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Recent Advances in Ultra-high Performance Concrete

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This paper presents a comprehensive review of recent advances in ultra-high performance concrete (UHPC). Fundamental characteristics of UHPC are elaborated with focus on its material constituents, mixing, and formulation procedures. Use of state-of-the-art materials such as carbon nanotubes or nano-silica is discussed as well, whose inclusion may enhance the performance of UHPC. The review evaluates supplementary treatment methods (e.g., pressuring curing) and identifies applicable standard test methods for determining the properties and behavior of UHPC. Site implementation is provided to link laboratory research with full-scale application. Research needs are suggested to further develop UHPC technologies from technical and socio-economical perspectives.

Keywords : Review, State-of-the-art, Test methods, Ultra-high performance concrete (UHPC)

1. INTRODUCTION

Demand for sustainable structures is increasing nowadays. Ultra-high performance concrete (UHPC) is a promising material to address such a requirement from state or federal agencies. UHPC is a specially designed concrete that meets the needs for specific service conditions, particularly infrastructure and multi-story buildings. UHPC is generally defined as a very high strength cementitious composite material, containing optimally graded aggregate and fiber reinforcement. Typical composition of UHPC includes Portland cement, fine aggregate, water, supplementary cementitious materials, a superplasticizer, and discrete reinforcing fibers. Unlike conventional concrete, coarse aggregate is not used. UHPC has demonstrated superior mechanical properties compared to conventional concrete (FHWA 2011). For example, compressive strength of UHPC ranges between 170 MPa and 230 MPa in most cases (Ahlborn et al. 2008). To achieve such a high strength, UHPC requires a low water-to-cementitious binder ratio (e.g., less than 0.25). Porosity characteristics of UHPC reduce the flow of water, thereby improving durability in aggressive environment (FHWA 2011). Use of a superplasticizer addresses the workability issue of UHPC. Potential application of UHPC is broad from bridge structures to nuclear power plants. UHPC has increasingly been used around the world (Blais and Couture 1999; Rouse et al. 2011; Planete 2012). Advantages of UHPC include the long-span of flexural members with light weight, minimal use of steel reinforcement, increase in tensile strength and toughness, resistance to harsh service conditions, accelerated construction, and reduced long-term maintenance costs (Graybeal 2009; Al-Azzawi et al. 2011). The relatively high material costs of UHPC can be offset with reduced long-term maintenance expenses (Semioli 2001).

Extensive effort has been made on formulating UHPC (to be discussed), whereas its development is still in infancy. Of interest are the material costs of UHPC and the application of

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local materials. Limited research has been conducted to address these issues from a practical point of view. Technical challenges associated with the site application of UHPC are as follows:

- *Readiness of formulation and implementation*: special mix design and procedures are necessary to adequately formulate UHPC; however, there are no code provisions or standards in the United States which makes enduser sector hard to enjoy the benefit of UHPC.
- *Excellent performance with reasonable costs*: although the material costs of UHPC have consistently been decreasing since it was first introduced to the construction community, UHPC is still an expensive material to use. Positive approaches to reduce costs are necessary. Use of regionally available materials can decrease transportation expenses and the dependency of commercial products.

To accomplish the success of various construction projects with the benefit of UHPC, these challenges must be thoroughly addressed. It is important to note that the technical and economical issues identified are critical for those who are interested in sustainable structures. This paper reviews the state-of-the-art relevant to the practical application of UHPC and further elaborates critical research needs for improving the design and implementation of UHPC. Emphasis is placed on material characteristics, design and implementation, supplementary treatment, applicable test methods, and site application.

2. CHARACTERISTICS AND IMPLEMENTATION OF UHPC TECHNOLOGY

2.1 Design of UHPC

Typical concrete shows a compressive strength (f'_c) from 20 MPa to 35 MPa. The need for high strength and improved performance is emerging to build sustainable structures. The advent of reactive powder concrete with f'_c ranging from 200 MPa to 800 MPa overcomes the limitations of conventional normal strength concrete (Reactive 2002). UHPC addresses the following engineering characteristics: strength, elastic modulus, abrasion, durability, permeability, chemical resistance, impact, placement difficulty, and long-term maintenance costs. The strength range of UHPC mentioned above exceeds the strength of high strength concrete by two to six times (Lubbers 2003; Schneider et al. 2004). Table 1 compares typical engineering properties of UHPC with those of normal and high strength concrete. Although the theory of traditional reinforced concrete may be used for the application of UHPC, care should be exercised because some empirical factors have been developed based on the behavior of conventional concrete. No codified provisions are available for UHPC in the United States. Therefore, experienced technical personnel can only assure the adequacy of UHPC design and construction. Optimal use of constituent materials is important for the implementation of UHPC. According to a comparative study (Blais and Couture 1999), steel fibers in UHPC (a length of 25 mm and a diameter of 0.2mm) are equivalent to reinforcing bars of 8 mm in diameter and 1000mm in length for normal

Table 1. Typical comparison of engineering properties of UHPC with normal and high strength concrete (compiled based on Ahlborn et al. 2008)

Property	Normal concrete	High strength concrete	UHPC
Compressive strength	3,000-6,000 psi	6,000-14,000 psi	25,000-33,000 psi
Tensile strength	400-500 psi	-	1,000-3,500 psi
Elastic modulus	2,000-6,000 ksi	4,500-8,000 ksi	8,000-9,000 ksi
Poisson’s ratio	0.11-0.21	-	0.19-0.24
Porosity	20-25%	10-15%	2-6%
Chloride penetration	>2000	500-2000	<100
Water-cement ratio	0.40-0.70	0.24-0.35	0.14-0.27

concrete. Removal of coarse aggregate will reduce the interfacial transition zone between the cementitous binder and aggregates and thus improve tensile strength (Mindess et al. 2003; Mehta and Monteiro 2006). Supplementary cementitious materials such as silica fume fill micro-voids to produce a dense mixture with low permeability. Limited effort has been done on using nano-scale materials for the design and practice of UHPC (Kowald 2004).

2.2 Material composition

Most composition of UHPC is dry particles, while liquid-oriented constituents are limited. UHPC is typically comprised of Portland cement, supplementary cementitious materials, quartz powder, water, fine aggregate, a superplasticizer, and fibers. Use of fine aggregate and quartz powder increases density, whereas decreases porosity. The particle size of fine aggregate affects the homogeneity of UHPC (Richard and Cheyrezy 1995). Quartz is easily obtainable and has a very strong compressive strength (1,100 MPa) with an inexpensive price (about $150 per ton). Steel or organic fibers are commonly used for UHPC, including a fiber ratio from 1.0% to 2.0% (Al-Azzawi et al. 2011). Because of the embedded fibers, the crack width of UHPC is much less than that of conventional concrete (FHWA 2011). The effect of fiber content influences the post-peak behavior of UHPC in tension, while such an effect may not be critical for compressive strength (Ali 2007; Redaelli and Muttoni 2007; Al-Azzawi et al. 2011). Attention needs to be paid when the tensile strength of UHPC is measured because the internal fibers can have an impact on the cracking response of the concrete such as strain-hardening (FHWA 2011). Silica fume and high reactivity metakaolin are widely used materials (Ali 2007). Silica fume includes amorphous silica dioxide and reacts with calcium hydroxide (Al-Azzawi et al. 2011). Metakaolin is white clay and is obtained by treating kaolin. Metakaolin (typically 0.005 mm in diameter) is an abundant material and its primary composition includes SiO_2 and Al_2O_3 (Sabir et al. 2001). These supplementary cementitious materials chemically react with the hydration process of cement so that the performance of UHPC is enhanced. A compressive strength of 97 MPa may be a good indicator of adequate hydration (FHWA 2011). Qian and Li (2001) reported that the tensile strength and corresponding strain of concrete increased with an increasing metakaolin content, whereas the elastic modulus of the concrete was independent of metakaolin. UHPC mixed with silica fume showed a higher compressive strength than that with high reactivity metakaolin (Al-Azzawi et al. 2011). Due to the dense mixture of the constituents, UHPC demonstrates low permeability (Ahlborn et al. 2008). The performance of UHPC is enhanced accordingly, such as freeze-thaw resistance and reduced corrosion of reinforcing steel. Permeability of concrete controls chloride penetration, thereby increasing the corrosion potential of embedded reinforcing steel bars (Lubbers 2003; Ahlborn et al. 2008). UHPC effectively addresses this concern according to experimental investigations (e.g., oxygen permeability less than $3.9\times10^{-12}mm^2$, AFGC 2002). The water-cementitious binder ratio of UHPC (typically ≤ 0.25) is lower than that of normal concrete. A superplasticizer improves workability that may be problematic because of such a low water-binder ratio. Collepardi et al. (1996) studied the efficacy of a superplasticizer and silica fume on the compressive strength of UHPC. Test results include that acrylic polymer demonstrated better performance than sulfonated melamine and sulfonated naphthalene. Strength gain at early age of UHPC is of interest. The reason is that UHPC exhibits a gradual decrease in strength with time owing to a reduction in water content and the chemical reaction associated with supplementary cementitious materials commencing in a few days of concrete-casting (Al-Azzawi et al. 2011). Although some research has been conducted as to the behavior of UHPC with carbon nanotubes it is still inconclusive (Wille and Loh 2010). For example, an increase in compressive strength over 12% was observed when multi-walled carbon nano tubes (MWNT) were included in a UHPC mix (Li et al. 2005; Kowald et al. 2008); however, some experimental programs reported that the inclusion of MWNT caused the reduction of strength (Musso et al. 2009). Alternative nano-scale materials may be used for the mix of UHPC, such as nano silica.

2.3 Mixing, curing, and formulation procedures

Mixing is an important component to attain the best performance of UHPC. Fig. 1 shows typical procedures to mix UHPC. The mix design and procedures of UHPC are different from those of normal concrete. Selected mix designs for UHPC are summarized in Table 2. Improving the density of UHPC is a critical factor to achieve high strength and durable performance when subjected to aggressive service conditions. The particle size of aggregate needs to be carefully determined because it governs the homogeneity of UHPC. Improved homogeneity increases the reliability of UHPC (Lubbers 2003). UHPC uses significantly smaller aggregates in comparison to other types of concrete (Richard and Cheyrezy 1995; Bonneau et al. 1997): cement particles (0.01mm to 0.08mm), quartz powder (0.01mm to 0.015mm), and silica fume (0.1×10^{6}mm to 0. 2×10^{6}mm). Typical size of steel fibers in UHPC is 0.2 mm in diameter and less than 25mm long (Blais and Couture 1999). Embedded fibers tended to align in the direction of concrete flow when UHPC is cast and thus the modification of concrete rheology requires technical attention (FHWA 2011). The embedded fibers can replace temperature and shrinkage steel reinforcement in concrete. In some cases, shear stirrups are not included in a reinforced concrete beam (Reactive 2002). Supplementary cementitious materials can fill the pore space between constituents so that the durability performance of UHPC is improved (Lubbers 2003). To maintain the water-cementitious binder ratio of an UHPC mix as designed, the surface of the concrete should be covered immediately after a casting event. It is important to note that water content affects the behavior of UHPC because the concrete requires a hydration process. Inadequate hydration action causes premature shrinkage cracks and degraded engineering properties accordingly (FHWA 2011). The low water-cementitious binder ratio of UHPC may cause disintegration of the constituents during mixing. Inclusion of nano particles may improve bond between the steel fibers and cementitious binder of UHPC (Wille and Loh 2010). Special procedures are required to ensure consistent quality on site. Care should be exercised when casting UHPC because of its extended setting time and potential segregation (i.e., discrete fibers may not function well if excessive vibration is done). The mixing procedures of UHPC can thus influence material properties depending upon the sequence and mixing time (Lubbers 2003).

2.4 Supplementary treatment

A variety of treatment methods are used to enhance the performance of UHPC. Heat treatment during the curing of UHPC can accelerate the action of silica fume, resulting in an increase in strength (Schachinger et al. 2008). Previous research reports optional heat treatment has improved the

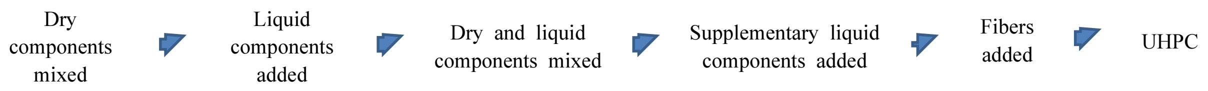
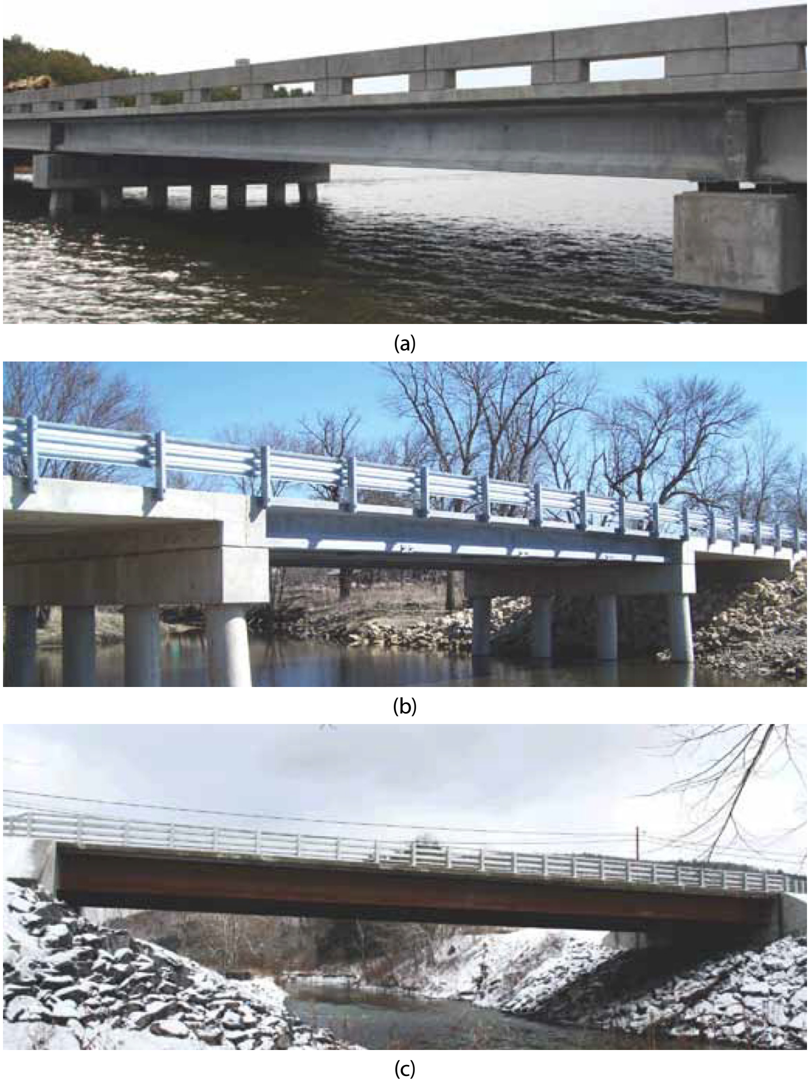


Fig. 1. Typical sequence of mixing UHPC

Table 2. Composition of materials for UHPC (percent by weight)

Reference	Cement	W/C ratio	Fiber	SCM	Quartz powder	Super-plasticizer	Sand	Compressive strength
B&C	28%	0.28	7%(S)	9%(SF)	8%	1%	40%	200 MPa
Bonneau	28%	0.27	6%(S)	9%(SF)	9%	2%	41%	190 MPa
HDR	37%	0.14	6%(S)	9%(SF)	0%	2%	41%	160 MPa
R&C	32%	0.19	6%(S)	7%(SF)	13%	1%	35%	200 MPa
W&L	32%	0.22	0.007%(CNT)	8%(SF)	8%	0.2%	44%	194 MPa
Ahlborn	26%	0.20	6%(S)	Pre	Pre	1%	Pre	194 MPa


(a)

(b)

(c)

Fig. 2. Bridges with UHPC (photos are used with permission from ASPIRE): (a) Cat Point Creek Bridge in Warsaw, Virginia; (b) Jakway Park Bridge, Aurora, Iowa; (c) State Route 23 over Otego Creek, Oneonta, New York

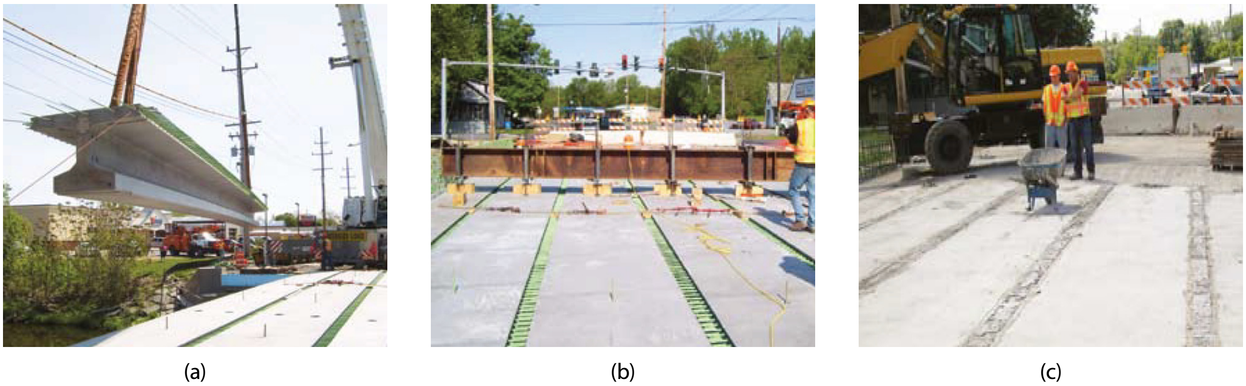

(a) (b) (c)

Fig. 3. UHPC joint (photos are used with permission from ASPIRE): (a) erection of a bulb-tee girder; (b) installed steel cage for a UHPC joint; (c) casting of UHPC

strength of UHPC as high as 70% (Bonneau et al. 1997). Typical conditions for such heat treatment include a temperature range between 50℃ and 90℃ in moisture for 48 hours (Bonneau et al. 1997; Reda et al. 1998). Heat treatment can reduce shrinkage and creep by improving the reaction of silica fume and a hydration process (Bouygues et al. 2002). It should, however, be noted that overheating may take place when UHPC is mixed because of its longer mixing time compared to conventional concrete (FHWA 2011). Improvement in mix-procedures is necessary to preclude potential heat-induced residual damage in UHPC. Ahlborn et al. (2008) examined the effect of steam treatment on the strength variation of UHPC, including durability performance. Test results showed that UHPC effectively resisted freeze-thaw and chloride ion penetration. Additional pressure may be applied to reduce the porosity of UHPC that is caused by the LeChatelier contraction (Aitcin 1998). The pressure applied during curing tends to decrease porosity by reducing entrapped air and excessive water and hence the compressive strength of the concrete increases (Blais and Couture 1999).

2.5 Test methods

Standard test methods are currently unavailable for measuring the properties of UHPC. The following test methods developed for concrete materials may be used for UHPC until specific standards are published. ASTM C39 (*Standard test method for compressive strength of cylindrical concrete specimens*) and C109 (*Standard test method for compressive strength of hydraulic cement mortars*) can be used for the compressive test of UHPC (ASTM 2011, 2012a). ASTM C469 (*Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression*) may be used to measure the elastic modulus of UHPC (ASTM 2010a). ASTM C1018 (*Standard test method for flexural toughness and first-crack strength of fiber-reinforced concrete*) will be a reference for examining the flexural strength of UHPC (ASTM 1997). ASTM C1437 (*Standard test method for flow of hydraulic cement mortar*) can measure the rheological characteristics of UHPC (ASTM 2007). ASTM C1202 (*Standard test method for electrical indication of concrete's ability to resist chloride ion penetration*) may be used to assess the degree of chloride ion penetration (ASTM 2012b). AASHTO TP-60-00 (*Standard method of test for coefficient of thermal expansion of hydraulic cement concrete*) may be utilized to measure the coefficient of thermal expansion (AASHTO 2007). If the long-term behavior of UHPC is concerned, ASTM C512 (*Standard test method for creep of concrete in compression*) will be useful for a creep test (ASTM 2010b). The freeze-thaw durability of the concrete may be examined by ASTM C666 (*Standard test method for resistance of concrete to rapid freezing and thawing*) (ASTM 2008b).

2.6 Site implementation

Potential application of UHPC is broad such as bridge structures, tunnels, nuclear power plants, and liquid storage facilities. UHPC is an ideal material for structures exposed to abrasion environment. Several site projects using UHPC have been completed, including Sherbrooke Footbridge in Canada, Footbridge of Peace in Korea, and Jakway Park Bridge in the United States (Blais and Couture 1999; Resplendino and Petitjean 2003; Kollmorgen 2004; Schmidt and Fehling 2005; Rouse et al. 2011; Planete 2012). Figure 2 illustrates some selected examples of UHPC-based bridges in the United States: the depth and length of the girders shown in Fig. 2(a) and (b) vary from 838 mm to 1143 mm and 25.9 m to 26.5 m, respectively. Another application is given in Fig. 3 with the details of installing UHPC joints connecting bulb-tee girders. A comprehensive study of UHPC was recently published by the Federal Highway Administration (Graybeal 2006). Steel fibers are widely used for site application, while polypropylene fibers can improve permeability, and abrasion and impact resistance (Toutanji 1999; Lubbers 2003). Considering the reduced use of reinforcing steel, more versatile architectural and structural design may be available. The increased toughness of UHPC makes this material ideal for concrete structures in seismic regions (Reactive 2002). Although the initial expenses associated with UHPC are more than those of normal concrete, material costs are consistently decreasing with more site projects.

3. SUMMARY AND CONCLUDING REMARKS

This paper has dealt with an overview of UHPC for civil infrastructure. The state-of-the-art construction material consists of Portland cement, mineral supplementary admixtures such as silica fume or metakaolin, quartz powder, water, fine aggregate, a superplasticizer, and steel or organic fibers. The following characteristics of concrete are improved when UHPC is used: homogeneity, density, ductility, and micro-structural integrity. Strength and durable performance of UHPC are primary considerations for building sustainable concrete structures. Integration effort with nano-scale materials has recently been made to further enhance the property of UHPC. The following is concluded:

- UHPC has a number of advantages compared to conventional concrete in terms of strength, durability, resistance to impact and abrasion, and permeability. Adequate mixing of UHPC results in enhanced density and homogeneity that are beneficial to accomplishing reliable performance on site.
- A very low water-to-binder ratio is used to increase the compressive strength of UHPC, typically less than 0.25. The role of a superplasticizer is important to provide acceptable workability to such a densely mixed concrete. Optimal use of constituents is a crucial factor. Inclusion of fibers controls the cracking behavior of UHPC, in particular its post-peak response. Care should, therefore, be taken when selecting fiber types.
- Given UHPC does not use coarse aggregate, the size of embedded constituents (e.g., fine aggregate, cementitious materials, and fibers) dominates the behavior of the concrete. Emerging materials such as nano-silica may be added when designing UHPC, while the efficacy of nanoscale materials is not conclusive yet.
- Various treatment methods can increase the effectiveness of UHPC, including heat treatment and pressuring during a curing period. Currently available test methods may be used for determining the properties of UHPC, whereas standard test methods to meet the specific needs of UHPC shall be released.
- Quality control in UHPC production is an interesting issue to warrant satisfactory in-situ performance, provided the history of UHPC is much shorter than that of normal concrete. Several field demonstration projects have exhibited the successful implementation of UHPC. Longterm monitoring of field data are, however, unavailable at this time. Structural health monitoring technologies are recommended to be along with UHPC construction.

4. CURRENT CHALLENGES AND RESEARCH NEEDS

Despite the recent advancements in UHPC research, significant effort is still necessary to improve its engineering properties and applicability on site. The following challenges and research needs are proposed to be addressed technically and socioeconomically:

- Design approaches dedicated to UHPC should be developed so that those based on conventional concrete can be replaced to better facilitate the application of UHPC with corresponding technical benefits; for example, design provisions on the minimum member depth of normal concrete may result in the over-design of UHPC members. Codified design provisions need to follow for practicing engineers. In so doing, uniform structural performance is anticipated with a consistent level of reliability.
- Chemical reaction between the supplementary cementitious materials and aggregate requires further research from a long-term durability perspective, including freeze-thaw and corrosion issues for UHPC-based concrete structures in aggressive environmental regions. Self-healing technologies may be incorporated with UHPC to improve the sustainability of constructed structural members.
- Early age behavior needs more research because the initial hydration process of UHPC causes noticeable heat-dispersion that can reduce the moisture content of the concrete. Premature shrinkage cracks may then develop. Disintegration of fibers from the cementitious binder can be another problem associated with the moisture issue. Microme-

chanical models will be useful for better elucidating the behavior of UHPC such as the interfacial transition zone between the binder and mineral admixtures.

- The cost of UHPC is one of the most notable challenges interfering broad use of such a promising technology in practice. Inexpensive alternative materials should be incorporated into the design of UHPC to reduce material expenses. Of interest are locally available constituents, which will influence construction costs.
- Development of non-conventional environmentally friendly cementitious binders is urgent to address socio-economical issues related to energy consumption and greenhouse gas emission. Lifecycle cost analysis will be an important component to assess the feasibility of such a new approach.

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