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Ultra-High-Performance Concrete (UHPC): A state-of-the-art review of material behavior, structural applications and future

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Abstract

Ultra-high-performance concrete commonly known as UHPC is rising curiosity among structural engineers all over. Though early research on this material dates back to a couple of decades, some initial knowledge about this material, its behavior, and its properties is largely limited to a few research circles in a handful of advanced countries. This paper introduces UHPC as a material, elaborates on its ingredients, and describes its properties. A detailed review of available research literature about UHPC is made. The contributions made by several researchers have been discussed in detail. Following this, the structural behavior and strength of the material are reviewed comprehensively. Comparisons are made between conventional concrete and UHPC with respect to their properties, stress-strain relation, cracking behavior, compressive, tensile, and shear strengths. A detailed evaluation is made of the enhanced properties of the material with respect to its durability and long-term performance. The resistance of this material to moisture permeability, chloride ingress, and chemical attacks is understood. The impact resistance and energy absorption characteristics of the material are compared with conventional concrete. The study documented the structural applications of UHPC as well as the potential applications in the field of civil engineering. Finally, the authors enlisted the impacts of this new material (UHPC) on the future direction of structural engineering and the innovative solutions it can provide to structural engineering problems.

Keywords

Ultra-high-performance concrete (UHPC), Mechanical behavior, Strength, Durability, Structural applications

1. Introduction

Concrete materials and technology have evolved so much over the last century. Achieving M50 grade concrete was a challenge until a few decades back. However, as the understanding of constituent materials has improved tremendously, the evolution of new materials is made possible. Development of composite materials, factory-made aggregates, fine ground materials, pozzolanic supplements, new admixtures for strength, workability, and water reducers, addition of fibers and fillers all contributed to major advancements in concrete technology. All the aforesaid initiatives lead to achieving the high magnitude of the characteristic strength which once assumed to be improbable. The idea of high-strength cementitious mixes originated from studies on cement mixes. Yudenfreund et al (1972) prepared portland cement pastes of low porosity and low water-to-cement (w/c) ratios in the range of 0.2 to 0.3 to report very high compressive strength cement paste in the range of 240 MPa at an age of 180 days. This strength was achieved with the use of finely ground cement that has high cement surface areas combined with a low w/c ratio of the mix. Hot temperatures of about 250°C and high pressure of 50 MPa to cure cement mortars were used by other researchers (Roy and Gouda 1973, Roy and Gouda 1972) and reported high compressive strengths in the range of about 510 MPa. Bache (1987) concluded that when ultra-fine cementitious particles are packed into a homogenous matrix to form densified cement systems using low water-cement ratio and high-range water-reducing admixtures, it aided in achieving high compressive strengths. These early research studies laid the basis for the development of high-performance concrete mixes. Finally, in 1994, Larrard and Sedran (1994) first proposed the concept of Ultra-high-performance concrete, which is more recently defined as a cementitious composite with a compressive strength of over 150 MPa. UHPC is defined as concrete with very high compressive strength, high tensile strength, large ductility, and durability when compared with traditional concrete. One problem with these high-density homogenous concrete materials is that they exhibited brittle failure at ultimate loads. The introduction of fibers into concrete mixes took the concrete design target strengths to a new level. To mitigate this brittle behavior and impart ductility to these high-strength concretes, researchers proposed the addition of fibers. Several combinations of steel, carbon, and synthetic fibers are used to increase the ductility of concrete . Richard and Cheyrezy (1995) developed Reactive Powder Concrete (RPC) in collaboration with Lafarge at the Bouygues laboratory in France. Their RPC used steel micro-fibers of diameter 0.15 mm and 13 mm in length are added up to 3 percent by volume of concrete. The RPC 800 mixes used steel fibers as well as steel aggregates. High pressure of about 50 MPa and temperatures up to 400°C are used during the treatment process. Their RPC 800 mix achieved compressive strength up to 810 MPa. The addition of fibers made the concrete more continuous and held the constituent particles together to form more homogenous concrete mixes. Fibers also changed the pattern of crack propagation in concrete. Fibers improved the ductile behavior of concrete near failure loads. They aided in reducing crack widths, length of crack propagation as well as the number of bigger cracks. Pozzolanic materials such as silica fume and ground granulated blast furnace slag contributed to higher strengths of the mixes by improving the binder properties of cement. Powdered silica, ground quartz, metakaolin, and fine sand are finer particles that enabled dense packing of concrete thereby improving the density, strength, and permeability of concrete. The common ingredients of UHPC are Portland cement, fine silica sand, silica fume, quartz flour, water reducer admixtures, brass-coated steel, or other fibers. Proprietary mixes usually contain some additional ingredients and admixtures that are targeted for specific outcomes. The utilization of nanoparticles to enhance concrete properties is studied by Norhasri et al (2016). Using ScienceDirect database, all the literature pertaining to UHPC or any of its equivalent terminology such as High-Performance Concrete (HPC), Ultra-high Strength Concrete (UHSC), Reactive Powder Concrete (RPC) and any other word forms are extracted, In total, about 2500 journal publications in the last 20 years that focused on this material are compiled. Two visualization maps created in Vosviewer® software based on the above data are presented in Figure 1. These heat maps clearly indicate that though research of significant value is available, it is mostly focused about strength and mixes. Large research opportunities are still to be explored for many structural applications.

While conventional concretes have compressive strength in the range of 20 MPa to 55 MPa, the UHPC is designed to achieve a minimum compressive strength of about 150 MPa. This is more than double the upper bound strength of conventional concrete. UHPC was manufactured in two classes: Class 200 MPa and Class 800 MPa (Tadros and Voo, 2016). In general, the water-to-cementitious materials (W/C) ratio in UHPC is kept under 0.25 [Aziz and Ahmed, 2012]. A high compressive strength relates to high tensile strength and better overall properties such as high modulus of rupture and shear strength. It was learned that the design modulus of rupture value for UHPC concrete can be taken higher than 8 MPa for design purposes (Gee et al, 2020). In comparison to this, the modulus of rupture value for conventional normal weight concrete as calculated by ACI 318-14: 19.2.3.1 is about 4.5 MPa for 55 MPa concrete. The high strength of UHPC combined with its ductile deformation capability beyond the range of cracking strains make it an ideal material for building seismic structures. UHPC members lead to efficient and economic designs. The high strength of UHPC aids in slim member designs thus cutting down the self-weight of these members significantly lower as compared to conventional concrete peers. Typically, self-weight of structural members constitutes a significant portion of the gravity loads these members are designed for. Using UHPC member can bring in major economies of design and improve design efficiency by enabling higher live load to dead load capabilities. The lighter members are attractive for precast concrete manufacturers because of cost efficiencies in stacking, storage, handling, shipping, and erection operations. With the obvious potential advantages of superior material properties, UHPC has become a major focus for researchers and engineers to consider it for various structural applications. One such application that could achieve huge efficiencies for the economy is the standard precast double tee market. In US markets every year, millions of square foot of double tee beam-slab members are used for building vehicular parking garages. The highly streamlined current geometric design of these members does not leave much scope for further optimization with conventional concrete. Even though it was investigated to trim the weight of these double-tee members using Styrofoam voids in stems (Jonnalagadda et al, 2021), the benefits due to minor weight reduction may be offset by the increased construction costs. For such members, UHPC-based designs can provide a significant reduction in geometry and their self-weight (Gee at al, 2020). Using UHPC also enables the usage of lesser concrete cover to steel reinforcement because of the high impermeability, corrosion resistance and durability of this concrete which further improves the design efficiencies. In typical cast-in-place construction too, lighter member designs lead to lesser steel, reduced formwork, construction equipment, and labor costs.

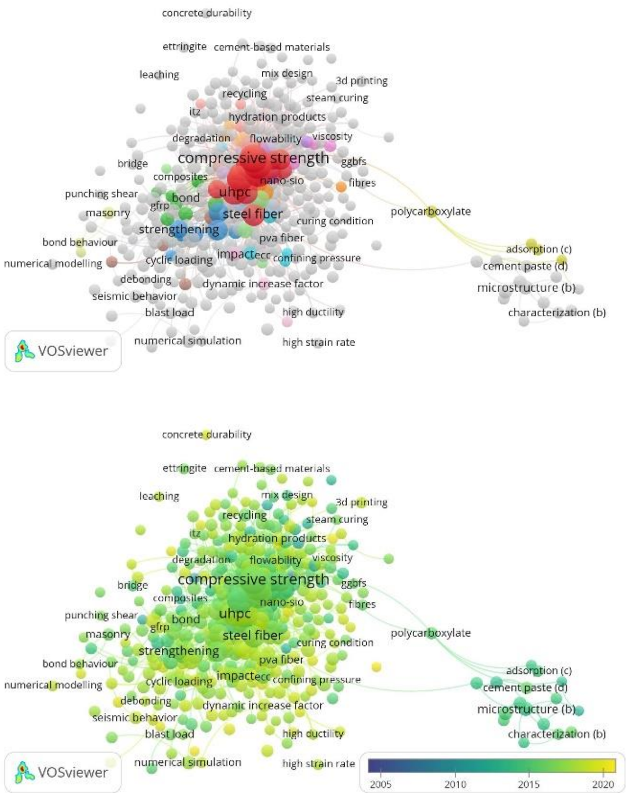

Figure 1: Heat Maps showing distribution of research studies on UHPC, HPC and similar concretes

In this research review study, a comprehensive literature review has been made about the origins of UHPC, its material ingredients, and some concrete mix proportions that are available in the literature. Throughout this paper, the usage of the term UHPC is in no way a reference to any registered or unregistered proprietary product, it is rather a general reference to a type of concrete that provides better performance in terms of material properties and behavior as compared to conventional concrete. The properties of UHPC, the stress-strain relationship of the material, the load-deflection characteristics, and the energy absorption capabilities are presented. Comparisons are made between conventional concrete and UHPC in terms of engineering properties such as energy absorption, durability, and service life. The current applications and potential applications for UHPC in civil engineering are discussed. The study is concluded with a detailed discussion and the future scope of UHPC and its impacts on the direction of structural and construction engineering. This research overall fills the gaps in synthesizing the previous findings and research on UHPC and attempts to enlist its full benefits, its superior properties, and its great potential to solve the problems of structural engineering. The study in essence addressed the relevance of UHPC to the current and future evolution of civil engineering and how it can bring novelty, efficiency, and innovation to civil engineering applications.

In the following sections, the common civil engineering properties of UHPC concrete are discussed to start with. Common properties that include typical mix proportions are presented. This is followed by giving some insights into tensile, flexural and shear behavior of UHPC concrete and its comparison with normal concrete. Stress-strain curves and load-deflection behaviors subjected to axial and flexural loading are presented and contrasted with normal concrete. Following these, the behavior of UHPC members subjected to impact loads, blast and seismic loads are discussed. The common structural properties of UHPC such as corrosion resistance, durability and cracking behavior are analyzed and compared with normal concrete members. The large array of potential applications of UHPC concrete in structural engineering are postulated in subsequent sections of the paper. Finally, the authors' opinion about the future of structural engineering with UHPC concrete and its impacts on civil engineering and construction methods for coming generations are put forward before the paper is concluded.

2. Properties of UHPC

2.1 Composition and Mix proportions

In this study, an effort is made to document the different UHPC mixes that are commercially available as well as mixes proposed by some researchers in the past. Ductal™ is a popular commercially available UHPC mix in the United States. The typical ingredients of Ductal as proposed by Graybeal (2006) are presented in Table 1, which is referenced in ACI239R (2018). The RPC mixes originally developed by Richard and Cheyrezy (1995) formed the basis for the production of Ductal (Fehling et al, 2008). The UHPC class material developed by the U.S Army Corps of Engineers is commercially called Cor-Tuf™ (Williams et al, 2009). The mix proportions of Cor-Tuf based on report by Williams et al (2009) are presented in Table 2. Bonneau et al (1996) presented mix proportions for achieving high-strength UHPC mixes (Table 3). An important aspect of UHPC mixes that requires attention is the variability in the strength and workability of these mixes. Local material properties have major impacts on these aspects. Therefore, attention needs to be given to the choice and quality control of the ingredient materials. Cement composition, sand size, grading, and type of sand could cause major differences in the final concrete product. Pozzolanic material properties vary quite significantly based on their source of procurement. Fly ash, ground granulated blast furnace slag (GGBS), metakaolin, and silica fume are typically sourced as by-products from other industrial applications though metakaolin can sometimes be sourced from clay deposits. The properties of these by-products can vary significantly based on the raw material sources. Proprietary mixes are expensive and as such prompted some of the researchers to investigate the use of local materials for the manufacture of UHPC mixes (Shahrokhinasab et al 2021, Eltawil et al 2021). The addition of these materials to UHPC could alter the concrete product and vary its physical and chemical properties very markedly. Thus, it is essential to conduct a variety of trials of mixture proportions when using local materials. A large number of trials of mix proportions may be necessary.

Table 1 Mix proportions of Ductal™ by Graybeal et al (2006) and referenced in ACI 239R (2018)

Ingredient	Proportion by weight
Portland cement	1.00
Sand	1.43
Silica fume	0.32
Ground quartz	0.30
Steel fibers	0.22
Water	0.15
High-range water reducing admixture	0.04
Accelerator	0.04

Table 2 Mix proportions of Cor-Tuf™ by Williams et al (2009) and referenced in ACI 239R (2018)

Ingredient	Proportion by weight
Portland Cement	1.00
Sand	0.967
Silica Fume	0.389
Silica Flour	0.277
Steel Fibers	0.310
Water	0.208
High-range water reducing admixture	0.017

Table 3 UHPC Mix proportions by Bonneau et al (1996) and referenced in ACI 239R (2018)

Ingredient	Proportion by weight
Cement	1.00
Sand	1.432
Silica fume	0.325
Silica flour (quartz powder)	0.300
Steel fibers	0.200
Water	0.280
High-range-water-reducing admixture	0.027

The promising trial mix proportions are then to be followed by experimental investigations by testing physical and chemical properties after casting and curing standard cube or cylinder specimens and prisms (also called 'beams' in many countries). The properties to be investigated should include setting and hardening times of UHPC, workability of the mixes, the stress-strain behavior, the compressive and tensile strengths, and the water- permeability of the concrete before the mix proportions can be established for the set of the local materials.

2.2 Tensile behavior

The tensile stress-strain behavior curve for various UHPC in comparison with fiber-reinforced concrete and conventional concrete was depicted in Figure 2. As can be noticed from Figure 2, UHPC shows significant yielding and ductile behavior post formation of first cracks as compared to conventional concrete. This behavior is referred to as strain-hardening. After multiple cracks form and cracking stresses are reached, strain-softening and crack localization occurs. In short, UHPC exhibits a range of ductile behavior before it shows a brittle failure which is way different from the behavior of conventional concrete. Strain-hardening is not seen in conventional concretes, this is normally seen in materials such as steel. As can be seen from Figure 2, the average axial tensile stress at the first crack for UHPC is 3 to 4 times that of conventional concretes. The UHPC concretes consistently exhibit a tensile strength in the range of 7-11. A very important observation to be made from Figure 2 is that the UHPC is showing great levels of yielding well beyond the first crack without exhibiting significant loss of strength. Even at a strain level of 0.01, this concrete is still safely carrying tensile stress of 7 MPa. This strain is about 30 times higher than the maximum ultimate strain in conventional concrete, a value of 0.003 typically used in all engineering designs.

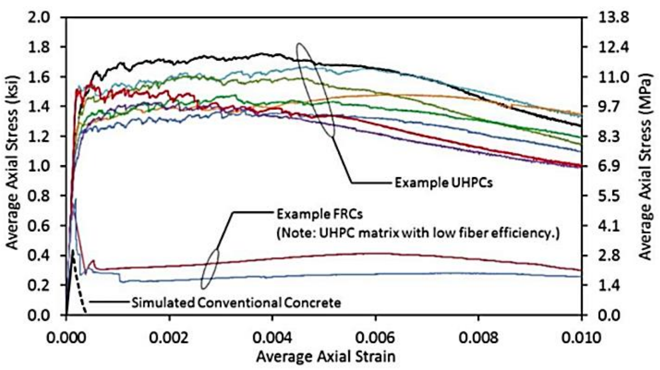

Figure 2 Tensile stress-strain behavior of UHPC (from ACI239R, 2018)

Another important observation to be made from Figure 2 is the series of the small local crests and troughs in the stress-strain curves of UHPC. These points correspond to the formation of a series of smaller and narrower cracks in UHPC as compared to one or two major cracks in conventional concrete. Unlike conventional concrete, UHPC does not show large localized rapid propagation of a crack (Graybeal, 2015). They show a significant distribution of cracks that are much smaller and shallower. A number of small and minor cracks are hallmarks of UHPC. Because of this behavior, UHPC exhibits strain hardening. For simple understanding, this can be thought of as the distribution of stress from heavily stressed zones to lightly stressed zones. This behavior of strain-hardening and redistribution of stresses is typically seen in ductile materials such as steel. This property greatly enhances the usability of the material beyond the first crack. Similar behavior is originally reported by Naaman (2002). The study compared the cracking pattern and behavior of UHPC and fiber-reinforced concrete. While Fiber Reinforced Concrete (FRC) mixes made of conventional concrete exhibited instant large cracks without any additional strength during the yielding phase, the UHPC showed significant strain-hardening beyond the first crack in the form of multiple cracks and ductility with a large range of deformations. Eventually, final cracking with loss of strength is reported at σ_{pc} (Figure 3) which is ultimate stress before final cracking and failure and this stress level is much higher than σ_{cc} which is stress at the first crack level. As you may see, the FRC does not have a strain-hardening phase as is typical of conventional concretes. In comparison, not only is σ_{cc} and σ_{pc} for FRC much lower than those values for UHPC, the σ_{pc} for FRC is a sudden drop from σ_{cc} at the point of the first crack. This indicates a brittle and sudden failure after initial cracking in the case of conventional concretes. The pictures on the right side of Figure 3 show the concrete matrix for both mixes. A single crack formation and localization are visualized in the case of conventional concrete based FRC whereas a single crack propagating into multiple cracking followed by strain hardening before localization of major cracks is observed in the case of UHPC. In typical conventional concrete design methods, the tensile strength of concrete is completely neglected. However, owing to the significant tensile strength of UHPC, the same is considered and included in the design of UHPC concrete members. In fact, tensile strength is the hallmark advantage of UHPC because the amount of reinforcement (either steel rebars or prestress strands or tendons) in UHPC members is significantly lower than conventional concrete designs, and in some minor structures these members may not need any reinforcement at all. This provides an opportunity for highly economic fabrication and construction of concrete members. This unique property of UHPC also might change some of the basic design rules in structural engineering.

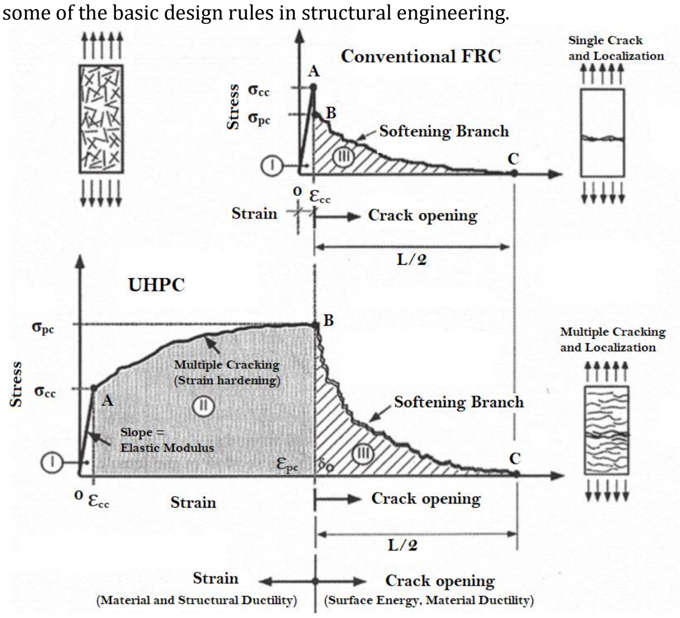

Figure 3 Cracking behavior of UHPC (from ACI239R, 2018)

2.3 Shear and Flexural behavior

The modulus of rupture during prism tests (or beam tests) is a measure of the flexural tensile strength of concrete. This value is typically specified by most of the code specifications as about 6 to 7 times the square root of concrete strength at 28 days of the age of concrete. By virtue of its high compressive strength, UHPC members exhibit significantly higher flexural tensile strength than conventional concretes, however, this is attributed to cementitious and pozzolanic ingredients in UHPC, the low water-cement ratio, the mix designs, and properties. These are the same factors that impart density and homogeneity to the mix.

A schematic comparison based on UHPC prism test results to find flexural tensile strength and deflections is presented in Gee et al (2020) and reproduced here in Figure 4. This study states that the contribution of steel fibers as a material in UHPC to its flexural strength is minimal. However, the shear resistance of UHPC is superior to conventional concrete because of the fiber orientation across the principal diagonal tension plane. These fibers improve the shear resistance of UHPC. The shear strength of UHPC is estimated to be about 5 MPa as against a 1-2 MPa for conventional concretes. As can be seen from Figure 4, multiple cracks appear in UHPC at the first crack point and there is no local widening of the cracks. The load capacity keeps increasing beyond the first cracks and the post-cracking strength is significantly higher until the ultimate load level. Localization of cracks is seen only at the ultimate strength stage with well-defined ductility beyond the ultimate strain. Looking at the conventional concrete which is indicated by the red triangular plot in Figure 4, the failure is abrupt after the cracking strength and the total energy absorbed which is represented by the area under the plots is much lower in the case of conventional concrete than in UHPC.

The superior shear strength of UHPC helps achieve great economies in concrete construction because shear reinforcement in the form of ties, spirals, or stirrups is significantly reduced or even eliminated in UHPC members. The webs of concrete beams and girders which typically take shear forces can be made significantly thinner and shear may not govern the minimum web geometry in many cases of UHPC members.

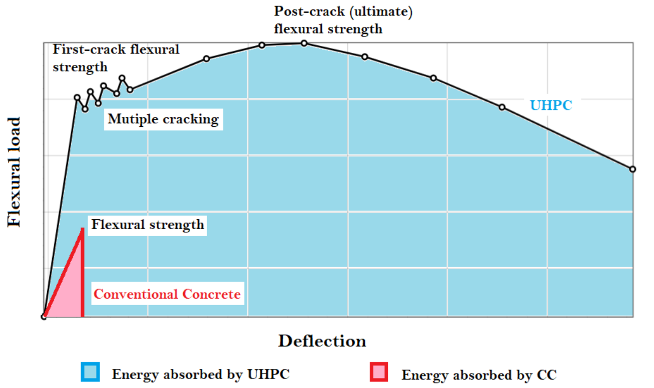

Figure 4 Load-Deflection curve for UHPC (from Gee at al (2020), Aspire Winter 2020 edition)

2.4 Impact and blast resistance

Blast loads can cause very high impact forces. The energy dissipation capabilities of UHPC were assessed by Dugat et al (1996) while studying the mechanical properties of Reactive Powder Concretes with compressive strength of 200 MPa (29 ksi) .They reported the fracture energy of this concrete is about 250 times more than the energy of ordinary concrete. This ensures great energy absorption and ductility of this material when subjected to high energy impact such as blasting. It is also suggested that the addition of a 2-3% by volume of steel fibers appeared to give optimum results.

Ngo et al (2007) meanwhile conducted experimental investigations on 100mm (4 inch) and 75mm (3 inch) concrete panels made of Ultrahigh-strength concrete (UHSC) of 164 MPa strength (24 ksi) reinforced with prestressing strands as well as Normal Strength Reinforced Concrete (NSC) of 40MPa (6 ksi) strength to compare their responses for blast impact. The specimen slabs were subjected to blast loading using 6-ton TNT from a standoff distance of 30m (100ft) and 40m (130ft). The central deflection and post blast damage of these panels were recorded and observed. It was reported that 4-inch UHSC panels performed the best with only minor damage whereas the NSC slabs had severe damage. In addition, Finite Element Modeling (FEM) was performed using these UHSC panels to understand the non-linear behavior of these members during testing. The results of FEM models agreed with experimental investigations in predicting the response of these slabs to blast loading. It was also suggested that the ultimate strength of UHSC specimen at high strain rates increased in the range of 17 to 50% which is often attributed to the Dynamic Increase Factor at very high strain rates that occur in the event of blast. It was also noticed that this dynamic increase at high strain rates is less pronounced in UHSC as compared to NSC. However, this aspect of UHPC is still under development and needs further affirmation (Li et al, 2015). Similar results were reported by Yi et al (2012) while investigating blast resistance characteristics of ultra-high strength concrete and reactive powder concretes.

Rebentrost and Wight (2011) studied the resistance of UHPC to blast loads which are high intense forces acting for a short duration. By virtue of its high absorption and high density, the resistance of UHPC to blast and impact loads is reported to be much better than that of conventional concrete.

2.5 Seismic behavior

Seismic forces are dynamic and impart huge energies to the structures they are exciting. By virtue of its high resilience and energy absorption characteristics, UHPC can be a good choice for the design and construction of structures in high seismic zones (Buck et al, 2013). Another characteristic of UHPC which is discussed above is the strain-deformability and strain-hardening beyond the first cracking stage. This can prove to be very useful in a seismic event. Deformability of a structural material helps dissipate energy and allows design for lower-level forces than maximum seismic level forces. This improves design efficiency and reduces the cost of building structures in seismic zones. Also, seismic-induced inertial forces are always proportional to the weight of the structure. Heavier structures attract high inertial forces upon seismic excitement. However, UHPC members are significantly slim and lesser in weight as compared to conventional concrete structures. The lighter member reduces the seismic forces considerably. Thus, the design of UHP structures in moderate and high seismic zones is economic and efficient as compared to conventional concrete member designs.

2.6 Corrosion resistance and Durability

UHPC is a densely packed material. This dense packing of ingredient materials gives very little room for pore spaces. It is reported that the porosity of UHPC concrete is just nine percent whereas that of conventional concrete is around 15 percent (Du et al, 2021). The water permeability of UHPC is ten to a hundred times less than the permeability of conventional concrete (Toutlemonde et al, 2016). These properties make this concrete more resistant to the infiltration of harmful chemicals and deleterious substances. This low permeability significantly improves the resistance to chemical agents such as chloride and sulfate attack. It also provides better resistance to freeze and thaw damage which is more often the case in structures built in cold climate regions where permeated water freezes inside the concrete. UHPC exhibited better electrical resistivity than conventional concrete (Toutlemonde et al, 2016). This property combined with very low permeability and chloride ingress makes UHPC an excellent choice for structural concrete in corrosive and aggressive saline or marine environments. The low porosity, permeability, and chemical ingress make a good case for lesser concrete cover requirements for UHPC as compared to conventional concrete. Historically, it is reported that UHPC performed significantly better than conventional concrete in abrasion tests, resistance to chloride ingress, alkali-silica reaction, carbonation, and freeze-thaw tests (Du et al 2021, Hosinieh et al 2015).

3. Applications of UHPC in Structural Engineering

The structures built with UHPC include many pedestrian bridges and some highway bridges. Due to its high strength and durability (Roux et al 1996, Charron et al 2007, Russell et al 2013), UHPC is a very good option for the rehabilitation and repair of aging bridge inventory in the United States. The high tensile and shear strength of UHPC makes it the right material for structural strengthening of elements such as bridge columns, beams, and key components of major water retaining structures such as dams whose service life needs extension over long periods. As mentioned in previous sections of this study, UHPC by virtue of its ability to absorb high energy yields with large deformations beyond the first crack and thus makes it a great candidate for seismic applications. Ductile behavior is very sought after in seismic designs. Designs made of UHPC are suitable for high-strength seismic joints in structural components such as shear keys in bridge decks, structural columns, and walls. In the United States, many state agencies are now relying on UHPC shear keys in precast slab and column joints for accelerated bridge construction methods. Aaleti and Sritharan (2014) developed design guidelines for waffled deck systems using field-cast UHPC connections between girder and slab for composite behavior. The keys are usually the zones of high stress and fatigue due to moving loads and often are a maintenance nightmare when built with conventional concrete. UHPC joints are very promising in terms of durability and longevity.

It can be said that UHPC construction with its high durability could prove to be cost-effective when considering life-cycle costs. High durability can extend the service life of bridges and improve the sustainability of our infrastructure (Gee et al, 2020). Though the age of a bridge is found to have the most significant correlation with the deterioration of bridges in the United States in an Artificial Intelligence data-driven study (Jonnalagadda et al, 2016), the cause for structural deterioration is often attributed to weathering, material durability, and truck overloading in many instances (Jonnalagadda et al, 2015). The superior material durability of UHPC as such can enhance the service life of bridges. Longer service life reduces maintenance interventions and helps lower bridge infrastructure costs. This is vital to building a sustainable bridge infrastructure as advocated by Jonnalagadda (2016) in his doctoral thesis. UHPC could have huge impacts on the sustainability of general infrastructure as well. UHPC can be a great fit for other special structures such as nuclear reactors, wastewater structures, high-rise structures, and marine structures. All these structures commonly demand either high resistance to physio-chemical ingress or high shear and tensile forces due to wind or seismic events. Some of the potential replacements that UHPC can do for the current conventional concrete applications are listed below.

1. UHPC enables the design of thinner and lighter structural members.
2. UHPC enables the development of impervious and durable structures (Li et al 2020, Schmidt et al 2005, Xue et al 2020, Zhou et al 2018, Azmee and Shafiq 2018, Gu and Sun 2015, Wille et al 2011, Rebentrost et al 2008)
3. UHPC can create durable and impervious water retaining structures such as dams, water tanks, and hydraulic structures.
4. UHPC can enable the design of strong but deformable seismic structures.
5. UHPC is a great material for structural repair and rehabilitation treatments.

6. UHPC viaducts are promising for high-speed rail due to fatigue resistance.
7. UHPC makes great material for tunnel construction due to low permeability.
8. UHPC is a good choice for environmental structures such as sewage tanks, sewers, wastewater facilities, and retention ponds because of its low chemical ingress.
9. UHPC is ideal for nuclear facilities due to its high density and impermeability.
10. UHPC is a good choice for defense structures due to its high energy absorption and blast resistance.

4. Future of Structural Engineering with UHPC

The authors believe that UPHC has the potential for very strong impacts on the future and direction of structural engineering. This material has the potential to be a very impactful invention and could have major impacts on the engineering philosophy and methods of analysis and design of structures. When Eugene Freyssinet invented prestressing, few people saw the everlasting impacts it had on the design and construction of structures. These days prestressed concrete has very significantly replaced reinforced concrete construction and design philosophy.

The authors strongly believe that UHPC will have profound and long-lasting impacts on the field of structural engineering similar to prestressed concrete. This could bring a partial replacement of prestressed concrete philosophy or at least effect a hybrid construction and design using UHPC and prestressing methods. The material will also affect changes to design methods and principles (Alsalman et al 2017, Marvila et al 2021, Magureanu et al 2012, Shi et al 2019, Carbonell et al 2014, Zhou et al 2021). As a versatile and superior material (Alsalman et al 2017, Abbas et al 2016, Jungwirth and Muttoni 2004, Van et al 2011, Wu et al 2016, Su et al 2016, Shah et al 2022) when combined with the benefits of precast construction (Srimaruthi and Sitaram, 2023a) can offer novel construction and engineering alternatives (Srimaruthi and Sitaram, 2023b). With higher strength and ductile behavior post cracking, UHPC offers promising applications in tall buildings where fatigue resistance of joints to lateral winds and seismic forces is critical (Sitaram and Srimaruthi, 2023a). Various studies on UHPC also indicated its superior fire resistance capabilities at higher temperatures though high energy spalling is reported as compared to normal concretes (Hedayati et al 2015, Liang et al 2018, Qin et al 2021, Missemer et al 2019, Li et al 2021)

The biggest hindrance to UHPC construction currently is the cost of making this material. Proprietary UHPC concrete typically is about ten times more expensive than conventional concrete. Proprietary mixes and batch mixing times are the two factors that make this material not so economical. To put this in perspective, the cost of normal plain concrete as reported by many precasters in North America is in the range of 150-250$ per cubic yard. Comparing this with commercial UHPC mixes, such as Ductal®, CorTuf® which employ fibers in the mixes can cost anywhere from 1500-2000 $ per cubic yard (Ehrlich, 2023). The material cost of fibers alone can range about 500$ per cubic yard. This indicates how expensive these proprietary mixes can be. Other than cost, the biggest hurdle to UHPC manufacture is the mixing times and mix material consistency. These mixes are very stiff owing to very low water-cement ratios and thus need large mixture times to achieve mix consistency. Mixing times as high as 20 minutes are commonly reported by Cor-tuf® (Lysett, 2023) and in the trial mixes developed by many concrete fabricators. Apart from the above two limitations, need for major over haul of construction and manufacturing methods is other major hurdle. Many contractors, engineers and owners would need to redesign the construction facilities, erection methods and materials in order to be able to bring in UHPC structures. For example, concrete manufacturers would need new form work equipment for modified member geometry and reinforcing requirements. They need to develop infrastructure required for new curing methods such as steam curing. Usage of fibers would need changes to batch plants. Ready mix trucks would need to be designed specially. Engineers would need to gather design tools that can perform UHPC based member designs based on several code bodies. Overall, this is going to be a long-term process that can involve significant learning and adaptation of construction industry overtime.

However, with more drive toward local material-based mixes, evolving capabilities of concrete mixer machinery and open attitudes of contractors, engineers and owners , UHPC construction has huge potential to bring efficiencies and economies to building infrastructure.

5. Summary and Conclusions

This report consolidates the research and the literature available on the properties, behavior and performance of Ultra-High-Performance Concrete commonly known as UHPC. To start with, the background of development along with commonly known proprietary mix proportions are presented. The strength and serviceability of UHPC in flexure and shear are compared with conventional concrete. It is observed that at service condition of structures, the flexural stress levels in UHPC members are well below the allowable cracking stresses which resulted in lighter reinforcement requirements. The high shear strength of UHPC concrete enabled significant reduction in shear reinforcement in these members and in some cases can remove the need for shear reinforcement altogether. Overall, UHPC concrete is understood to perform significantly superior to traditional concrete in terms of water permeability, corrosion resistance, impact and fatigue resistance. UHPC concrete offers promising applications with respect to repair and rehabilitation of aged infrastructure with deteriorated and distressed members. Finally, the authors believe that the potential implications of UHPC on structural engineering design and philosophy can last for many generations to come. The next generations of civil engineers need to brace themselves for the paradigm shift that UHPC is going to bring to current typical methods of analyses, design, and construction of structures ((Sitaram and Srimaruthi, 2023b) and train themselves to getting ready for living with this novel concrete.

Disclaimer

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