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Ultra-high-performance concrete: Constituents, mechanical properties, applications and current challenges

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A B S T R A C T

Ultra-high-performance concrete (UHPC) is a new class of concrete developed in France in the 1990s with superior characteristics including high workability, high compressive strength, increased ductility, and high resistance to environmental attacks. UHPC is increasingly used in local and international construction markets in the construction of high rise structures, long-span precast/prestressed bridge girders, marine, aviation, and defense construction applications due to its superior mechanical properties, and favorable long-term performance.

This study presents recent research findings regarding the UHPC mix designs, fresh and hardened concrete properties, and current UHPC applications in the construction industry including specific bridge applications. Despite of UHPC advantages, multiple impediments are present that delays the widespread of UHPC application in the construction industry including lack of design codes and specifications for estimating UHPC performance, the need for special batching, mixing, and curing.

This study assists different construction stakeholders in understanding the unique characteristics, advantages, and impediments to the widespread of UHPC applications. The deciphering of UHPC will help increase its overall market share in local and global construction markets.

1. Introduction

Ultra-high-performance concrete (UHPC), also known as reactive powder concrete (RPC) is a new class of concrete developed in the 1990s in France. UHPC is characterized by high flowing ability, high early strength, high final strength, and superior durability. To-date, there is no universal definition for the UHPC. In the United States, the Federal Highway Administration (FHWA) defines UHPC as a cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement. The mechanical properties of UHPC include compressive strength greater than 150 MPa and sustained post-cracking tensile strength greater than 5 MPa. UHPC has a discontinuous pore structure that reduces liquid ingress and significantly enhances durability compared to conventional concrete [1].

The Association Francaise de Genie Civil (AFGC) Interim Recommendations define UHPC as a material with a cement matrix and a characteristic compressive strength in excess of 150 MPa and containing steel fibers in order to achieve a ductile behavior. According to the AFGC, the main differences between UHPC and other types of concrete are: 1) UHPC has higher compressive strength, 2) UHPC incorporates random steel fibers in the mix, which ensures the mix non-brittle behavior, and alters the conventional requirement for

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Nomenclature

$E_c^{`}$	modulus of elasticity
$f_c^{`}$	UHPC compressive strength at 28 days
$f_{ct}^{`}$	UHPC compressive strength at age t days
t	time after casting in days

passive and/or active reinforcement, and 3) UHPC mix design includes high binder content and a special selection of aggregates

The Japan Society of Civil Engineers (JSCE) recommendations for design and construction of ultra-high strength fiber reinforced concrete define the UHPC as a type of cementitious composite reinforced by fibers with characteristic values in excess of 150 MPa in compressive strength, a minimum first cracking strength of 4 MPa. The UHPC matrix should be composed of aggregates; whose maximum particle size is less than 2.5 mm, cement and pozzolans, and water-to-powder ratio less than 0.24. UHPC contains random reinforcing steel fibers of more than 2% (by volume), whose tensile strength exceeds 2000 MPa, and ranges from 10 mm to 20 mm in length and 0.1 mm to 0.25 mm in diameter In a different research, UHPC is broadly defined as a cementitious composite material that has enhanced strength, durability, and tensile ductility compared to high performance concrete (HPC). UHPC frequently uses high strength fibers to increase ductility and post-cracking strength. UHPC minimum compressive strength us 120 MPa, and is attained using a multi-scale particle packing of inorganic materials of less than 0.6 mm in diameter [2].

Different UHPC proprietary mixes are available in the international markets with standard characteristics. Example of the proprietary mixes are BSI "Beton Special Industrial" (Special Industry Concrete) developed by Eiffage, Cemtec developed by LCPC, and different kinds of Ductal concrete mixes jointly developed by Bouygues, Lafarge, and Rhodia. Ductal concrete marketed by Lafarge and Bouygues is the only proprietary UHPC mix commercially available in the United States local construction market. Therefore, the mix constituents and material properties of Ductal are used to represent proprietary UHPC mix constituents, introduce different projects and applications in the construction market, and explain UHPC main advantages and implementation challenges.

This paper presents different types of UHPC proprietary mixes available in local and international markets, mechanical advantages attained when UHPC are used, possible applications of UHPC mixes, and the main impediments to the wide spread of UHPC in different construction markets. In addition, non-proprietary UHPC mixes developed are presented and compared to commercially available proprietary mixes.

2. Literature Review

According to its definition, UHPC mix designs exhibit the properties of 3 different types of special concrete mixes. First, the flowing and passing abilities of self-consolidating concrete (SCC), also known as self-compacting concrete, second, the superior strength and long-term performance of high-performance concrete (HPC), and third, the increased ductility and post-cracking strength of fiber reinforced concrete (FRC). The inclusion of the afore-mentioned concrete properties results in a self-consolidating ultra-high-performance fiber-reinforced concrete (UHPFRC), presented to the construction industry as UHPC, as shown in Fig. 1.

Due to the lack of coarse aggregates in proprietary UHPC mixes, some researchers suggested that UHPC is not a conventional concrete. Different research projects used the term "mortar concrete" and other used the term "reactive powder concrete" [3–5]. The material characterization and mix design of UHPC mixes are studied in multiple research projects. The effect of micro and nano-sized particles on developing high compressive strength is highlighted in different research projects including the effect of fly ash, micro-sized silica (also known as silica fume), and multi-wall carbon nano-tubes [6–12]. Relevant research projects showed that

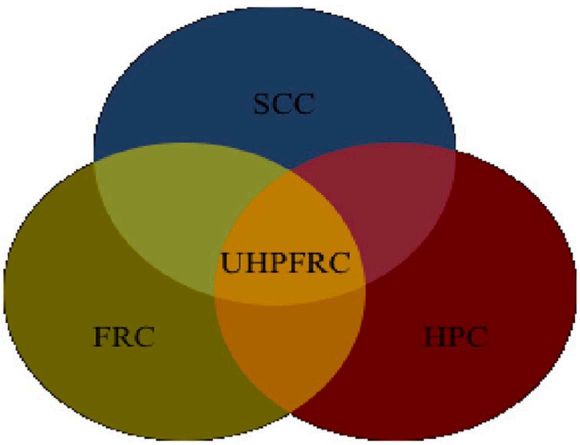

Fig. 1. Different types of special concrete [2].

well-graded small granular particles result in a high packing order and limited voids within the UHPC mix. Reduced voids result in improved long-term performance of developed mixes due to higher resistance to harsh environmental attacks. Silica fume, fly ash, and quartz flour as pozzolanic supplementary cementitious materials (SCMs) result in the mitigation of alkali-aggregates reaction (AAR). The incorporation of 15 % of silica fume in concrete mixes, used in partial replacement of cement substantially delays alkali-silica reactivity (ASR), and 30 % inclusion of silica fume will halt the ASR and its deleterious effect on concrete [13,14]. Similarly, glass sand was incorporated in UHPC mixes to develop flowable UHPC mixes, with high compressive strength, and a dense micro-structure that mitigates ASR [15].

The impact of SCMs size and percentage on the effect of UHPC mixes were investigated. The use of SCMs with average particle size of 4 μm instead of 2 μm resulted in sufficient mix flowing ability using lower quantity of high range water reducers (superplasticizers), without altering the compressive strength of UHPC. These findings could be used in developing non-proprietary UHPC mixes with comparable properties at a fraction of the proprietary UHPC cost [16]. In a different research, ultra-fine fly ash, with mean particle size of 4.48 μm, was successfully used in replacement of 20 % of cement weight to produce UHPC mixes with 153 MPa compressive strength and a spread diameter of 37.5 cm in flowing ability test. The same research used metakaolin as a pozzolanic material. Despite the high compressive strength developed, metakaolin mixes demonstrated lower flowing ability, and the overall definition of UHPC was not achieved [17].

Several research programs investigated the possibility of developing economic non-proprietary UHPC mixes using different SCMs due to the higher cost of proprietary UHPC mixes. Ternary blends of fine class F fly ash, metakaolin, and portland cement were successfully used in developing non-proprietary UHPC mixes with comparable characteristics [18]. The optimum percentage of silica fume required for attaining specified UHPC compressive strength was investigated. A 20 % content of silica fume is found sufficient to produce UHPC mixes with adequate compressive strength (greater than 150 MPa) [19]. In a different approach, the feasibility of using UHPC mixes in bridge construction is investigated considering the smaller cross sections produced for bridge structural elements poured using UHPC mixes. Smaller sections, larger spans, and fewer number of bridge girders were required for UHPC bridge construction. This provides substantial labor and material savings; and requires construction equipment with smaller capacities. Attained advantages of UHPC are maximized when welded wire reinforcement (WWR) is used in bridge girder fabrication [20], and larger prestress strands are used for tension reinforcement [21,22]. Proprietary and non-proprietary UHPC mixes are currently used in accelerated bridge construction application due to their fast set, and superior performance characteristics [23].

In a relevant study, proprietary UHPC mixes were used in designing four different UHPC bridge piers following the standard AASHTO design guidelines [24]. The pier performance, material cost, and cost of construction was compared to similar piers poured using conventional concrete mixes. The cost analysis showed that UHPC designs are not necessarily cheaper, but they will slightly increase the overall cost. The slight increase in cost of construction is offset by safer structure, longer service life, and low maintenance cost [25]. The reliability of girders poured using ultra-high-performance concrete mixes are investigated and reliability indexes for bridge girders are calibrated to ensure their compliance to current AASHTO LRFD design equations [26]. A relevant study showed that reliability of NU I-girders, fabricated using UHPC, in shear and flexure is compliant to current AASHTO LRFD provisions [27]. The following sections of this paper present the UHPC mix constituents, different constituent sizes, their role in UHPC mix behavior, and examples of different UHPC mix designs including proprietary mixes and economic non-proprietary mixes developed for specific project parameters.

2.1. UHPC mix constituents

The general formulation of proprietary UHPC consists of a high binder content including portland cement and SCMs as silica fume and quartz flour. Coarse aggregate is removed from UHPC mixes to avoid the formation of high voids and to create a densified interfacial transitional zone around the aggregates, thus, eliminate the weakest region within the matrix [28,29]. Coarse aggregate is replaced by well-graded fine sand to ensure a high mix packing order. The UHPC mix design incorporates two different types of chemical admixtures, namely: high range water reducers (superplasticizers), and concrete setting accelerator. Finally, micro-sized steel fibers are incorporated to increase the mix strength and ductility [30]. A typical proprietary UHPC mix composition, provided by Lafarge, for Ductal as a the most widely used proprietary UHPC product in the United States, is shown in Table 1.

A special type of UHPFRC, known as Compact Reinforced Composite (CRC), developed and patented by Aalborg portland is widely used in construction markets outside the USA. CRC is characterized by a compressive strength greater than 150 MPa and high tensile strength and ductility due to its high steel fiber content [31]. A typical CRC proprietary mix is shown in Table 2.

Table 1
Typical composition of proprietary UHPC mix (Ductal).

Material	Kg/m3	Percentage (by weight)
Portland Cement	712	28.5
Fine Sand	1020	40.8
Silica Fume	231	9.3
Ground Quartz	211	8.4
High Range Water Reducer (HRWR)	30.7	1.2
Accelerator	30	1.2
Steel Fibers	156	6.2
Water	109	4.4

Researchers at the Laboratoire Central des Ponts et Chaussees (LCPC) in France developed a UHPC mix, commercially known as CEMTEC. Similarly, the U.S. Army Corps of Engineers developed a UHPC-class material known as Cor-Tuf. The LCPC and Cor-Tuf mix proportions are shown in Table 3.

The successful design of proprietary UHPC mixes depends on the high binder content, low water-to-powder ratio, and availability of ductile steel fibers. The following represents the contribution of different mix design constituents to the final UHPC characteristics:

2.2. Cementitious materials

2.2.1. Type III cement

Type III cement is used in UHPC mix development to secure high early strength. Type III is typically used for precast applications to allow fast mold removal. Non-proprietary UHPC mixes were developed by different researchers in an attempt to use local construction materials and reduce the material cost of proprietary mixes [35]. The following constituents are used in non-proprietary UHPC-class materials:

2.2.2. Silica fume

Silica Fume as a byproduct of producing silicon metal or ferrosilicon alloys is used as a reactive pozzolan in partial replacement of portland cement to enhance the concrete mix properties. The incorporation of silica fume in concrete results in increased binder content, which improve the concrete compressive strength. The silica fume extremely small sized particles (0.5 micro-meter) results in a high packing order and reduced voids ratio for the produced concrete [36]. The average silica fume content in UHPC mixtures is between 20 % and 30 % by mass of cementitious materials [37]. Prior studies have found that this quantity of silica fume can decrease the calcium hydroxide content in the mixture, improve the fiber-matrix bonds, and increase the compressive and flexural strengths of the concrete [38,39]. Other studies concluded that lower silica fume content (between 5% and 15 %) can lead to decreased viscosity and marginal improvement in the performance of the concrete [40,41]. Higher silica fume content leads to increased viscosity and higher material cost.

2.2.3. Class C fly ash

Class C Fly Ash is a by-product of coal-powered electrical plants. Class C fly ash is generated from lignite or subbituminous coal [42]. Class C fly ash has pozzolanic characteristics, in addition to self-cementing properties due to its higher calcium content. It contributes to and remove calcium hydroxide from the mixture. Class C fly ash is typically preferred in UHPC concrete mix development because it provides the strength and durability characteristics without negative impacts or increased cost of the mix [43].

Concrete mixtures that contain fly ash tend to have higher ultimate strength, but lower early strength when compared with traditional portland cement mixtures. When 10%–20% of cement are replaced with Class C fly ash, the compressive strength of the samples at 3 days and 7 days of the control mix was greater than fly ash samples. As the samples continued to cure, the strength gain became more pronounced for the fly ash samples. At 90 days, the 10 % fly ash mixture had the highest strength (171 MPa) compared to a compressive strength of 161 MPa for control specimens. The researchers determined that replacing 10%–20% of the cement with class C fly ash would be beneficial in increasing compressive strength at later age [44].

2.2.4. Quartz flour

Quartz Flour is a ground crystalline quartz that is used in concrete mixing as a general filler that reduces the mix permeability (voids). Quartz flour, also known as silica flour, is considered a non-reactive pozzolanic material in normal (ambient temperature). However, quartz flour is considered reactive in elevated temperatures and under high pH value. Inert pozzolanic material as quartz flour doesn't react with mixing water, thus, the mix rheology is not altered. However, the addition quartz flour improves the packing order of the binder and result in more dense mix, which improves physical properties of the mix. Recent research should that using quartz flour and silica fume in developing ternary UHPC mixes results in increased strength and long-term durability [45]. SCM used in partial replacement of cement should not exceed 30 % of cement weight, otherwise, binder formation will be decreased, and the concrete compressive strength is negatively impacted.

2.2.5. Chemical admixtures

UHPC mixes require relatively high dosage of chemical admixtures, mainly high range water reducers (HRWR), commercially known as superplasticizers. HRWR is required for concrete mixes with very low water-to-powder ratio to attain required flowing

Table 2
UHPC mix proportions by CRC [32].

Materials	Kg/m3	Percentage (by weight)
Portland Cement	861	34
Fine Sand	792	31.2
Silica Fume	215	8.5
Glass Powder	215	8.5
HRWR	9.45	0.4
Steel Fibers	218	8.6
Water	220	8.8

Table 3
LCPC and Cor-Tuf UHPC-class material mix design.

	Cor-tuf Mix [33]	CEMTEC Mix [34]
Material	Kg/m^3	Kg/m^3
Portland Cement	790	1050
Sand	765	514
Silica Flour	216	–
Silica Fume	308	268
HRWR	14	44
Steel Fibers	247	858
Water	166	180

ability. UHPC mixes use lignosulfate formaldehyde based HRWR which might require tempering or redosing when mass concrete is poured to account for slump loss with time [46,47], or polycarboxylate based HRWR which is more efficient in maintaining the slump when time elapses [48–50].

2.3. UHPC mechanical properties

UHPC is characterized by its high binder content, low voids ratio, and random steel fiber content that results in post cracking stiffness of UHPC. Due to its special mix design, UHPC displays superior characteristics as compared to conventional concrete mixes. Significant increase in mechanical properties of UHPC mixes is shown in the following section:

2.3.1. Design compressive strength

Design Compressive Strength of proprietary UHPC mixes are mainly measured using 76 mm by 152 mm cylinders due to their high compressive strength. Regression analysis of tested UHPC mixes resulted in the following equation to approximately estimate UHPC compressive strength:

$$f'_{ct} = f'_c \left[1 - \exp(-\left(\frac{t-0.9}{3}\right)^{0.6})\right] \quad (1)$$

According to different reported research and specifications, proprietary UHPC mixes display a 24 -h compressive strength greater than 85 MPa and a final compressive strength greater than 150 MPa [51].

2.3.2. Flexural strength

Flexural Strength is measured by testing UHPC poured concrete prisms using 1-point load. Steam cured prisms poured using UHPC had a minimum strength of 9 MPa. As a result of conducted research, the following equation for UHPC modulus of rupture is proposed [52].

$$f_{ct} = 7.8\sqrt{f'_c}(\text{steam cured specimens}) \quad (2)$$

Or

$$f_{ct} = 6.7\sqrt{f'_c}(\text{untreated UHPC specimens}) \quad (3)$$

2.3.3. First crack strength

First Crack Strength displays the stress at which UHPC section can start to develop hair cracks. Unlike conventional concrete, UHPC specimens displays post-cracking strength due to their steel fiber content. According to recent research, proprietary UHPC mixes has a minimum first-cracking strength of 6 MPa

2.3.4. Elastic Modulus

Elastic Modulus of UHPC exceeds conventional normal strength concrete mixes as the elastic modulus is a function of the final concrete compressive strength. UHPC proprietary mixes have a minimum modulus of elasticity of 50 MPa. The following equation is proposed to estimate the value of UHPC modulus of elasticity [53].

$$E_c = 46200\sqrt{f'_c} \quad (4)$$

2.3.5. Spread flowing ability

Proprietary UHPC mixes have self-consolidating properties. The average spread diameter for UHPC ranges from 55 – to 75 cm. In order to attain SCC flowing ability, sufficient dosage of HRWR are used. When ambient temperature is high, ice chips are used to mix UHPC in lieu of mixing water. The afore-mentioned UHPC characteristics, including relevant ASTM standards, are shown in Table 4.

The afore-mentioned mechanical advantages are attained when mixing time of UHPC is kept below 20 min. The mixing time is recommended by precast/prestressed concrete industry professionals to avoid the formation of cold joints when layered concrete pours are used in fabricating larger and deeper sections, with heavy reinforcement.

Alkali-Silica Reactivity: resulting in the deterioration of concrete projects due to the formation of expansive gel-like material has represented a major problem that results in billions of dollars in losses. UHPC, with extremely low-void ratio, results in reduced rate of ASR. In addition to mitigating the delayed-ettringite formation (DEF), which positively impact the concrete durability [53].

Free-Thaw Strength of UHPC: is investigated in recent research. The high-performance of UHPC under freeze-thaw cycle enable the use of UHPC layers of 1 cm–2 cm in thickness in wrapping regular concrete members exposed to freeze-thaw cycle. The outcomes of this research showed that UHPC performance started to deteriorate significantly after being exposed to 600 freeze-thaw cycles [54].

2.4. Applications of UHPC in construction industry

The high material cost of proprietary UHPC mixes limits its application in the local and international markets. In North America, UHPC was first used in constructing a pedestrian bridge in Quebec, Canada in 1997. UHPC became commercially available in the United States in year 2000 and was used in constructing the first UHPC girder bridge, known as Mars Hill Bridge, Wapello County, Iowa. The bridge was completed in 2006 as a direct result of five years of collaborative research between the Federal Highway Administration (FHWA) and Iowa Department of Transportation. The Mars Hill bridge is a single-span 3-beam cross-section with span of 33.5 m, as shown in Fig. 2.

To-date, UHPC proprietary mixes are used in the fabrication of multiple UHPC bridge projects within the United States. UHPC contribution includes the fabrication of full UHPC bridges, construction of shear connectors and panel joints, pier jacketing. And/or deck overlays. According to recent report by the FHWA, approximately 200 bridge construction projects utilized UHPC proprietary mix at a given scale on the period from 2006 to 2018 when constructing a new bridge or maintaining an existing bridge within the state DOT bridge network. UHPC bridge numbers in North America constructed in the period from 2006 to 2016 are shown in Fig. 3.

UHPC contribution to bridge construction and maintenance within the United States include the following:

2.4.1. Bridge beam repair

Bridge Beam Repair due to the improved fatigue resistance of UHPC and UHPC shear connectors. UHPC proprietary mixes are used to repair the corroded steel girders ends negatively impacted by expansion joints located above the girders due to water leakage. UHPC treatment of steel girder ends are successfully replacing the conventional treatment methods of corroded steel elements.

2.4.2. Bridge deck overlays

UHPC is currently used in pouring bridge deck overlays to improve the conditions of bridge decks. To-date, there is a high demand for effective and durable rehabilitation of bridge decks being deteriorated under the increased vehicle number, increased vehicle loading, freeze-thaw cycles, deck cracking, delamination of concrete cover, and corrosion of reinforcing steel. The technique of bridge deck rehabilitation depends on available budget and the desired service life of rehabilitated structure. Traditionally, normal concrete overlays, latex-modified concrete, and special asphalt mixes with polymer-based materials were used. Currently, UHPC overlays are successfully used. UHPC overlays are advantageous due to the possibility of using slim 2.5 cm–5.0 cm thick overlays, with superior bond to existing concrete. The very low permeability and superior strength characteristics of UHPC provide sufficient strengthening required, in addition to protection from ingress of contaminators as chemical attacks and de-icing salts.

2.4.3. Bridge piles

The use of piles to support bridge load has been a common practice to produce infrastructure with high performance. Traditionally, piles are fabricated using steel sections, precast or cast-in-place concrete. Challenges facing concrete piles includes limited capacity, pile failure during installation, and deterioration of piles due to environmental attacks

The use of UHPC mixes in fabricating piles has substantially improved the piles capacity and long-term performance. UHPC mixes, with high strength, are easily driven with minimal to no damage. The very low permeability of UHPC mixes results in improved resistance to environmental attacks. The high material cost of UHPC mixes are offset by reduced material requirement due to smaller pile sizes, and the lower demand to maintenance during the life cycle of the construction project.

Accelerated Bridge Construction (ABC) Applications: using Prefabricated Bridge Elements and Systems (PBES) technique where UHPC mixes are used in pouring different bridge elements to be used in expedited bridge construction. The use of UHPC in ABC technique enabled bridge design engineer to design innovative bridge sections with geometrical dimensions that results in significant

Table 4
Mechanical Properties of UHPC mixes.

Properties	Value	ASTM Standard
Design Compressive Strength	Greater than 150 MPa	ASTM C39/C39M
Flexural Strength	Greater than 20 MPa	ASTM C78/C78 M - 18
First Crack Strength	Greater than 4 MPa	ASTM C1018 – 97
Creep Coefficient	0.2	ASTM C512/512 M – 15
Linear Expansion Coefficient	12×10^{-6}	ASTM C531 – 18
Elastic Modulus	45 GPa	ASTM C469/C469 M - 14
Spread (Flowing Ability)	55 to 75 cm	ASTM C1611 M - 18

Fig. 2. Mars Hill UHPC bridge in Wapello County, Iowa [55].

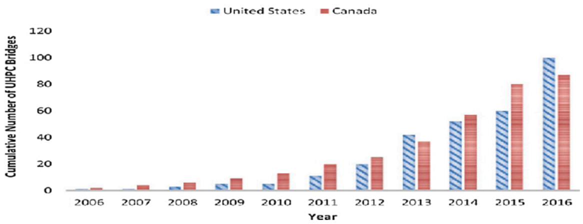

Fig. 3. Number of UHPC bridge projects in North America.

material savings and ease of construction. Example of innovative UHPC prefabricated sections used in ABC techniques is the modified Pi-girder designed by researchers at the Massachusetts Institute of Technology (MIT) and tested at the Federal Highway Administration Turner Fairbank Highway Research Center (TFHRC) in Mclean, Virginia [56].

2.4.4. Seismic columns

UHPC sections are characterized by attaining their ultimate compressive strength undergoing a linear/elastic behavior. The linear behavior of UHPC sections provides UHPC fabricated columns to avoid plastic performance and brittle failures under minimal lateral loading. UHPC behavior results in improved performance of structural elements/columns under lateral dynamic loads and seismic activities

2.4.5. Security and blast mitigation

UHPC superior strength properties, including high compressive strength, high tensile capacity, high shear strength, and high ductility allowed for the use of UHPC mixes in constructing projects that could potentially be a target for terrorism.

2.4.6. Connections

In current accelerated bridge construction techniques, bridge elements are fabricated off-site, transferred to the construction site, and assembled according to the construction drawings. The strength of the structure depends on the strength of the connections between prefabricated members. In-situ UHPC connections allow for small-sized and simple-to-construct connections with superior structural performance [57]. UHPC connections are characterized by their simplicity, speedy construction, and early high strength

2.4.7. Wind turbine towers

UHPC mixes are successfully used in the development of new wind towers for improved harvesting of clean energy. UHPC are successfully used in fabricating wind towers with 100 m high, in comparison to the conventional wind turbine heights of 80 m. The increased height of towers results in exponential increase in energy harvesting due to higher winds in higher elevations. UHPC towers are fabricated in multiple sections to avoid transportation problems; and are successfully assembled in construction site using post-tensioning techniques [58].

2.5. UHPC implementation challenges

Proprietary UHPC mixes display superior characteristics compared to other types of conventional concrete mixes. Despite of its advantages and increased market share, there are many impediments that delays the wide spread of proprietary UHPC mixes and developed non-proprietary mixes in the local and international construction market [59,60]. The main impediments include:

1 Lack of specifications and code provisions: which provide accurate estimation for UHPC sections structural capacity under different types of static and dynamic loading. Currently, guidelines and specifications are developed in France, Japan, and Australia to

standardize UHPC mixes behavior and performance. In the United States, UHPC has been commercially available for the past 2 decades. However, no authoritative document is published to describe UHPC constituents, mixing, batching, and quality control procedures. Similarly, there are no design code that can be used in accurately calculating a UHPC member performance. Current projects conducted at Federal and State levels depend on foreign guidelines and conducted lab tests. In addition, reliability studies and calibration of available international guidelines and specifications is not are required to ensure the consistency of design upon implementation of the limited resources available for design and construction

2 Lack of industry experience: among different contractors and subcontractors regarding the batching, mixing, and quality control procedures. Proprietary UHPC mixes incorporating steel fibers requires a multi-step batching and specific curing regimen

3 High material cost of proprietary UHPC mixes: due to the incorporation of relatively large amount of random steel fibers, high cost SCMs, and high dosage of chemical admixture. The average cost of proprietary UHPC mixes ranges from $2500 to $3000 per cubic meter as compared to $170 per cubic meter for conventional concrete mixes

3. Conclusions

Proprietary UHPC mixes are available in local and international markets at a material cost ranging from $2500 to $3000 per cubic meter. The significant increase in proprietary UHPC mixes is attributed to the incorporation of high strength random steel fibers, a percentage of micro silica to increase the binder content and mix compressive strength, and the use of relatively high dose of high range water reducers to maintain flowing and passing abilities of the mix at low water-to-binder ratio. Non-proprietary mixes are developed with comparable compressive strength at a fraction of the proprietary mix cost. The reduced material cost of non-proprietary mixes is mainly attributed to the elimination of high strength steel fibers and using economic supplementary cementitious materials.

Successful non-proprietary mixes compressive strength is comparable to the proprietary UHPC mixes. However, non-proprietary mixes tensile strength, modulus of rupture, and modulus of elasticity are not comparable to proprietary-mixes properties due to the absence of steel fibers, and the lack of post cracking strength developed by fibers high tensile capacity. Thus, additional section reinforcement is required when non-proprietary mixes are used including prestress strands and shear reinforcement of precast/prestress bridge girders.

Despite their cost, UHPC mixes are currently used in construction applications including high-rise buildings, construction of long-span bridge girders, defense, aviation, and marine application due to UHPC mixes high durability and reduced maintenance required during projects life span.

4. Recommendations for future research

Research investigation is required to investigate the possibility of using alternative mix constituents to reduce the high material cost of proprietary UHPC mixes. Research investigation is required to target potential steel fibers alternatives for significant mix economy.

Additional research is required to develop code equations that can successfully estimate the ultimate capacity of UHPC sections in shear and flexure. To-date, available specifications providing strength estimate for UHPC sections are not capable of providing a reliable measure for UHPC ultimate capacity.

The afore-mentioned research required for UHPC mix constituents and behavior will help increasing the market share of UHPC in different types of construction projects on national and international markets.

Data availability statement

All data, models, and code generated or used during the study appear in the submitted article.

Declaration of Competing Interest

The authors report no declarations of interest.

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