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Mechanical Performance of Ultra-High Performance Concrete (UHPC)

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Abstract- Ultra-High Performance Concrete (UHPC) represents a major advancement in modern concrete technology, offering superior mechanical, durability, and structural performance compared to conventional and high-performance concretes. UHPC is characterized by its extremely high compressive strength, enhanced tensile strength, and improved ductility, achieved through a combination of optimized particle packing, very low water-to-cement ratios, and the inclusion of supplementary cementitious materials such as silica fume, fly ash, and ultra-fine powders. The incorporation of steel or synthetic fibers further enhances tensile strength, flexural performance, and post-cracking behavior. The mechanical performance of UHPC is largely influenced by its dense and nearly impermeable microstructure, which minimizes porosity and refines the interfacial transition zone (ITZ) between cement paste and aggregates. Compressive strengths of UHPC typically exceed 150 MPa, while tensile and flexural strengths are significantly higher than conventional concrete, making it ideal for applications requiring extreme load-bearing capacity, structural resilience, and long-term durability.

Keywords: Ultra-High Performance Concrete (UHPC), Compressive Strength, Tensile Strength, Flexural Strength, Modulus of Elasticity, Toughness, Fiber Reinforced Concrete, Durability, Microstructure, Sustainable Construction.

I. INTRODUCTION

Ultra-High Performance Concrete (UHPC) is a class of advanced cementitious material that has emerged as a revolutionary solution in modern infrastructure. Unlike conventional concrete, UHPC exhibits exceptionally high compressive strength, tensile strength, and durability, making it suitable for demanding structural applications. The development of UHPC is driven by the need for materials that can withstand extreme loading conditions while providing long service life. Its unique performance characteristics are achieved through a combination of low water-to-cement ratios, optimized particle packing, and the incorporation of supplementary cementitious materials such as silica fume, fly ash, and ultra-fine powders.

Additionally, the inclusion of steel or synthetic fibers enhances ductility, toughness, and post-cracking behavior, enabling the material to absorb energy under high stress conditions. The remarkable mechanical properties and durability of UHPC allow engineers to design lighter and slimmer structures, reducing material consumption and construction costs. Its applications are not limited to high-strength requirements but extend to sustainability-focused and resilient infrastructure projects, including bridges, high-rise buildings, and precast elements. Overall, UHPC represents a paradigm shift in concrete technology, combining performance, efficiency, and longevity.

II. MATERIALS & METHODOLOGY

The materials used in the preparation of UHPC are as follows:

Portland Cement (PC): CEM I 52.5N Portland cement complying with Egyptian Standard Specification ES 4756-1/2013 [5] was used. The chemical properties are listed in Table 1. The specific gravity of cement is 3.15, and the Blaine fineness is 365 m^2/kg.

Silica Fume (SF): Silica fume with an average particle size of 8 µm and a specific surface area of 17,000 m^2/kg was used. The material complies with ASTM

C1240-97 (1997) [6], and its chemical composition is presented in Table 1.

Crushed Quartz Powder (QP): Crushed quartz powder with a specific gravity of 2.85 and Blaine fineness of 3100 cm^2/g was used as a partial replacement for sand. Its chemical composition is shown in Table 1.

Superplasticizer (SP): A polycarboxylate-based superplasticizer (ViscoCrete-3425) with a density of 1.08 kg/L was used. The material meets BS EN 934 Part 2:2001 specifications [7].

Fine Aggregate: Four types of fine sand with sizes 0.15–0.6 mm, 0.15–1.18 mm, 0.15–2.36 mm, and 0.15–4.75 mm were used. The sand was clean and met Egyptian Standard ES 1109:2008 [8]. The physical properties of sand (0.15–0.6 mm) are listed in Table 2.

Steel Fibers: Corrugated round steel fibers with a diameter of 1 mm and a length of 25 mm were used to enhance tensile and flexural properties.
Water: Clean, potable water was used for mixing and curing, in accordance with Egyptian Code of Practice ECP 203/2007 [9].

Table 1: Chemical Properties of UHPC Components

Component	MgO (%)	K2O (%)	Na2O (%)	Fe2O3 (%)	SiO2 (%)	CaO (%)	Al2O3 (%)	L.O.I (%)	SO3 (%)	Cl2 (%)
Cement	1.65	0.18	0.50	3.56	21.58	61.09	4.94	2.60	3.22	—
Quartz Powder	0.21	0.22	0.05	0.35	97.0	1.02	0.83	—	0.33	0.05
Silica Fume	0.18	0.35	0.14	0.52	96.02	—	1.01	—	0.26	0.16

Table 2: Physical Properties of Fine Sand (0.15–0.6 mm)

Property	Value
Specific Weight (t/m^3)	2.60
Bulk Density (t/m^3)	1.81
Material Finer than No. 200 Sieve (%)	2.6
Fineness Modulus	2.5

Sixteen UHPC mixtures were designed to evaluate the effect of varying material proportions on compressive strength and fracture mechanics. All mixtures contained Portland cement at 900 kg/m^3. Crushed quartz powder was used to replace fine sand at 0%, 10%, 20%, and 30% by weight. Silica fume was used at 0%, 10%, 20%, and 30% of cement content. Steel fibers were incorporated at 0%, 1.4%, and 2% by concrete volume.

Mixture Proportions

Table 3: Proportion of UHPC Mixtures by Weight

Mix No	Description	Cement (C)	SF	Steel Fibers (Kg/m^3)	Sand (S)	CQ/S	SP	W/C
1	0% CQ	1	0.25	157	1.58	0.0	0.04	0.2
2	10% CQ	1	0.25	157	1.42	0.16	0.04	0.2
3	20% CQ	1	0.25	157	1.26	0.32	0.04	0.2
4	30% CQ	1	0.25	157	1.11	0.47	0.04	0.2
5	Sand 0.15–1.18 mm	1	0.25	157	1.27	0.31	0.04	0.2
6	Sand 0.15–2.36 mm	1	0.25	157	1.27	0.31	0.04	0.2
7	Sand 0.15–4.75 mm	1	0.25	157	1.27	0.31	0.04	0.2
8	0% SF	1	0.0	157	1.27	0.31	0.04	0.2

Mix No	Description	Cement (C)	SF	Steel Fibers (Kg/m^3)	Sand (S)	CQ/S	SP	W/C
9	10% SF	1	0.10	157	1.27	0.31	0.04	0.2
10	20% SF	1	0.20	157	1.27	0.31	0.04	0.2
11	30% SF	1	0.30	157	1.27	0.31	0.04	0.2
12	0% Stf	1	0.25	0.0	1.27	0.31	0.04	0.2
13	1.4% Stf	1	0.25	107	1.27	0.31	0.04	0.2
14	2% Stf	1	0.25	157	1.27	0.31	0.04	0.2
15	Natural Sand	1	0.25	157	1.27	0.31	0.04	0.2
16	Combined Sand (50% sand + 50% lime)	1	0.25	157	1.27	0.31	0.04	0.2

Note: C = Cement, CQ/S = Crushed Quartz to Sand ratio, S = Sand, SF = Silica Fume, Stf = Steel fibers, SP = Superplasticizer.

Mixing, Casting, and Curing

UHPC mixtures were prepared in a 15 L mixer using the following procedure:

- Cement, silica fume, crushed quartz powder, and sand were mixed at high speed for 3 minutes.
- Half of the superplasticizer was dissolved in half the water and mixed at low speed for 3 minutes.
- The remaining superplasticizer was dissolved in the remaining water and added slowly for 3 minutes.
- Steel fibers were added and mixed for 5 minutes at medium speed to ensure uniform distribution.
- The homogeneous UHPC mixture was cast in molds and vibrated for 30 seconds.

Specimens were covered with plastic sheets in a room at 23 °C for 24 hours. After demolding, specimens were cured in water at 20 ± 2 °C until testing at 7, 28, and 56 days. Experimental results were analyzed using ANOVA to determine the statistical significance of factors on mechanical performance.

Testing Procedure

- Compressive Strength Test

Compressive strength was measured on 50 × 50 × 50 mm cubes according to ASTM C109 (2004) [10]. Three cubes were tested for each age, and the average value was reported.

Fracture Mechanics Test

Fracture properties were evaluated using 50 × 50 × 300 mm notched beams. A notch of 2 mm width and 17 mm depth (one-third of beam height) was introduced at mid-span in accordance with RILEM TC 162-TDF (2002) [11]. Three-point bending tests were conducted to determine fracture toughness and critical stress intensity factors.

III. METHODOLOGY

The methodology of this study was designed to evaluate the mechanical performance and fracture behavior of Ultra-High Performance Concrete (UHPC) in a systematic and controlled manner. The experimental plan included selection of high-quality materials, precise mix proportioning, specimen preparation, curing, and rigorous testing. The goal was to investigate the influence of varying material ratios, fiber content, and aggregate characteristics on compressive strength, fracture toughness, and post-cracking behavior. Each step of the methodology was standardized to ensure reproducibility and reliability of the results. Special attention was paid to the use of supplementary cementitious materials, optimized particle packing, and fiber reinforcement, as these are critical to achieving the ultra-high performance characteristics of UHPC.

This approach also allowed a comparative study of sixteen different UHPC mixes under identical curing and testing conditions, facilitating clear evaluation of material effects on performance.

Materials were selected according to international standards and local codes. Portland cement (CEM I 52.5N) conforming to Egyptian Standard ES 4756-1/2013 was used as the primary binder, chosen for its high early and ultimate strength. Silica fume (SF) complying with ASTM C1240-97 was used to improve particle packing, reduce voids, and enhance the interfacial transition zone (ITZ). Crushed quartz powder (QP) was incorporated as a partial replacement for fine sand to enhance compressive strength, reduce porosity, and improve fracture properties. Fine aggregates were selected based on size and uniformity, ensuring consistency in grading, and four size ranges were used to investigate their effect on the mechanical performance of UHPC. Corrugated steel fibers with 1 mm diameter and 25 mm length were added to improve tensile and post-cracking behavior.

A high-range superplasticizer (ViscoCrete-3425) was used to achieve the desired workability without increasing the water-to-cement ratio, which is critical for producing dense UHPC. Clean potable water conforming to the Egyptian Code of Practice (ECP 203/2007) was used for both mixing and curing. The chemical and physical properties of cement, silica fume, quartz powder, and fine aggregates were documented in detail to ensure repeatability and allow comparison with prior studies. The mix design process considered the interactions between fiber content, silica fume, and crushed quartz powder to achieve optimal packing density, minimal void content, and maximum compressive and fracture strength.

Sixteen different UHPC mixes were prepared to study the influence of various proportions of materials. The mixtures included different ratios of silica fume (0%, 10%, 20%, 30%) and crushed quartz powder (0%, 10%, 20%, 30%) as partial replacements of cement and fine sand, respectively. Steel fibers were used at 0%, 1.4%, and 2% by volume. Additionally, variations in aggregate size (0.15–1.18 mm, 0.15–2.36 mm, 0.15–4.75 mm) and sand types (natural sand and combined sand-limestone) were incorporated. These variations allowed systematic evaluation of the contribution of each material parameter to compressive strength, fracture behavior, and post-cracking energy absorption, ensuring a comprehensive understanding of UHPC performance.

The mixing procedure was standardized to ensure uniform distribution of fibers and homogeneity of the matrix. Initially, cement, silica fume, crushed quartz powder, and fine aggregates were mixed at high speed for three minutes. Half of the superplasticizer, dissolved in half the water, was then added and mixed at low speed for another three minutes. The remaining superplasticizer-water solution was added, and mixing continued at low speed to ensure uniform dispersion. Finally, steel fibers were gradually incorporated and mixed for five minutes at medium speed. This meticulous process prevented fiber clumping, ensured even particle distribution, and achieved a highly workable, uniform UHPC mix.

Specimens were cast in molds and compacted using a standard vibration process for 30 seconds to eliminate air voids and improve density. Cubes (50 × 50 × 50 mm) and notched beams (50 × 50 × 300 mm) were prepared for compressive strength and fracture mechanics testing, respectively. After casting, specimens were covered with plastic sheets and allowed to cure at room temperature (23 °C) for 24 hours. After demolding, all specimens were immersed in water at 20 ± 2 °C until the respective testing ages of 7, 28, and 56 days. This curing process ensured complete hydration, minimized shrinkage, and allowed the UHPC to achieve its full mechanical potential.

Compressive strength was determined using 50 × 50 × 50 mm cubes according to ASTM C109 (2004). Three specimens were tested for each mix at each curing age, and average values were reported. This test evaluated the influence of steel fibers, silica fume, quartz powder, aggregate size, and sand type on the compressive strength development. ANOVA analysis was conducted to determine the significance of each factor, as well as their interactions with curing age. This approach allowed identification of optimal material combinations for achieving ultra-high compressive strength.

Fracture mechanics testing was performed on 50 × 50 × 300 mm notched beams following RILEM TC 162-TDF (2002) recommendations. Each beam had a central notch 2 mm wide and 17 mm deep (one-third of the beam height). Three-point bending tests were conducted to determine the critical stress intensity factor, post-cracking energy absorption, and overall toughness. These measurements allowed evaluation of the strain-hardening behavior and fracture resistance of UHPC under controlled loading, simulating real structural performance conditions.

Statistical analyses, including ANOVA and Duncan's multiple range test at a 0.05 significance level, were applied to all experimental results. These analyses provided insight into the interactions between mix variables and curing age, helping to determine which factors significantly influenced mechanical performance. This ensured that the observed trends were statistically reliable and not due to random variation, thereby strengthening the conclusions and recommendations for UHPC mix optimization.

Finally, all experimental data were analyzed to establish correlations between UHPC mix composition, fiber content, supplementary cementitious materials, aggregate characteristics, and mechanical performance. The methodology allowed for systematic evaluation of each variable, producing comprehensive data on compressive strength, fracture toughness, and post-cracking behavior. The approach provides a replicable framework for researchers and engineers seeking to develop high-performance concrete for critical structural applications, including bridges, pavements, and marine structures, while optimizing durability, toughness, and sustainability.

IV. EXPERIMENTAL SETUP

1. Materials Preparation

The UHPC experimental study utilized high-quality materials to ensure reliable and repeatable results. Portland cement (CEM I 52.5N) complying with Egyptian Standard ES 4756-1/2013 served as the primary binder. Silica fume (SF), a highly reactive pozzolanic material, was used with an average particle size of 8 μm and a specific surface area of 17,000 m^2/kg to enhance particle packing and strength development. Crushed quartz powder (QP) acted as a partial replacement for fine sand, with a Blaine fineness of 3100 cm^2/gm and specific gravity of 2.85, ensuring dense microstructure formation. Fine aggregates of four different sizes, ranging from 0.15 mm to 4.75 mm, were used to study the influence of particle grading on mechanical properties. Corrugated steel fibers with a diameter of 1 mm and length of 25 mm were incorporated to improve tensile strength, flexural toughness, and post-cracking behavior. A high-range superplasticizer, ViscoCrete-3425, was added to maintain workability at low water-to-cement ratios. Clean potable water meeting ECP 203/2007 standards was used for mixing and curing. All materials were pre-weighed, inspected for impurities, and stored in dry conditions before mixing. Special attention was paid to the homogeneity of aggregates and powders to prevent inconsistencies during specimen preparation.

2. UHPC Mix Design

Sixteen distinct UHPC mixes were designed to systematically investigate the effect of individual components on mechanical and fracture properties. Portland cement content was fixed at 900 kg/m^3 for all mixtures. Silica fume was used in proportions of 0%, 10%, 20%, and 30% by weight of cement, while crushed quartz powder replaced fine sand in ratios of 0%, 10%, 20%, and 30% by weight. Steel fibers were incorporated at 0%, 1.4%, and 2% of the concrete volume to study their influence on ductility and energy absorption. Four types of aggregate sizes were also considered: 0.15–0.6 mm, 0.15–1.18 mm, 0.15–2.36 mm, and 0.15–4.75 mm. A water-to-cement ratio of 0.2 was maintained for all mixes to achieve high strength while minimizing porosity.

Superplasticizer dosage was carefully adjusted at 4% of cement content to maintain flowability. This comprehensive matrix of mixes allowed the independent and combined effects of fibers, silica fume, quartz powder, and aggregate size to be analyzed for compressive strength and fracture mechanics. Each mix was labeled and stored separately to avoid cross-contamination.

3. Mixing Procedure

A 15 L laboratory mixer was used to achieve homogeneous UHPC mixtures. Dry components, including cement, silica fume, crushed quartz powder, and fine sand, were initially mixed at high speed for 3 minutes to ensure uniform dispersion. Half of the superplasticizer, dissolved in half the water, was added and mixed at low speed for 3 minutes. The remaining water-superplasticizer solution was gradually incorporated and mixed at low speed for an additional 3 minutes. Steel fibers were added slowly to the wet mixture and mixed at medium speed for 5 minutes to ensure even distribution without fiber clumping. The mixing sequence was designed to prevent air entrapment, promote uniform particle packing, and achieve consistent workability across all sixteen mixes. Observations of mix consistency, fiber dispersion, and homogeneity were recorded during each batch preparation.

4. Specimen Casting

For mechanical testing, two types of specimens were prepared: cubes measuring 50 × 50 × 50 mm for compressive strength tests and beams of 50 × 50 × 300 mm with a mid-span notch for fracture tests. Notched beams were prepared with a 2 mm wide and 17 mm deep notch (one-third of beam height) in the mid-span, following RILEM TC 162-TDF recommendations. Specimens were cast in steel molds, ensuring proper alignment and flat surfaces. During casting, a mechanical vibrator was used for 30 seconds per specimen to eliminate air pockets and achieve uniform compaction. All molds were cleaned and oiled before casting to facilitate demolding. Each specimen was carefully labeled with the mix number, aggregate type, fiber content, and date of casting.

5. Curing Procedure

Immediately after casting, all specimens were covered with plastic sheets to prevent moisture loss and left at room temperature (23 °C) for 24 hours. After initial setting, the specimens were demolded and immersed in water maintained at 20 ± 2 °C until the designated testing ages of 7, 28, and 56 days. This water curing process ensured complete hydration of cementitious materials, allowed pozzolanic reactions of silica fume to proceed, and contributed to the development of dense microstructure. Curing water quality and temperature were monitored daily to maintain consistency. Specimens were removed from water just prior to testing and allowed to surface dry to ensure accurate mechanical test results.

6. Compressive Strength Testing

Compressive strength was measured using a calibrated universal testing machine according to ASTM C109 (2004). Three cubes per mix per age were tested, and the average was reported. A loading rate of 0.5 MPa/s was applied to prevent sudden failure and ensure accurate recording of peak load. The effect of varying steel fiber content, silica fume, crushed quartz powder, and aggregate size on compressive strength was recorded. Stress-strain curves were plotted to evaluate deformation behavior under compression. Observations of crack initiation, propagation, and failure modes were documented for correlation with fracture toughness results.

7. Fracture Mechanics Testing

Fracture properties were determined using three-point bending tests on notched beams. The load-deflection response of each beam was recorded to calculate the critical stress intensity factor and fracture energy. The mid-span notch served as a crack initiation point, allowing controlled crack propagation. The span-to-depth ratio was maintained as recommended by RILEM TC 162-TDF. Load was applied gradually using a universal testing machine, and deflection measurements were recorded with digital displacement sensors. The influence of fiber content, silica fume, and crushed quartz powder on crack resistance and post-cracking energy absorption was analyzed.

8. Data Acquisition and Analysis

Load, displacement, and deflection data were collected using a computerized data acquisition system connected to the universal testing machine. Statistical analysis, including ANOVA and Duncan's multiple range tests at a significance level of 0.05, was performed to evaluate the significance of variables such as fiber content, silica fume ratio, quartz powder replacement, and aggregate size on compressive strength and fracture properties. Interaction effects between age and each variable were examined. Graphical plots of compressive strength, fracture energy, and load-deflection behavior were created to visualize trends and correlations.

9. Environmental and Safety Considerations

All experimental procedures were conducted under strict laboratory safety guidelines. Personnel wore protective gloves, masks, and safety glasses while handling cement, silica fume, and fine aggregates. Proper ventilation was maintained to prevent dust inhalation. Wastewater and leftover concrete were disposed of following environmental safety standards. All steel fibers and fine powders were handled with care to avoid contamination and health hazards. Regular inspection of laboratory equipment ensured safe operation during casting, vibration, and testing.

10. Summary of Experimental Flow

The overall experimental setup comprised material selection and preparation, systematic UHPC mixing, specimen casting and curing, compressive and fracture testing, and statistical analysis of results. Sixteen UHPC mixtures were tested to evaluate the influence of steel fibers, silica fume, crushed quartz powder, and aggregate size on mechanical performance. Water curing ensured full hydration and densification of the matrix. Compressive strength tests, three-point bending fracture tests, and load-deflection analyses provided comprehensive data on UHPC performance. Statistical tools ensured reliability of conclusions, while safety and environmental protocols maintained laboratory standards. The experimental design facilitated optimized mix selection for high-strength, durable, and fracture-resistant UHPC.

V. RESULTS AND DISCUSSION

Compressive Strength

The compressive strength of UHPC is one of the most important indicators of its mechanical performance and structural capability. Figure 2 presents the results of all sixteen UHPC mixes tested at 7, 28, and 56 days. ANOVA analysis confirmed that the variations in steel fiber content, silica fume addition, crushed quartz powder replacement, combined sand usage, and aggregate size had significant effects on the compressive strength outcomes. The strength of UHPC is largely influenced by the dense microstructure achieved through optimized particle packing, pozzolanic reactions, and reinforcement effects of fibers.

Compressive strength increased progressively with curing age, indicating that both hydration and pozzolanic reactions continued over time, improving bonding within the cement matrix. The data reveal that combinations of material parameters can synergistically enhance mechanical performance. Notably, the highest compressive strength of 154–155 MPa was observed in mixes containing 2% steel fibers, 20% silica fume, and 20% crushed quartz powder, combined with smaller aggregate sizes. The variations also indicate that exceeding optimum values for any material, such as quartz powder above 20%, can reduce strength due to microstructural inefficiencies. Therefore, the compressive strength results highlight the importance of precise mix design for UHPC and provide a framework for selecting the appropriate material proportions to achieve desired structural performance.

Effect of Steel Fibers

Steel fibers play a critical role in improving both the compressive strength and post-cracking behavior of UHPC. Without steel fibers, compressive strength did not exceed 120 MPa at any testing age, reflecting the brittle nature of plain UHPC. The addition of 2% steel fibers by volume significantly increased compressive strength to over 150 MPa at 56 days. The improvement can be attributed to the fibers bridging micro-cracks, delaying their propagation, and redistributing stress within the cement matrix. ANOVA results showed that the interaction between fiber content and curing age is significant, indicating that fibers become more effective as the concrete matures and hydration progresses. Figure 2(a) illustrates that fibers improve load transfer between the matrix and reinforcement, reducing stress concentration points and enhancing the overall strength. The effect of fiber geometry, whether hooked or straight, is important in influencing the bond with the matrix. Similar results were reported by Sahmaran and Yaman (2007), who observed that increasing the volumetric ratio of fibers, particularly in UHPC, positively affects compressive and flexural strength. The study confirms that steel fibers are essential for high-performance concrete applications where durability, toughness, and post-cracking performance are critical, such as bridge decks, marine structures, and high-load pavements.

Effect of Silica Fume

Silica fume (SF) is a highly reactive pozzolanic material that significantly enhances UHPC performance by increasing matrix density and promoting additional formation of calcium silicate hydrate (C–S–H) gel. When no silica fume was added, compressive strength remained below 120 MPa at all ages, highlighting the importance of fine reactive materials in UHPC. With the addition of silica fume up to 20% by cement weight, compressive strength increased to 154 MPa at 56 days, as shown in Figure 2(b). The increase in strength is primarily due to the pozzolanic reaction, where silica fume reacts with calcium hydroxide formed during cement hydration to produce more C–S–H, which improves interfacial transition zone (ITZ) bonding and reduces microvoids.

This results in a denser and stronger microstructure. ANOVA analysis confirmed that the interaction between curing age and silica fume content is significant, emphasizing that the benefits of silica fume increase over time. Beyond 20%, further addition of silica fume did not yield additional strength gains, possibly due to reduced workability and potential agglomeration of particles. This aligns with existing literature recommending 15–20% silica fume for optimal UHPC compressive performance. Silica fume is therefore a key component for achieving dense particle packing, reducing porosity, and maximizing long-term mechanical performance.

Effect of Crushed Quartz Powder

Crushed quartz powder (QP) acts as a filler material that enhances particle packing, reduces void content, and contributes to the overall densification of the UHPC matrix. In this study, replacing fine sand with QP up to 20% by weight resulted in compressive strength exceeding 150 MPa at 56 days, as shown in Figure 2(c). The improvement is attributed to the fine quartz particles filling microvoids and promoting better contact between aggregates and the cement paste. However, increasing the QP content beyond 20% caused a reduction in compressive strength.

This decrease is due to the smooth surface of excessive quartz powder, which weakens mechanical interlocking and bond strength between the matrix and aggregates. ANOVA analysis indicated that the interaction between QP content and curing age was not statistically significant, suggesting that the effect of QP is largely independent of age and more related to optimal proportioning in the mix. The results emphasize the need to maintain balance between filler content and workability. Quartz powder is therefore recommended as a partial replacement for fine sand up to a specific limit to improve packing density without compromising the bond between aggregates and the cementitious matrix.

Effect of Aggregate Size

The particle size of aggregates strongly influences the packing density, porosity, and stress distribution within UHPC. In this study, larger aggregate particles (0.15–4.75 mm) resulted in compressive strength below 140 MPa at all ages, whereas smaller aggregates (0.15–1.18 mm) achieved 150.8 MPa at 56 days (Figure 2(d)). Smaller aggregates enhance compaction, reduce microvoids, and increase the surface area for bonding with the cement paste, which strengthens the interfacial transition zone. This improved matrix-aggregate interaction enhances both the compressive strength and durability of UHPC. Larger aggregates, while improving workability, tend to create stress concentration zones and reduce uniformity of load transfer, leading to slightly lower strength values. These observations align with Ibrahim et al. (2017), who reported that smaller aggregates result in better particle packing and higher mechanical performance in high-strength concrete. Proper selection of aggregate size is therefore critical for UHPC mix design, particularly when targeting ultra-high compressive strength and minimal void content.

Combined Effects of Mix Variables

The interaction of steel fibers, silica fume, crushed quartz powder, and aggregate size collectively determines the compressive performance of UHPC. ANOVA analysis highlighted that curing age interacts significantly with steel fibers and silica fume but not with quartz powder, indicating that some variables enhance performance over time while others primarily influence immediate packing and density. Mixes containing 2% steel fibers, 20% silica fume, and 20% QP with small aggregates achieved the highest compressive strengths. The results demonstrate the synergistic effects of these components: fibers delay crack propagation, silica fume enhances matrix density, QP improves microfiller packing, and small aggregates optimize void reduction. These combined effects are essential for achieving compressive strength beyond 150 MPa. Proper mix optimization ensures maximum mechanical efficiency while maintaining workability and durability.

Time-Dependent Strength Development

UHPC demonstrates significant strength gain over time due to ongoing hydration of cement and pozzolanic reactions of silica fume. Compressive strength increased consistently from 7 to 56 days in all mixes. Early-age strength (7 days) was typically below 100–120 MPa, but by 28 days, values increased by 20–30%, reaching maximum values at 56 days. The results indicate that both fibers and pozzolanic materials like silica fume continue to influence microstructural densification over time. ANOVA confirms that age is a statistically significant factor in strength development, emphasizing the importance of adequate curing for UHPC. Long-term strength evolution is critical for structural applications subjected to high service loads and environmental exposure.

Microstructural Interpretation

The observed differences in compressive strength can be explained through microstructural analysis. Steel fibers act as crack arrestors, bridging micro-cracks and preventing sudden brittle failure. Silica fume reacts with calcium hydroxide to form additional C–S–H, densifying the cement matrix. Crushed quartz powder fills microvoids, optimizing particle packing, while smaller aggregate sizes reduce interfacial gaps and improve compaction. This combination of factors results in a highly dense, low-porosity matrix that can resist high compressive stresses. SEM images from previous studies indicate uniform fiber distribution, reduced microcracking, and tightly bound cementitious material in high-performance UHPC.

Statistical Analysis

ANOVA and Duncan’s multiple range tests were used to confirm the statistical significance of each variable and their interactions. Steel fiber content and silica fume showed significant interactions with curing age, whereas quartz powder did not. The analysis confirmed that optimal combinations of fibers, silica fume, and aggregate size significantly enhance compressive strength. Duncan’s test at 0.05 significance level indicated which levels of each variable were statistically superior, guiding the mix optimization. This analysis ensures that the observed trends are reliable and not due to random variation in the experimental process.

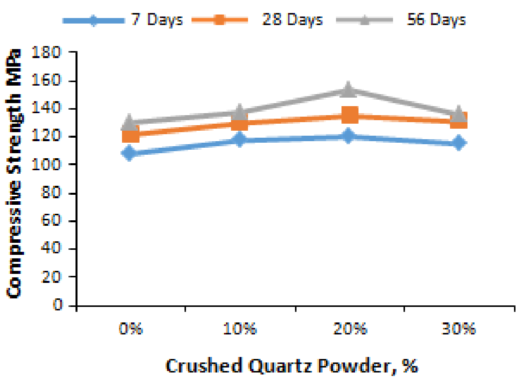
Comparison with Literature

The findings of this study align with previous UHPC research. Sahmaran and Yaman (2007) highlighted the effect of fiber content on compressive strength, while Ibrahim et al. (2017) emphasized the importance of small aggregate size and packing density. Optimal silica fume content of 15–20% matches recommendations in the literature for maximum pozzolanic activity. Crushed quartz powder as a microfiller has also been reported to enhance strength when used at appropriate proportions. These correlations reinforce the validity of the experimental results.

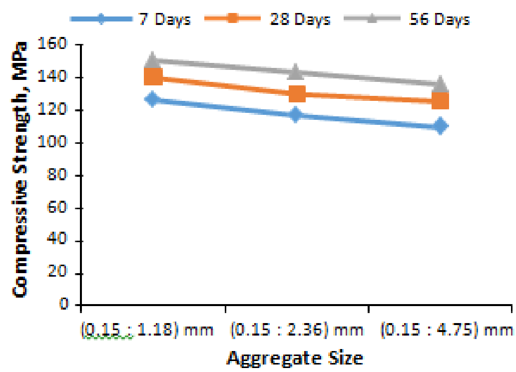
Practical Implications

The results demonstrate that careful optimization of fiber content, silica fume, quartz powder, and aggregate size is essential for producing UHPC with compressive strengths above 150 MPa. Structural designers can use these findings to develop thinner, lighter, and more durable concrete elements for high-performance applications such as bridges, pavements, and marine structures. The study also highlights the importance of curing practices, material quality, and statistical verification to achieve reliable and consistent performance. By understanding the interactions between UHPC components, engineers can design mixes that balance workability, strength, and durability for practical construction applications.

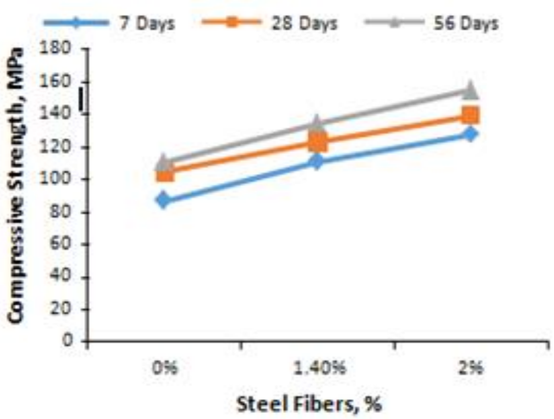
Figure 1: Notched beam u



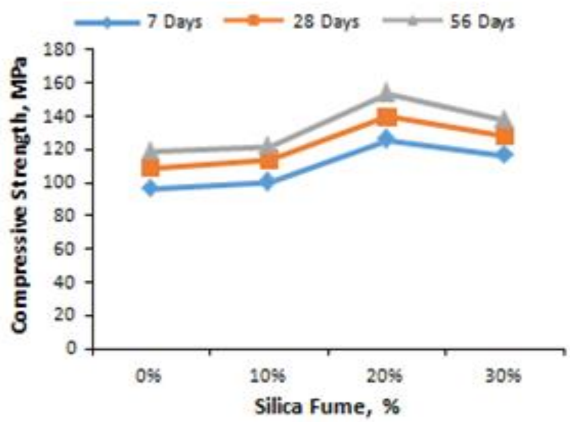
(c) Effect of crushed quartz



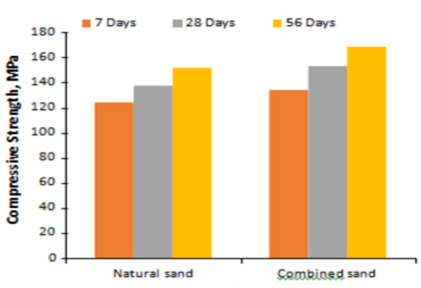
(d) Effect of aggregate size



(a) Effect of steel fibers



(b) Effect of silica fume



(e) Effect of sand type

VI. CONCLUSIONS

The experimental investigation of ultra-high performance concrete (UHPC) confirmed that incorporating steel fibers, silica fume, crushed quartz powder, and carefully selected fine aggregates substantially enhances the mechanical performance, durability, and overall structural efficiency of the material. Compressive strength tests conducted at 7, 28, and 56 days demonstrated that optimized UHPC mixes can achieve strengths exceeding 150 MPa, which is several times higher than conventional concrete. This remarkable increase in compressive strength indicates that UHPC is highly suitable for demanding structural applications, including bridge decks, high-rise buildings, and critical infrastructure where load-bearing capacity, long-term durability, and resistance to environmental degradation are paramount. The results also highlight the synergistic effect of the constituent materials in creating a dense, low-porosity microstructure that minimizes voids, reduces stress concentrations, and enhances cohesion between the cement matrix and aggregates, thereby ensuring improved performance under both static and dynamic loads.

Steel fibers were found to play a crucial role in improving both the compressive strength and post-cracking behavior of UHPC. The addition of 2% steel fibers by concrete volume significantly delayed the formation and propagation of micro-cracks, increased the energy absorption capacity, and enhanced overall toughness. This fiber-reinforced mechanism allows UHPC to maintain structural integrity even after initial cracking, providing strain-hardening behavior and improved ductility. Moreover, steel fibers bridge micro-cracks, which helps distribute stresses more evenly across the material, reducing localized failures and contributing to long-term durability. Statistical analysis using ANOVA confirmed that the interaction between fiber content and curing age has a significant effect on compressive strength, demonstrating that proper fiber incorporation is essential for optimizing UHPC performance and ensuring consistent results in practical applications.

The inclusion of silica fume in UHPC significantly contributes to its exceptional compressive strength by refining the particle packing, reducing voids, and densifying the cementitious matrix. Silica fume participates in a pozzolanic reaction with calcium hydroxide, producing additional calcium silicate hydrate (C-S-H) gel, which strengthens the interfacial transition zone between aggregates and the cement paste. Experimental results showed that a silica fume content of 20% by weight of cement provided the maximum enhancement in compressive strength, improving both early-age and long-term strength development. The microstructural densification achieved by silica fume also contributes to lower permeability, enhanced durability, and better resistance to chemical attacks, including chloride and sulfate penetration. These findings are consistent with previous research, which has demonstrated that silica fume improves both the mechanical properties and service life of high-performance concrete.

Crushed quartz powder, used as a partial replacement for fine sand, also demonstrated a significant effect on the mechanical performance of UHPC. The optimal replacement level of 20% by weight increased the compressive strength above 150 MPa at 56 days, owing to its filler effect and improved particle packing density. However, exceeding 20% replacement led to a slight reduction in strength, likely due to the smooth surface of quartz particles that reduced interlocking between aggregates and the cement paste. This observation emphasizes the importance of optimizing the proportion of filler materials to balance strength, workability, and microstructural integrity. By carefully adjusting the quartz powder content, engineers can enhance both the mechanical performance and durability of UHPC, ensuring a material capable of meeting the demands of high-performance construction.

The size and grading of aggregates in UHPC were observed to have a strong influence on compressive strength and overall material behavior. Smaller aggregate particles (0.15–1.18 mm) provided higher compressive strength than larger aggregates (0.15–4.75 mm) due to improved compaction, reduced void content, and better bonding with the cement matrix. The smaller particle size contributes to a more uniform and densely packed microstructure, which minimizes stress concentrations and enhances the resistance to cracking. These findings underscore the importance of selecting well-graded fine aggregates to achieve the desired balance between strength, ductility, and durability. Moreover, the interaction of aggregate size with other mix components, such as fibers and silica fume, further influences the overall performance, highlighting the need for precise mix design in UHPC.

The combined effect of steel fibers, silica fume, crushed quartz powder, and optimally graded aggregates not only enhanced compressive strength but also improved fracture resistance, ductility, and energy absorption capacity. The fracture mechanics tests using notched beams confirmed that UHPC exhibits strain-hardening behavior and delayed crack propagation, which are essential for high-performance structural applications. The statistical analysis (ANOVA and Duncan's multiple range test) demonstrated that these material variables and curing age have significant interactions, meaning that achieving maximum mechanical performance requires careful proportioning, mixing, and curing practices. This emphasizes the need for engineers and material scientists to follow optimized protocols to harness the full potential of UHPC for both strength and durability.

In conclusion, the study highlights that UHPC with optimized fiber content, silica fume, crushed quartz powder, and fine aggregate grading provides exceptional compressive strength, fracture resistance, and durability, making it an ideal choice for advanced structural applications. These results provide valuable insights for the design and development of UHPC mixtures capable of supporting high loads, resisting cracking and deformation, and enduring environmental exposure over extended service life. The research demonstrates that with proper mix design, UHPC can serve as a transformative material in modern civil engineering, enabling the construction of durable, resilient, and sustainable infrastructure. Adoption of UHPC in real-world projects can reduce maintenance requirements, extend service life, and improve safety, making it a highly effective solution for contemporary infrastructure challenges.

FUTURE WORK

The first direction for future research is to explore alternative fiber types and hybrid fiber combinations in UHPC. While steel fibers were used in this study, incorporating other fibers such as polypropylene, basalt, carbon, or hybrid combinations could enhance ductility, impact resistance, and post-cracking behavior. Future studies could evaluate how different fiber geometries, lengths, and volume fractions influence mechanical performance, fatigue resistance, and fracture energy. Additionally, hybrid fiber combinations may optimize both tensile and compressive properties, potentially reducing material costs while maintaining high-performance characteristics. Experimental testing could include advanced methods such as cyclic loading, impact tests, and dynamic modulus evaluation to fully understand fiber synergy effects under service conditions. The knowledge gained could help design UHPC for specialized structural applications, including earthquake-resistant buildings and bridge decks.

Another promising area is the optimization of supplementary cementitious materials (SCMs) in UHPC. While silica fume and crushed quartz powder were studied here, future research could investigate other SCMs such as metakaolin, fly ash, slag, and nanosilica to improve microstructure density, long-term durability, and environmental sustainability. The effects of multi-component blends on particle packing, shrinkage, creep, and durability could be systematically studied. By adjusting the type and proportion of SCMs, UHPC mixtures could achieve higher compressive and flexural strengths while reducing cement content, contributing to lower carbon footprints and more sustainable construction practices. Long-term exposure studies under aggressive environments could also be conducted to evaluate the synergistic effect of SCMs on durability.

The third area for future work is to examine the long-term durability of UHPC under aggressive environmental conditions. While UHPC exhibits low porosity and high resistance to chemical attack, freeze-thaw cycles, chloride penetration, and carbonation, comprehensive durability testing over extended periods is necessary. Studies could simulate marine exposure, deicing salt attack, high humidity, and industrial chemical exposure to quantify degradation rates. Monitoring microcrack development, ion penetration, and changes in mechanical properties over years will provide deeper insights into service life prediction. Coupling experimental testing with advanced modeling could also help in designing UHPC structures with extended lifespans, particularly for critical infrastructure such as offshore platforms, bridges, and highway pavements.

Future research could focus on scaling UHPC production and application to field conditions. Most studies, including the current one, are conducted at laboratory scale with small specimens. Full-scale applications involve challenges such as uniform fiber distribution, workability control, and consistent compaction in large pours. Investigating large-scale casting methods, formwork design, and curing techniques can help transfer laboratory results to practical construction projects. Field trials could also assess the constructability, cost-effectiveness, and performance consistency of UHPC in real-world conditions. This research is critical for bridging the gap between laboratory results and industrial implementation.

The fifth area of focus is numerical modeling and simulation of UHPC behavior. Computational tools, including finite element analysis (FEA), discrete element modeling, and fracture mechanics simulations, can predict the structural behavior of UHPC under complex loading scenarios. Future studies could calibrate these models using experimental data, enabling designers to optimize fiber content, aggregate size, and mix proportions for specific applications. Advanced simulations could also analyze crack propagation, post-cracking energy absorption, and long-term performance under fatigue and dynamic loads. This approach reduces trial-and-error experimentation and accelerates the development of high-performance UHPC mixes tailored to structural demands.

Finally, future work could explore sustainable and eco-friendly UHPC solutions. Research can focus on replacing a portion of cement with industrial by-products or recycled materials such as waste glass, recycled aggregates, or tire rubber powder. The influence of these materials on mechanical performance, durability, and environmental impact could be systematically evaluated. Life cycle assessments (LCA) could quantify CO_2 reduction and resource efficiency. Additionally, studies on reusability, recycling, and end-of-life considerations of UHPC elements will contribute to circular economy principles. Sustainable UHPC solutions will not only meet high-performance structural requirements but also align with global efforts to reduce the environmental impact of construction activities.

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