by calipers. The measured (cross-sectional area) was then weighed and the amount of bearing force of the sample was recorded from the machine and the compressive strength was obtained. The compressive strength setup test is presented based on **Figure 3** and the findings of compressive strength of tested samples are reported in **Table 5**.

Figure 3. Real image of compressive strength test setup.

The bending strength was calculated through the flexural test of a beam measuring 60 × 80 × 320 mm. In order to determine the flexural strength of the samples, 60 beam

Table 4. The mix design of constructed samples.

Mix Design No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
W/C			0.4					0.3					0.24		
Fibers (%)	0	5	10	15	20	0	5	10	15	20	0	5	10	15	20
Cement (kg m^{-3})	400	380	360	340	320	500	475	450	425	400	600	570	540	510	480
Fiber (kg m^{-3})	0	20	40	60	80	0	25	50	75	100	0	30	60	90	120
Fine aggregates (kg m^{-3})	718	712	705	698	692	662	653	645	637	627	593	583	573	563	553
Coarse aggregates (kg m^{-3})			1000					1057					1137		
Super lubricant (%)			1.2					1.6					2.4		

Table 5. The results of compressive strength of samples (MPa).

Mix Design No.	W/C	CF %	Steel Fiber			Polypropylene Fiber			Glass Fiber		
			F_{c91}	F_{c28}	F_{c7}	F_{c91}	F_{c28}	F_{c7}	F_{c91}	F_{c28}	F_{c7}
1		0	89.1	75.7	57.9	76.7	64.4	50.6	74.6	61.4	45.5
2		5	94	82.5	63.6	83.1	71.1	55.9	78.8	67.8	49.7
3	0.4	10	99.2	89	70.5	86.2	74	58.7	86	72.7	54.2
4		15	103.4	84.3	65.5	86.6	72	56.6	81	68	50.8
5		20	92	79.5	62	81	70	55.2	77.4	65.6	48.5
6		0	108	86	71	90	75.4	61.6	81	73	59
7		5	117.2	91	75.5	99	81.8	66.8	84.5	77	61.2
8	0.3	10	121	105	84	102	87	71	95.4	86.2	70.7
9		15	127	100	77.1	104	84.3	68.2	98	82	65.5
10		20	115.8	89	73	98	81	66	82.8	74.8	61.4
11		0	117.8	95.3	86	101	84.8	71	88	79.7	67.3
12		5	125	103	92	110	92.5	78	91.7	84.3	70.8
13	0.24	10	132.4	115	105	114	97.6	83.5	105	91.7	79.8
14		15	142.9	117.2	98.2	119.3	98	81	116	89.1	75.2
15		20	136	109	96	117	95	79.7	109.7	84.6	72.6

samples were tested. The general symbol of the flexural test machine and constructed samples is shown in **Figure 4**.

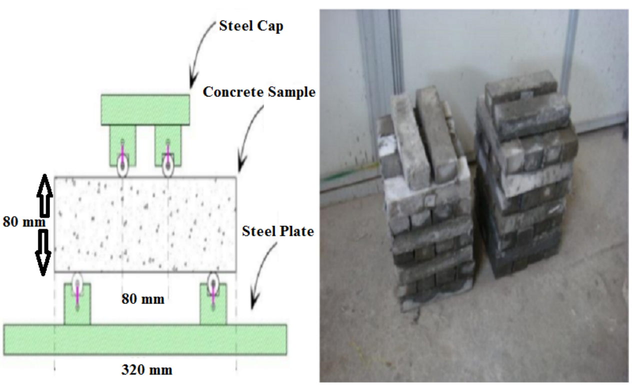
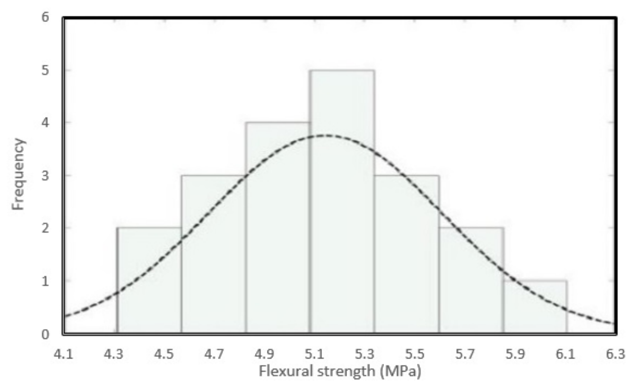
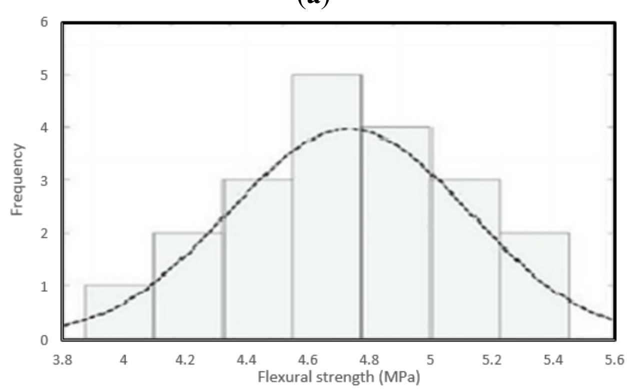


Figure 4. View of the constructed samples flexural strength test and its setup.

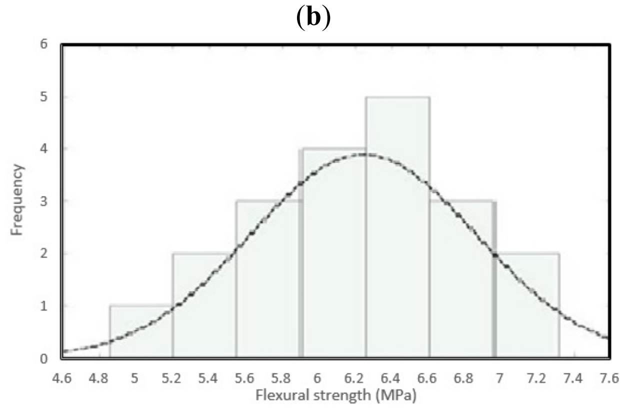
The results of the flexural strength test on 60 samples for three groups are presented in **Table 6**. According to this table, the third group has the highest average value among the other two groups. The average flexural strength of the concrete group with steel fibers is 29% and 21% higher than the flexural strength of glass and polypropylene group samples, respectively. The standard deviation of concrete with steel fibers is 42% and 33%, respectively, of the groups of concrete with glass fibers and concrete with polypropylene fibers. **Figure 5** shows the histogram of the flexural strength of all samples, which shows that the flexural strength for the three groups has an almost normal distribution. The coefficient of variation of concrete with steel fibers is 11% and 8% higher than the coefficient of variation of concrete with glass fibers and concrete with polypropylene fibers, respectively. As can be seen, the coefficient of variation increases with polypropylene, steel and glass fibers respectively. **Figure 6** indicates the normal probability distribution of flexural test data of constructed samples with the studied fibers. The enhancement in the coefficient of variation by adding fibers shows that the use of fibers causes the data to be more scattered. Also, in steel fibers, compared to the rest of the fibers, it also increases the flexural strength. The results show that fibers play a crucial role in mitigating the early tensile cracking of concrete due to their ability to arrest cracks and their superior tensile strength. Similar to the outcomes observed in compression testing, the enhancement of flexural strength is significantly greater when steel fibers are utilized compared to the improvements seen with polypropylene and glass fibers.



(**a**)

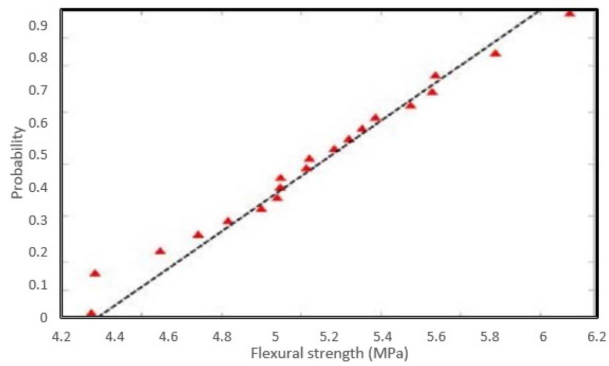


(**b**)

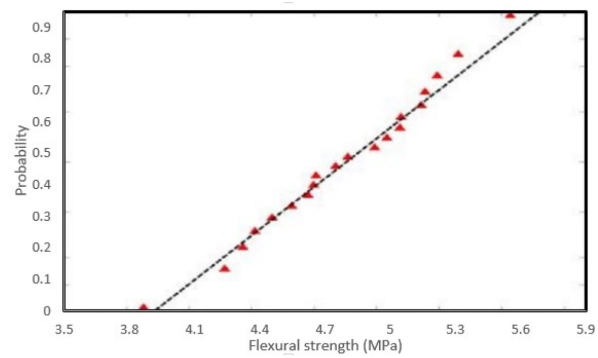


(**c**)

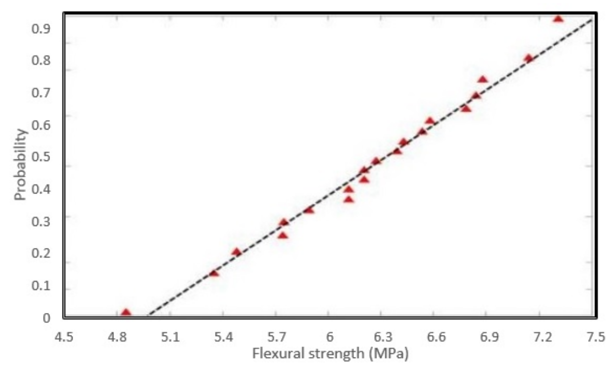
Figure 5. Flexural strength histogram and normal distribution curve of data: (**a**) polypropylene fiber, (**b**) glass fiber, and (**c**) steel fiber.



(**a**)



(**b**)



(**c**)

Figure 6. Normal probability distribution of flexural test data: (**a**) polypropylene fiber, (**b**) glass fiber, and (**c**) steel fiber.

7. Conclusions

UHPC is a distinct type of cementitious composite that is defined by its use of fine aggregates and a consistent matrix. This unique composition imparts exceptional compressive strength and superior durability against severe environmental factors. Incorporation of steel fibers is a prevalent practice in UHPC, as these fibers significantly enhance the material's flexural ductility, durability, and energy absorption capabilities. Additionally, the introduction of polypropylene and glass fibers into UHPC represents an innovative approach

Table 6. The results of flexural strength of samples.

Mix Design No.	**Modulus of Rupture (MPa)**		
	Steel Fiber	**Polypropylene Fiber**	**Glass Fiber**
1	6.11	5.27	4.70
2	6.88	5.13	4.80
3	5.89	5.60	5.64
4	6.58	5.02	4.35
5	5.74	5.11	4.42
6	6.39	4.71	5.21
7	6.84	4.31	4.67
8	6.20	5.51	4.27
9	5.74	5.59	5.38
10	6.78	4.94	3.88
11	6.20	4.53	4.86
12	7.14	4.32	5.29
13	6.53	5.83	5.11
14	4.85	5.32	4.69
15	6.27	5.37	5.11
16	6.43	6.11	4.99
17	6.11	4.82	5.04
18	7.31	5.22	5.23
19	5.48	5.00	4.59
20	5.35	5.02	4.49
Mean	6.24	5.14	4.83
Standard Deviation	0.61	0.46	0.43
Coefficient of Variation	9.88	9.08	8.94

that not only enhances its mechanical properties but also offers advantages such as reduced weight and lower cost compared to traditional steel fibers.

In this research, the effects of fibers such as steel, polypropylene, and glass on the mechanical properties of UHPC were investigated. Based on the new findings of compressive strength on cubic samples, it is clear that with the addition of fibers, changes in the compressive strength of the samples increase. By adding fibers, the change coefficient of compressive strength increased from 4.96% to 8.42%. The increase in the compressive strength of concrete with the increase of fibers is not noticeable. However, by adding fibers, the compressive strength of concrete increases and the behavior of concrete becomes softer. The use of fibers dramatically increases the flexural strength of concrete, and this issue has a very tangible relationship with the concrete strength. It is necessary to mention that steel fibers increase the compressive and flexural strength of UHPC samples versus polypropylene and glass fibers. For example, in 0.4 w/c of UHPC samples, the average of compressive strength values is 82.2 MPa, 70.3 MPa and 67.1 MPa for steel, polypropylene and glass fibers, respectively. Also, in the flexural strength test, the modulus of rupture is obtained averagely 6.24 MPa, 5.24 MPa, and 4.83 MPa for UHPC samples with steel, polypropylene, and glass fibers, respectively.

While this research has achieved notable advancements, it is important to recognize certain limitations. The investigation was confined to examining the effects of polypropylene, steel, and glass fibers at only four specific percentages: 5%, 10%, 15%, and 20% relative to the cementitious materials, and three different w/c ratios 0.24, 0.3, and 0.4 for computing compressive strength and flexural strength. Consequently, the study primarily concentrated on the short-term mechanical properties of UHPC, leaving long-term performance aspects, such as durability and resilience over time, outside its purview. Moreover, as future works, the following points can be considered as suggestions:

1. Investigating the effect of cement type on the performance of fiber UHPC.

2. Investigating the effect of combining different fibers simultaneously in UHPC.

3. Investigating the effect of fiber diameter and dimen-

sions on the strength of UHPC.

4. Investigating the potential of hybrid fiber reinforcement in UHPC.

Author Contributions

Conceptualization, methodology, experimental tests, data curation, M.Y.N.; Formal analysis, investigation, supervision, project administration, M.B.; Resources, visualization, A.S. (Amirreza Sadeghi); Validation, resources, writing—review and editing, K.M.; Conceptualization, methodology, investigation, writing—original draft preparation, writing—review and editing, A.S. (Abbasali Sadeghi).

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Data Availability Statement

The data that support the findings of this study are openly available in this article.

Conflicts of Interest

The authors declare that there are no conflicts of interest in this manuscript.

References

[1] Russell, H.G., Graybeal, B.A., 2013. Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community. Federal Highway Administration Office of Infrastructure Research and Development: McLean, VA, USA. pp. 1–163.

[2] Meng, W., Valipour, M., Khayat, K.H., 2017. Optimization and performance of cost-effective ultra-high performance concrete. Materials and Structures. 50(29), 1–16. DOI: https://doi.org/10.1617/s11527-016-0896-3

[3] Graybeal, B., Crane, C.K., Perry, V., et al., 2019. Advancing ultra-high-performance concrete. Concrete International. 41(4), 41–45.

[4] Kusumawardaningsih, Y., Fehling, E., Ismail, M., et al., 2015. Tensile strength behavior of UHPC and UHPFRC. Procedia Engineering. 125, 1081–1086. DOI: https://doi.org/10.1016/j.proeng.2015.11.166

[5] de Larrard, F., Sedran, T., 1994. Optimization of ultra-high-performance concrete by the use of a packing model. Cement and Concrete Research. 24(6), 997–1009. DOI: https://doi.org/10.1016/0008-8846(94)90022-1

[6] Graybeal, B., 2011. Ultra-High Performance Concrete (FHWA-HRT-11-038). Federal Highway Administration: Washington, DC, USA. pp. 1–8.

[7] Wille, K., Naaman, A.E., El-Tawil, S., et al., 2012. Ultra-high performance concrete and fiber reinforced concrete: Achieving strength and ductility without heat curing. Materials and Structures. 45, 309–324. DOI: https://doi.org/10.1617/s11527-011-9767-0

[8] Wang, D., Shi, C., Wu, Z., et al., 2015. A review on ultra-high performance concrete: Part II. Hydration, microstructure and properties. Construction and Building Materials. 96, 368–377. DOI: https://doi.org/10.1016/j.conbuildmat.2015.08.095

[9] Kang, S.T., Lee, B.Y., Kim, J.-K., et al., 2011. The Effect of fibre distribution characteristics on the flexural strength of steel fibre-reinforced ultra-high strength concrete. Construction and Building Materials. 25(5), 2450–2457. DOI: https://doi.org/10.1016/j.conbuildmat.2010.11.057

[10] Sbia, L.A., Peyvandi, A., Soroushian, P., et al., 2014. Enhancement of ultrahigh performance concrete material properties with carbon nanofiber. Advances in Civil Engineering. Volume 2014, 854729. DOI: https://doi.org/10.1155/2014/854729

[11] Iqbal, S., Ali, A., Holschemacher, K.A., et al., 2015. Mechanical properties of steel fiber reinforced high strength lightweight self-compacting concrete (SHLSCC). Construction and Building Materials. 98, 325–333. DOI: https://doi.org/10.1016/j.conbuildmat.2015.08.112

[12] Krahl, P.A., Carrazedo, R., El Debs, M.K., 2018. Mechanical damage evolution in UHPFRC: Experimental and numerical investigation. Engineering Structures. 170, 63–77. DOI: https://doi.org/10.1016/j.engstruct.2018.05.064

[13] Ryabova, A., Kharitonov, A., Matveeva, L., et al., 2018. Research on long-term strength of glass-fiber reinforced concrete. Proceedings of the International Scientific Conference Energy Management of Municipal Transportation Facilities and Transport EMMFT 2017; 10–13 April 2017, Far Eastern State Trans-

port University, Russian Federation. 640–646. DOI: https://doi.org/10.1007/978-3-319-70987-1_68

[14] Madhkhan, M., Katirai, R., 2019. Effect of pozzolanic materials on mechanical properties and aging of glass fiber reinforced concrete. Construction and Building Materials. 225, 146–158. DOI: https://doi.org/10.1016/j.conbuildmat.2019.07.128

[15] Ali, B., Qureshi, L.A., 2019. Influence of glass fibers on mechanical and durability performance of concrete with recycled aggregates. Construction and Building Materials. 228, 116783. DOI: https://doi.org/10.1016/j.conbuildmat.2019.116783

[16] Algburi, A.H.M., Sheikh, M.N., Hadi, M.N.S., 2019. Mechanical properties of steel, glass, and hybrid fiber reinforced reactive powder concrete. Frontiers of Structural and Civil Engineering. 13, 998–1006. DOI: https://doi.org/10.1007/s11709-019-0533-7

[17] Liu, J., Jia, Y., Wang, J., 2019. Experimental study on mechanical and durability properties of glass and polypropylene fiber reinforced concrete. Fibers and Polymers. 20, 1900–1908. DOI: https://doi.org/10.1007/s12221-019-1028-9

[18] Khan, F.A., Shahzada, K., Ullah, Q.S., et al., 2020. Development of environment-friendly concrete through partial addition of Waste Glass Powder (WGP) as cement replacement. Civil Engineering Journal. 6(12), 2332–2343. DOI: https://doi.org/10.28991/cej-2020-03091620

[19] Madhkhan, M., Saeidian, P., 2021. Mechanical properties of ultra-high performance concrete reinforced by glass fibers under accelerated aging. International Journal of Engineering. 34(5), 1074–1084. DOI: https://doi.org/10.5829/ije.2021.34.05b.01

[20] Dang, C-T., Pham, M., Dinh, N-H., 2023. Experimental study on compressive and flexural performance of lightweight cement-based composites reinforced with hybrid short fibers. Materials. 16(12), 4457. DOI: https://doi.org/10.3390/ma16124457

[21] Hosseinzadeh, H., Salehi, A.M., Mehraein, M., et al., 2023. The effects of steel, polypropylene, and high-performance macro polypropylene fibers on mechanical properties and durability of high-strength concrete. Construction and Building Materials. 386, 131589. DOI: https://doi.org/10.1016/j.conbuildmat.2023.131589

[22] Ghasemzadeh Mousavinejad, S.H., Radman, A., Ghorbani GilKalaye, S., 2024. A effects of fiber types on UHPC mechanical properties after high-temperature heating and cooling method: Ultra-high performance concrete. Journal of Building Material Science. 6(1), 17–31. DOI: https://doi.org/10.30564/jbms.v6i1.6095

[23] Luo, L., Shi, J., Wang, J., et al., 2024. Experimental study on flexural performance of ultra-high-performance concrete with recycled aggregate co-modified by nano-silica and steel fiber. Construction and Building Materials. 411, 134417, DOI: https://doi.org/10.1016/j.conbuildmat.2023.134417

[24] Haruna, S.I., Ibrahim, Y.E., Hassan, I.H., et al., 2024. Bond strength assessment of normal strength concrete–ultra-high-performance fiber reinforced concrete using repeated drop-weight impact test: Experimental and machine learning technique. Materials. 17(12), 3032. DOI: https://doi.org/10.3390/ma17123032

[25] Huang, Y., Shu, S., Li, Y., et al., 2025. Effects of fiber shape and nanopalygorskite on the long-term performance of steel fiber–reinforced ultrahigh-performance concrete. Journal of Materials in Civil Engineering. 37(3), 1–14. DOI: https://doi.org/10.1061/JMCEE7.MTENG-18683

[26] Simanjuntak, R.P., Aslani, F., 2025. Constitutive relationships for ultra-high-performance concrete at elevated temperatures. Scientific Reports. 15, 4957. DOI: https://doi.org/10.1038/s41598-025-88788-6

[27] Wang, T., Yu, M., Tian, J., et al., 2025. Residual properties of ultra-high performance concrete containing steel-polypropylene hybrid fiber exposed to elevated temperature at early age. Journal of Building Engineering. 99, 111507. DOI: https://doi.org/10.1016/j.jobe.2024.111507

[28] Abdal, S., Mansour, W., Agwa, I., et al., 2023. Application of ultra-high-performance concrete in bridge engineering: Current status, limitations, challenges, and future prospects. Buildings. 13(1), 185. DOI: https://doi.org/10.3390/buildings13010185

[29] Amran, M., Huang, S.-S., Onaizi, A.M., et al., 2022. Recent trends in ultra-high performance concrete (UHPC): Current status, challenges, and future prospects. Construction and Building Materials. 352, 129029. DOI: https://doi.org/10.1016/j.conbuildmat.2022.129029

[30] Li, J., Wu, Z., Shi, C., et al., 2020. Durability of ultra-high performance concrete—A review. Construction and Building Materials. 255, 119296. DOI: https://doi.org/10.1016/j.conbuildmat.2020.119296

[31] Khalily, M., Saberi, V., Saberi, H., et al., 2022. An experimental study on the effect of high temperatures on performance of the plastic lightweight concrete containing steel, polypropylene and glass fibers. Journal of Structural and Construction Engineering. 8(12), 284–307. (in Persian). DOI: https://doi.org/10.22065/jsce.2021.254752.2277

[32] Nadi, S., Beheshti Nezhad, H., Sadeghi, A., 2022. Experimental study on the durability and mechanical properties of concrete with crumb rubber. Journal of Building Pathology and Rehabilitation. 7(17), 1–12. DOI: https://doi.org/10.1007/s41024-021-00156-9

[33] Kocak, S., Korkmaz, K., Boztas, E., 2022. Impact of polymer coating on the flexural strength and deflection characteristics of fiber-reinforced concrete beams. Journal of Building Material Science. 4(2), 26–35. DOI: https://doi.org/10.30564/jbms.v4i2.5304

[34] ASTM C150/ C150M-20. 2020. Standard Specification for Portland Cement.
[35] ACI (American Concrete Institute) Building Code Requirements for Structural Concrete ACI 211-4R-93. 2014. ACI, Farmington Hills, NJ, USA.
[36] ACI (American Concrete Institute) 21-89. 2014. Building Code Requirements for Structural Concrete.
[37] ASTM C 39/C 39M-03. 2003. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.
[38] ASTM C617M-15. 2015. Standard Practice for Capping Cylindrical Concrete Specimens.