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Ultra-High-Performance Concrete (UHPC) application comparison based on Metallic Vs. Non-Metallic Fibers.

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Abstract
This paper presents metallic and non-metallic fibers used in Ultra-High-Performance Concrete (UHPC) and their mechanical properties. Fibers lend to UHPC the ductility required to manufacture intricate and sophisticated panels that are thin and lightweight for architectural facades, and landscape and pedestrian bridges. Steel fibers are commonly used in the manufacture of UHPC due to their mechanical properties. UHPC also utilizes non-metallic fibers in the concrete mix that helps in the production of lightweight elements. The paper also discusses some challenges associated with the universal acceptance of UHPC, the lack of sufficient research, and the challenges faced in implementing UHPC.

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I. Introduction

Ultra high-performance concrete (UHPC) is quickly emerging and establishing itself as a promising alternative to conventional concrete in the manufacture of a variety of precast concrete elements. The distinguishing feature of this concrete is its use of fiber reinforcement in place of conventional meshing or reinforcement bars. The use of fibers lends to UHPC the ductility required to manufacture intricate and sophisticated panels, especially in the field of architectural facades for building exteriors, landscape bridges, and pedestrian bridges. UHPC also allows for the use of non-metallic fibers and hybrid fibers, which are a mix of metallic and non-metallic fibers in the concrete mix, further enhancing its architectural properties. Some of the most important benefits of the use of non-metallic fibers are the production of lightweight elements with thin sections, freedom of design in formwork, and manpower reduction especially in the design and layout of steel reinforcement bars. Steel fibers are mostly used for the manufacture of UHPC elements due to their high tensile strength and elasticity modulus. However, non-metallic fibers are gaining popularity due to their noticeable performance, ductility, resistance to alkali attack, and cost-effectiveness.

The Rise of UHPC for Architectural Applications

UHPC has been under development for almost three decades since its conceptualization for structural application by Bache in 1964 **[1]**. Today it is mainly used as a material for specialized construction projects such as safe rooms, nuclear power plants, seawall anchor plates, structural beams, and thin-profile bridges. The American Concrete Institute (ACI) Committee 239 defines UHPC as having a minimum compressive strength of 150 MPa or 24.7 ksi but in general UHPC it is considered to have compressive strength higher than 120 MPa or 17 ksi.

UHPC is the latest development in the history of ordinary Portland cement (OPC) and is thought to have originated in Europe some 55 years ago. In the United States (US), UHPC was first used by the U.S. Army Corps of Engineers and in the year, 2000 became available in its present form for commercial use. Since then, the Federal Highway Administration (FHWA) is involved in its research and optimal use for highway bridge infrastructure **[2]**. The production of UHPC is fast gaining momentum and its global market is projected to reach US $1.3 billion by 2025. Researchers are now developing non-proprietary mixes that use locally available material to avoid importing ingredients and paying royalties.

The strength characteristic of UHPC is because of its low water/binder ratio and dense microstructure due to the addition of fine particles that increase its packing density. The dense microstructure helps increase the resistance against freeze-thaw cycles, wind loads, and impact. It also allows for a reduction in concrete thickness to less than 1 inch or 25.4 mm. The use of very fine particles and aggregates helps obtain high-quality surfaces from a smooth finish to intricate designs. The versatility of UHPC has given architects the freedom to design decorative elements for interior as well as exterior architectural applications. The formulations for UHPC can be engineered by varying mix proportions to obtain performance characteristics necessary for specific applications.

Metallic Fibers in UHPC

Steel fibers are the most popular and widely used reinforcement in the manufacture of UHPC due to their mechanical properties. Steel fibers used in UHPC are mainly micro steel fibers, i.e., steel fibers with a diameter of less than 0.2 mm and a length of less than 30 mm **[3]**. The parameters affecting the mechanical properties of UHPC utilizing steel fibers are size, shape, volume fraction, distribution, orientation, minimum tensile strength, and average bonding strength. Studies have shown that with an increase in fiber volume fraction, there is an increase in the compressive and tensile strength of hardened UHPC, however, there is a decrease in the flowability of fresh UHPC, weakening the reinforcing effect **[4]**.

The mechanical properties of UHPC and its mesostructure can be influenced by factors such as the orientation and distribution of fibers and the average bonding strength between the matrix and the fiber. The bonding strength can be improved by modifying the matrix, changing the shape of the fiber, roughing the surface of the fiber, and applying heat-treated curing. Excessive bonding strength can however be unfavorable for the UHPC as it can cause the steel fiber to rupture under tension, especially when the bonding strength exceeds the strength of the fiber **[5]**.

Straight steel fibers are mainly used in UHPC research and engineering applications. Following are some of the aspects that need attention to attain good mechanical properties when using steel fibers.

Flowability – To ensure uniform dispersion and orientation of steel fibers in the UHPC mix the flowability must be good. It is understood from research that when steel fibers are added, it decreases the flowability of the mix as it increases the resistance to movement of fresh UHPC due to factors such as friction and cohesive forces, free water consumption, and the skeleton formed **[6]**. Due to a reduction in flowability, the distribution of fiber becomes uneven and the porosity of the matrix increases after hardening, weakening the element. Therefore, there is a maximum fiber volume fraction that must be maintained to prevent agglomeration that reduces flowability.

Tensile strength – The fiber bridging effect of steel fibers significantly improves the uniaxial tensile strength of UHPC as it restrains the initiation and propagation of cracks. The tensile strength can be affected negatively if there is a reduction in the rheological properties due to the addition of steel fibers as discussed in flowability. To utilize the benefits of high-content steel fibers in UHPC, it is important to control the flowability of the mix design. According to research, a considerable improvement in tensile strength was observed with a high volume fraction of steel fiber with a slight reduction in flowability **[7]**.

Compressive strength – The compressive strength of UHPC is mainly determined by the strength of the matrix **[8]** and steel fibers mainly influence the tensile properties. The metallic fibers in the matrix help achieve ductile behavior under tension. Since incorporating more fibers reduces flowability and increases defects in the microstructure, it can compromise the compressive strength of the UHPC. As per NF P18-470, UHPC with metallic fibers has a characteristic compressive strength of about 150 MPa. Care should be taken in controlling the water quantity added to the concrete. Shorter fibers are preferred when the fiber volume fraction is large as long fibers can significantly affect the mix's workability.

Modulus of elasticity – The modulus of elasticity under compression and tension is assumed to be equal for UHPC, though the values are not the same. Factors affecting the modulus of elasticity include volume fraction, size of steel fibers, the porosity of UHPC, hydration products, and aggregates. According to research, the modulus of elasticity increases with an increase in the volume fraction of steel fiber and/or aspect ratio **[9]**.

Mechanical Properties of UHPC with Metallic Fibers

The mechanical properties of proprietary UHPC (Metallic Fibers) mixes include **[10]**:

- **High compressive strength** – A 24-hour compressive strength greater than 85 MPa and final compressive strength greater than 150 MPa
- **First crack strength** – A minimum first cracking strength of 6 MPa, which is the minimum stress at which the section can start developing hair cracks. The post-cracking strength of UHPC is due to its steel fiber content.
- **Tensile strength** – Higher than traditional concrete, UHPC can exhibit sustained tensile strength after first cracking.
- **Elastic modulus** – A minimum elastic modulus of 50 MPa, which exceeds that of conventional concrete as it is a function of the final compressive strength of concrete.
- **Flowability** – They have self-consolidating properties with an average spread diameter from 55 to 75 cm.
- **Flexural strength** – Measured by testing UHPC poured concrete prisms using a one-point load; steam-cured prisms had a minimum strength of 9 MPa.
- **Creep and shrinkage** – Heat-cured UHPC shows much less creep than conventional concrete and almost no shrinkage with most of it being autogenous shrinkage.

- **Fatigue resistance** – It has sufficient fatigue resistance in both tension and compression that can resist many million cycles of loading.
- **Impact strength** – UHPC's impact strength is two to three times higher than its static strength. Under quasi-static loading, UHPC is shown to be two to three times stronger in flexure and capable of absorbing three times greater energy than conventional steel fiber reinforced concrete (FRC) or polypropylene FRC.
- **Bond strength** – Bonding between conventional concrete substrates and the UHPC layer is greater when subjected to freeze-thaw cycles and where the substrate is saturated before placing UHPC.

Application Examples of UHPC Using Metallic Fibers:

Figure 1. This Wapello County, Iowa structure was the first UHPC bridge constructed in the United States.

Figure 2. Connection Link Between Precast Elements

UHPC with Non-Metallic Fibers

The demand for non-metallic fibers for use in UHPC has increased due to some of its beneficial aspects compared to steel fibers **[11]**. Though the reinforcing effect of steel fibers used in UHPC is greater than non-metallic fibers, the drawback of steel is its tendency to rust when exposed to the surface and its sharpness that can cause injury to pedestrians and animals. Non-metallic fibers used in the manufacture of UHPC include fibers of carbon, glass, polymer, basalt, and plant. They are mainly used for structures like pedestrian and landscape bridges and architectural facades.Architectural UHPC utilizes fibers with a minimum tensile strength of 140 ksi and a diameter of up to 300 microns**[12]**. Their use is, however, restricted due to the absence of a unified design guideline. Some of the non-metallic fibers that can be used in the manufacture of UHPC are briefly touched upon here.

Carbon fibers – The resistance to corrosion exhibited by carbon fibers is an attractive property for researchers. The strength and toughness imparted by carbon fibers are poor when compared to steel fibers but the enhanced resistance to early cracking is significant **[13] [14]**. It can also improve the crack resistance, tensile strength, and fatigue performance of UHPC. Since the carbon fiber surface easily absorbs water, the flowability of fresh UHPC can be significantly impacted. It is recommended to control the carbon fiber content to no more than 1% by volume **[15]**.

Glass fibers – The tensile strength of glass fibers is high and can improve the strength and toughness of UHPC. It has better reinforcement capabilities and lesser dry shrinkage than basalt and polyethylene fibers for the same aspect ratio and volume fraction. However, compared to steel fibers, the effect of reinforcement is poor **[16]**.

Polymer fibers – The modulus of elasticity and density of polymer fibers is low, and its effect on the mechanical properties of UHPC is inferior to that of steel fibers. Polymer fibers that are mainly used to increase the toughness and reduce shrinkage of UHPC are polyvinyl alcohol (PVA) fibers, polyethylene (PE) fibers, and polypropylene (PP) fibers **[17]**. Polymer fibers are included in UHPC to increase its fire resistance and prevent spalling as UHPC is prone to violent spalling at high temperatures owing to its dense microstructure. A small amount of PP fibers incorporated along with steel fibers was shown to be effective in preventing explosive spalling of UHPC **[18]**.

Basalt fibers – Like other non-metallic fibers, basalt fibers also have a limited reinforcement effect. However, it has high strength and a high modulus of elasticity **[19]**. It is also easily dispersed in the matrix due to the low average bonding strength between the basalt fiber and the cement matrix.

Plant fibers – Though fibers such as jute, banana, sisal, etc. can be used in the cementitious mix, their properties are unstable and can result in degradation in an alkaline environment. These fibers if they can be incorporated are eco-friendly and sustainable, however, they must be pretreated **[20]**.

The Use of Hybrid Fibers in UHPC

All fibers have their limitation in their use in the UHPC cementitious mix. However, some fibers can be mixed with other fibers based on their properties to enhance the overall property of the UHPC cementitious mix. Hybrid fibers are mainly based on

- Straight steel fibers of different sizes
- Straight and deformed steel fibers
- Straight steel fibers and non-metallic fibers.

When steel fibers of different sizes are used, they can generate a wall effect by creating a boundary with each other and help with the flowability aspect. Long fibers (>10 mm) can increase the deformability of the element and short fibers can improve its tensile strength **[21]**.

For the hybrid utilizing straight and deformed fibers, the straight fibers are beneficial to the flowability and compressive strength of UHPC, while deformed fibers can help improve its tensile strength and toughness. Research has also shown that this combination of fibers can improve the bending property and tensile strength post-cracking **[22]**.

As discussed before, steel fibers are incorporated with polymer fibers like PP to enhance the resistance of UHPC to fire and spalling. It is possible to attain better performance of UHPC by mixing different kinds of fibers, however, the studies and research related to this aspect are limited, and it has not yet been applied to the real world.

A new class of cement-based composite called textile-reinforced concrete (TRC) is also becoming popular due to its improved tensile strength and ductility. Since textiles do not rust like steel, they do not require the cover of steel-reinforced concrete. This allows for the production of thin and lightweight elements. TRC, UHPC, and composite UHPC, which is a combination of TRC and UHPC, have already been applied in Europe in the last decade for façade elements such as ventilated façade cladding or sandwich elements owing to their high strength and durability **[23]**.

Figure 3. Baptist Health Regional Hospital Façade using Non-Metallic Fiber UHPC

Figure 4. The University of Southern Denmark - UHPC Facade

Lack of Reference Standards for UHPC with Non-metallic Fibers

Non-metallic fibers represent roughly 30% of the ultra-high-performance fiber-reinforced concrete (UHPFRC) market, with its main application in architectural facades. However, the lack of a unified design guideline for manufacturing using these fibers has restricted the use of non-metallic fibers. One of the most popular design guidelines, The Model Code 2010 **[24]** which is used for fiber-reinforced concrete (FRC) is also established based on steel fiber-reinforced concrete. The French standard for UHPFRC, the NF P18-710 and NF P18-470 also deals with metallic fibers **[25]**.

In North America, UHPC was used as façade material in the Atrium building in 2010 where a state-of-the-art evaluation of mechanical properties was carried out for the structural analysis of the façade. The analysis used finite element computer models and a new material constitutive law (stress-strain curve) to predict the structural behavior of panels made with organic fibers. Expensive and painstaking laboratory validation testing was also conducted to support the structural analysis and design. The American Concrete Institute (ACI) Committee 239 used the testing and design results of the Atrium panels as a starting point to develop UHPC material design guidelines and specifications for non-load-bearing architectural applications in North America.

Although ACI Committee 239 has made advances in the design, testing, and specification of UHPC, the focus is mainly on structural applications for bridges and those manufactured with metallic fibers having compressive strength higher than 150 MPa. The Committee was to provide a new standard for fabrication and testing of UHPC specimens reinforced with metallic and non-metallic fibers, in collaboration with the American Society for Testing and Material (ASTM) **[26]**. However, this new standard is also applicable to UHPC having a minimum specified compressive strength of 120 MPa. This leaves out several architectural UHPC compositions with lesser compressive strength.

Since no clear building codes are available, standards and specifications of established cladding materials like fiber-cement are being used by architects and manufacturers. The testing of UHPC and its composites are therefore based on ASTM C1185 – Standard test methods for sampling and testing non-asbestos

fiber-cement flat sheet, roofing and siding shingles, and clapboards; and the specifications of UHPC and its composites are based on ASTM C 1186 – Standard specification for flat fiber-cement sheets **[27]**.
A joint effort was made in 2014 by some UHPC cladding material manufacturers to develop more relevant guidelines. They produced an acceptance criterion (AC) 458 **[28]** to establish requirements for UHPC exterior thin-wall cladding panels to be recognized under 2015, 2012, and 2009 International Building Code (IBC). The AC uses different codes and reference standards from ACI, ASTM, the Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), the National Fire Protection Association (NFPA), etc. These are used for evaluation, specification, and design, but the AC 458 still requires upgradation to include the use of composite UHPC elements.
Despite these constraints, UHPC has been successfully applied in architectural cladding in numerous projects paving the way for long-lasting, strong, and beautiful facades that require less material and are environmentally friendly and sustainable. However, efforts need to be put into developing standards and design codes that will help the safe and efficient use of non-metallic UHPC in architectural designs worldwide.

The Need for Further Studies and Research

UHPC has been studied and researched for many decades now, but it is still evolving in terms of fiber usage, mix proportions, and applications. The ability of UHPC to be manufactured in thin sections is a big factor contributing to its popularity. Some aspects that need attention include **[29]**:

- Better numerical models that effectively consider the coupling effects of factors such as fiber shape, size, volume fraction, 3D distribution, and interface transition zone
- Increasing the upper limit of fiber content and enhancing fiber reinforcement effects by considering strength and flowability
- Research on mechanical properties of UHPC other than its compressive and tensile strength, for which there are many studies.
- In-depth study and research on the use of non-metallic and hybrid fibers

It is also necessary to address the challenges faced in implementing UHPC **[30]** such as:

- The low water-binder ratio of UHPC requires high-energy mixers to effectively mix the constituents. To use existing precast site mixers, several modifications are required before they can be successfully used to produce UHPC precast elements.
- UHPC mixtures have a higher shrinkage strain than normal concrete requiring preventive measures or special admixtures to mitigate dimensional stability issues, especially in full-scale structures.
- UHPC’s flexural properties are mainly influenced by the orientation of the fibers. A reliable method must be developed that will effectively distribute fibers in the matrix with the desired fiber orientation.
- Thermal treatment during curing is one of the main factors behind UHPC's high strength and durability. Special arrangements for the same need to be explored on-site as well as precast facilities.
- Development of a standard that is simple, rational, and accurate to optimize the ingredients and mix design instead of depending on trial mixes, which is an expensive process. Standardization will also help in its wider implementation.
- The number of skilled professionals and experts in the design and construction of UHPC is limited.
- It has a high initial cost, design issues, limited standards, limited available resources, and a complex fabrication technique are some of the barriers limiting its practical application.

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