Classification + Reference Standards for UHPC in Architectural Applications

George Quercia, PhD
[Director of Research, TAKTL LLC]

Kevin Gannon, RA
[Director of Program Development, TAKTL LLC]

ABSTRACT

Ultra-High Performance Concrete (UHPC) offers new capabilities for structural and aesthetic concrete architectural applications in building design. UHPC is over four times stronger than traditional pre-cast concrete, and it performs exceptionally well in demanding conditions. Its strength derives from its carefully calibrated ratio of engineered ingredients and a mixing sequence that packs molecules closely together to create very tight bonds. The high packing density yields excellent flexural and compressive strength, while virtually eliminating the capillary pores that cause freeze-thaw degradation in other cement-based products. These distinct material properties provide opportunities for greater spans, thinner profiles, and more complex geometries, with advantageous installation costs, while providing higher performance in extreme climates than other glass fiber reinforced concretes (GFRC), terracotta, or metal reinforced pre-cast concrete products. Specifying UHPC involves an understanding of code requirements, both existing and emerging, as well as comprehension of manufacturers' testing standards. In the present study, Architectural Ultra-high performance Concrete (A|UHPC®) basic material properties, classification, performance capabilities, and limitations are summarized and compared with other traditional building façade materials. Furthermore, an explanation of the relevant emerging codes, testing requirements, manufacturer accreditations and construction specifications are presented. Finally, a discussion of opportunities for continued development of practical A|UHPC® applications in the built environment is included.

INTRODUCTION

Architectural precast concrete cladding and façade elements were in use at the end of the 1950s in Europe to satisfy the increasing demand for affordable housing. For a long time, standard steel reinforced concrete (RC) elements dominated the pre-cast market for cement-based concrete building envelopes. From the 1960s to the 1980s, they dominated the architectural landscape in many urban areas all around the world (Mueller et al., 2015). The disadvantage of RC for architectural applications is the thickness of elements, which is due to the concrete cover required to protect the steel reinforcement from corrosion. For a building façade, the typical concrete cover ranges from 30 to 35 mm over the reinforcement (varying with the country design code) which limits the minimum wall thickness of a precast concrete cladding to 80 mm (Neville, 2002; ACI 318, 2014). This makes the elements particularly heavy and thick. Over the last 20 years, new concrete materials emerged on the market, enabling builders to drastically reduce the thickness and weight of cladding elements by removing the standard steel rebar and steel meshes in favor of other reinforcement alternatives. Two of those new materials are ultra-high-performance concrete (UHPC) – also called reactive powder concrete (RPC) - reinforced with inorganic/organic discrete fibers and textile reinforced concrete (TRC).

Originally conceptualized by Bache in 1964 for structural applications (Buitelaar, 2004), ultra-high performance concrete (UHPC) has been in development for the last three decades – and today remains primarily a material used in specialized civil engineering/infrastructure. The influential research of Bache (Bache, 1970, 1981, 1987, 1991) and others (Buitelaar, 1992) emphasized so-called reactive powder concrete (RPC) during the 1980s. After this, RPC was the subject of study and improvement during the early 1990s by researchers at Bouygues' laboratory in France and Aalborg Cement in Demark (Stovall et al., 1986; Larrard & Sedran, 1994; Richard & Cheyrezy, 1995). These last collaborations set the bases for current-day pre-mixes of UHPC available in the market by LafargeHolcim (Ductal®). To put the use of UHPC in context relative to building in the United States, the first use of UHPC was a bridge deck built in 2006. Most recently, several researchers (Willie & Graybeal, 2013; Berry et al., 2017) around the word have developed non-proprietary UHPC mixes which use local and more available raw materials, thereby avoiding the use of imported ingredients and payments of licensees or royalties. In general, UHPC is defined as having compressive strengths higher than 120 MPa (17 ksi). However, according to the structural definition given by the American Concrete Institute Committee 239 (ACI 239C minutes, 2017), the minimum compressive strength for UHPC is even higher, at 150 MPa (24.7 ksi). UHPC's high strength comes from a dense microstructure, the result of adding fine particles (increased packing density) and reducing the water/binder ratio to a range of about 0.18 to 0.35. The dense microstructure also increases the resistance against environmental impact (freeze-thaw cycles) and mechanical aggression (impact and wind loads) leading to very durable elements that afford a reduction of the concrete thickness to less than 25.4 mm (1 in.). Another advantage of the dense microstructure created with the use of very fine particles and aggregates (normally lower than 5 mm), is the high-quality surfaces that are obtained, ranging from extremely smooth to intricately textured. It is the combination of architectural UHPC's high strength, durability, and aesthetic range that allows architects to create subtle or dramatic articulated facades and is driving the demand for UHPC in a wide range of architectural applications, from exterior wall cladding, decorative elements to interior finishes.

UHPC formulations can be engineered to achieve the performance characteristics required for specific applications or manufacturing methods such as high compressive strength, tensile strength, rate of strength development and shrinkage to name a few. The very high compressive strength of UHPC is accompanied by a brittle failure mode that necessitates the addition of reinforcements to achieve the ductility required for structural and architectural applications. The typical reinforcements are high carbon steel fibers (load bearing structural application) and in the case of architectural application, organic (poly-propylene and poly-vinyl alcohol) and inorganic fibers (AR-glass). Although steel reinforcements produce the highest strength, they are typically not used in architectural applications for aesthetic reasons.

Like UHPC, textile reinforced concrete (TRC) is a new class of cement-based composites with improved tensile strength and ductility. Because the textiles do not rust, TRC composites do not require the cover of steel reinforced concrete, allowing the production of thin and lightweight TRC elements. Further, the use of a reinforcing textile (composite grid) solves the problem created by the short fibers added to increase toughness that, in most cases, are not along the loading direction, and consequently do not improve significantly the tensile strength of the concrete (Zargaran et al., 2014, 2017). TRC and UHPC, or the combination of both (called composite UHPC) have been applied in Europe over the last 10 years in façade elements in the form of ventilated (open joints) façade cladding (Engberts, 2006) or as sandwich elements (Hegger & Voss, 2008) due to their extraordinary high strength and durability (Ghoneime al. 2010; Rebentrost et al. 2008; Muller et al., 2008). Though UHPC and TRC have been in use over the last decade in Europe, their application emerged in North America only recently. The first architectural application of UHPC in North America was executed in 2010, at The Atrium, located in Victoria, B.C., Canada (D'Ambrosio, 2012), see Fig. 1a. In this building, UHPC flat and curved façade elements for a unitized curtain wall were cast with a proprietary UHPC mix reinforced with organics fibers. At the same time, TAKTL Llc entered the market from a research and development project started four years prior at Forms + Surfaces (an international designer and manufacturer of architectural products and urban elements). With the assistance of a known German UHPC consultancy company, a proprietary composite UHPC formulation using local materials was developed. The combined use of UHPC and TRC technologies allows TAKTL to produce cladding materials and elements with high tensile strength and durability as well as high ultimate strain for thin elements (extended ductility). 2010 marks the first time, a US based company established architectural ultra-high-performance concrete (A|UHPC®) formulation and integrated with a continuous manufacturing and standardized architectural composite panel designs. The first A|UHPC® project in North America was the Gateway Youth Center, in Pittsburgh, PA (Fig. 1b). Since 2010, more than 250 projects have been completed, including residential (Fig. 1c), healthcare (Fig. 1d), civic and university buildings (Fig. 1e) throughout the United States of America.

In the present study, the basic material properties of composite architectural ultra-high-performance concrete (A|UHPC®) as well as its classification, performance capabilities, and limitations are summarized and compared with other traditional building façade materials. An explanation of the relevant emerging codes, testing requirements, manufacturer' accreditations and how A|UHPC® is specified for architectural application are presented, followed by a discussion of opportunities for continued development of practical A|UHPC® applications in the built environment.

Figure 1 Examples of UHPC facades in North America, a) The Atrium (2010), Victoria, BC, Canada (Dialog, 2012); b) Gateway Youth Center (2012), Aliquippa, PA; c) 251 Fist, Park Slope (2017), Brooklyn, NY; d) Rancho Los Amigos Health Center (2017), Downey, CA; e) Western Michigan University (2017), Valley Dining Center, Kalamazoo, MI.

A|UHPC® classification and properties

As mentioned previously, according to the ACI committee 239 (ACI 239C, 2017), UHPC is a material with at least 150 MPa of compressive strength. However, European standards (Toutlemonde et al., 2016) define UHPC as any concrete with at least 120 MPa in compressive strength. Both of these definitions exclusively consider compressive strength to classify a concrete material because testing agencies been primarily focused on structural applications. Compressive strength is a good tool for structural application but excludes other properties that are of critical importance for architectural applications such as resistance to freeze-thaw, maximum strain capacity after initial fracture (ductility), permeability, water absorption, etc. The increasing number of new applications for UHPC and its composites in architecture and the wider range of performance requirements of architectural applications have generated a review of the one dimensional "compressive strength" definition. In fact, most recently researchers around the world are defining high-performing concretes not only with consideration to compressive strength, but also in terms of other properties that impart extended durability.

Figure 1 considers the compressive strength and water to binder ratio of concrete, establishing a compressive strength range for architectural UHPC of 90 to 140 MPa. This is still controversial because such range is out of the formal definition of structural UHPC for most high-performance concrete (HPC) compressive strength ranges, with Architectural UHPC, from the perspective of compressive strength, fitting in the gap between the definition of UHPC and HPC (Fig. 2). Factors affecting the compressive strength of architectural UHPC are cement type (white vs. gray) that influences color and color variation, fiber size and type, and production curing times. While compressive strength values are often the measuring stick for categorizing concrete, flexural strength, and anchor performance are the priorities for thin A-UHPC panels and elements – which the 'composite' of fiber textiles provide.

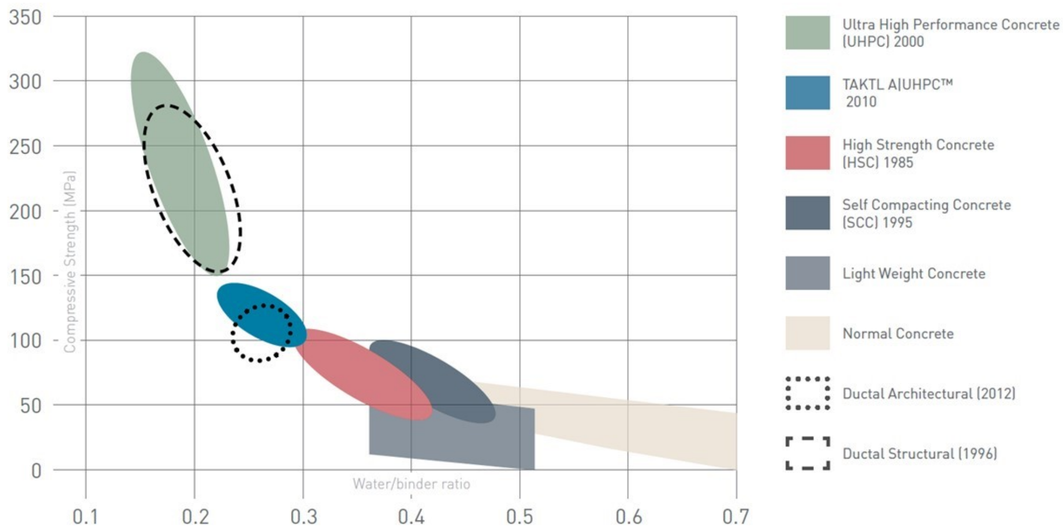

Figure 2 Classification of concrete according to compressive strength and water to binder ratio (based on CSBT report, 2005; fib, 2009; Batoz et al., 2011; Rigaud et al., 2012; Envel, 2016; Eklips, 2017; Cladia, 2017; Ductal®, 2017).

Table 1 shows a comparison between different UHPCs and other materials normally used for façade cladding and façade elements. As Table 1 demonstrates, the first difference is that with UHPC (standard and composite) it is possible to obtain façade panels that are less than 25.4 mm thick (thin wall elements) which, in general, is impossible with RC due to the presence of steel reinforcing. The most common UHPC thickness used for cladding are in the range of 12.7 to 15.9 mm. These thicknesses are similar to the most common GFRC sheet products and flat Terra-cotta cladding tiles. The characteristics that make UHPC façade panels unique are their impermeability and low porosity (Table 1) that impart high resistance to freeze-thaw cycles and eliminate the need for the specialized sealers that are commonly required to protect and assure the performance of fiber cement cladding elements - preventing the high water absorption and dimensional instability over time common to these products. Additionally, the high modulus of rupture (M.O.R.) and high anchor pull-out strength of UHPC allow the design of lightweight façade assemblies that use smaller amounts of framing materials and wider anchor spacing compared to standard fiber cement (M.O.R. ≥ 17.5 MPa), Terracota (M.O.R. ≥ 8.9 MPa), and GFRC (M.O.R. ≥ 5.0 MPa) facade elements. Furthermore, UHPC's lower coefficient of thermal expansion compared with GFRC provides high dimensional stability and durability during the service life of façade panels and elements.

Other comparisons between A|UHPC and common façade materials are worth noting. A|UHPC Panels are generally limited to smaller sizes than Pre-Cast concrete but A|UHPC panels can be manufactured at 5/8" thick in a range of sizes -as small as 6" X 60" and up to 60" X 144" or longer without exceeding 8.5 lbs./sf. Compared to Stone and Terracotta, A|UHPC can be larger (reducing frequency of attachment points and lighter by several pounds per square foot. Compared all common cladding materials with the exception of aluminum composite panels. And insulated glass units (IGU), A|UHPC is typically less. A\UHPC façade cladding panels are typically cut to size rather than cast to size – providing better control of dimensional tolerances and flexibility in panel size is easier to achieve compared to pre-cast concrete or spray-in GFRC. Excellent performance with regard to resistance to water penetration and moisture movement results in higher performance with regard to freeze thaw, strength retention and resistance to chemical deterioration (i.e.; carbonation, chloride, etc.) Although cement/concrete materials contribute to CO2 emissions and this is often cited as a negative aspect of the most widely used material in the world it may be surprising to learn that A| UHPC embodied energy is similar to Brick, and lower than Pre-Cast (by volume required), Limestone, Glass and Aluminum Composite panels *(Taktl/Carnegie Mellon University LCA study 2012 and University of Tennessee, Center for Clean Products Life Cycle assessment of Cladding Products, 2009)*

The greatest impact on A\UHPC is not the cement – which is much lower by volume than conventional concrete, but in the mold materials used. This indicates there is a great deal of embodied energy reduction that can be achieved through mold technology development without impacting the end product characteristics. Based upon the durability characteristics of A|UHPC the life span/serviceability is similar to and can exceed Brick, Granite and Pre-Cast Concrete.

Despite all the advantages of UHPC for architectural applications, the process required achieving its ideal performance and aesthetic properties present's challenges in its complexity and precision requirements. For example, the UHPC composition and exacting mixing sequence makes it more prone to dosing or mixing errors. All optimal mix proportions of UHPC are based on the particle size distribution of its components; thus, components need to be consistent in size and quality. This is translated to the need for strict quality control procedures for raw materials, mixing, workability and curing conditions as well as automated, very precise mixing/dosing equipment and process controls that provide continual monitoring of variables such as optimum mixing time, temperature, spread-flow range, and continuous thickness control in production. In addition, UHPC is more expensive per m^3 than reinforced concrete. Even so, UHPC can complement concrete solutions when more lightweight and thin structural elements are required, with the total installed cost of the panels and substructure cost competitive with many other façade cladding. Products Lastly, the extended durability and lower maintenance of UHPC façade elements decrease the life cycle costs and increase building sustainability and physical resilience of the buildings.

Table 1. Summary properties of materials used for façade panels and elements

Property	UHPC*	A|UHPC®	RC	GFRC	Fiber cement	Terracota
Thickness (mm)	< 25.4	< 25.4	> 80	> 10	< 12	10-50
Density (kg/m^3)	-	2,196	1,842-2,800	1,800-2,240	1,589-1,900	2,050-2,195
Unit weights (kg/m^2)	33-47	33-40	> 60	32-37	14-16	59-64
Compressive Strength (MPa)	117-124	95-137	≥ 34.5	28-82	22-26	40-100
Splitting tensile strength (MPa)	14.5	9.1	1.9-3.6	-	-	-
Flexural strength 3-point (MPa)	11.7-20.0	15.1	3.4-5.0	6.9-12.4	-	-
Panel Modulus of rupture (MPa)	23	42.6	-	5-30	17.5-32.9	8.9-23.8
Modulus of Elasticity (GPa)	-	25.4	25.0-40.0	7.0-21.0	16.0-18.5	13.0-44.0
Porosity (%)	-	6-9	10-25	16-25		-
Moisture content (%)	-	0.9	-	< 3.0	5.1-9.2	0.7
Water absorption (%)	4.6	3.9	< 10	8-13	9.2-22.3	< 10.0
Moisture movement (%)	0	0	-	-	0.02-0.80	0.02
Water tightness ½" thick panel	No droplets	No droplets	-	No droplets	No droplets	No droplets
Coeff. therm. exp. (mm/mm/°K)	$1.0\cdot10^{-5}$	$1.2\cdot10^{-5}$	$1.0\cdot10^{-5}$	$1.8\text{-}3.6\cdot10^{-5}$	$1.0\text{-}1.3\cdot10^{-5}$	$0.4\cdot10^{-5}$
Sur. burning charac. (flame/smoke)	0/0	0/0 Class A	-	0/5	0/0	0/0

Freeze-thaw F.S. ret. (%)	-	97.3-100	5% max. lost	-	82-103	3% max. lost

(*) UHPC with inorganic/organic fibers, A|UHPC®: composite UHPC/TRC, RC: Steel Reinforced Concrete, GFRC: Glass fiber reinforce concrete. (based on Neville, 2002; Gilbert, 2004; CSBT report, 2005; PCI, 2007; fib, 2009; Batoz et al., 2011; Rigaud et al., 2012; ASTM C1185, 2016, ASTM C1186, 2016; Envel, 2016; TerraClad™, 2017; GRCA, 2016; NBK™, 2016; Eklips, 2017; Cladia, 2017; Ductal®, 2017, Swisspearl, 2017; TAKTL, 2018).

A|UHPC® reference standards, emerging codes, and specifications

Since the first application of UHPC as façade material at the Atrium building in 2010 (Dialog, 2012), architects, engineers and specifiers have faced an absence of design standards, codes of practice and/or guideline specifications in North America for implementation of UHPC in architectural or structural applications. To overcome the technical challenge at The Atrium, a state of the art mechanical properties evaluation was carried out and the structural analysis of the facade was performed. This analysis utilized a new material constitutive law (stress-strain curve) along with finite element computer models to predict the structural behavior of 20 mm (3 mm ribs, 17 mm nominal) UHPC panels made with organic fibers (PVOH fibers). This structural analysis and design was supported and correlated by implementing laborious and expensive laboratory validation testing. The design and testing results of The Atrium panels were used as a starting point in 2011 for ACI Committee 239, whose mandate is to develop UHPC material design guidelines (ACI 318-14 criteria do not fit UHPC) and specifications suitable for use in North America for non-load bearing architectural applications. Since 2011 ACI Committee 239 has made advances in the testing, design, and specification for the use of UHPC. However, their efforts have been focused on structural applications for bridges (led by the Federal Highway Administration) and primarily UHPC manufactured with metallic fibers and compressive strength higher than 150 MPa. A portion of the activities of this committee, in collaboration with the American Society for Testing and Material (ASTM) was to provide a new standard practice for fabrication and testing specimens of UHPC (ASTM C1856/C1856M, 2017) reinforced with metallic and non-metallic fibers. Nevertheless, again this new standard is only applicable to UHPC with a specified compressive strength of at least 120 MPa, with nominal maximum size aggregate of less than 5 mm and a spread flow between 20 and 25 cm, as measured by the modified flow table test method described in ASTM C1437 and ASTM C230/C230M. These requirements, leave outside of the scope several architectural UHPC compositions possessing lower compressive strengths (<120 MPa) and high spread flow values (25 to 35 cm) that confer the self-compact ability needed to guarantee efficient air removal and high surface quality for complex texture and shapes (i.e. when decorative face aggregate are used).

Like the ACI and ASTM committees, the National Precast Concrete Association (NPCA), made an effort to provide some guidelines for manufacturing architectural precast UHPC elements, releasing a report in 2013 (NPCA, 2013). The purpose of this report was to provide a guide for the manufacture of architectural precast UHPC elements and to educate precasters on the potential opportunities. The report describes the general handling and quality control procedures, including storage of raw materials, forming, batching, curing, and plan requirements of architectural UHPC. Even considering all the efforts mentioned above, more work is needed to develop design guidelines and specifications for the architectural application of composite UHPC reinforced with organic/inorganic discrete fibers and/or composite textiles with recognition by the building code To achieve this, the engineering community will need clear and consistent guidelines for calculation methods and the authorities having jurisdiction need clear UHPC use in ACI 318 exist together with and the lack of established engineering standards for designing UHPC elements.

With no clear building codes yet available, manufacturers and architects in recent years have adopted standards and specifications of other well-known and mature cladding materials like Fiber-Cement. Thus, the specification and testing of UHPC and its composite have been based on the standards ASTM C1185 (*Standard Test Methods for Sampling and Testing Non-Asbestos Fiber-Cement Flat Sheet, Roofing and Siding Shingles, and Clapboards*) and ASTM C1186 (*Standard Specification for Flat Fiber-Cement Sheets*), respectively. This standard has also been working as the standard for quality programs and certifications. In 2014, some UHPC manufacturers of cladding materials made a joint effort to develop more applicable guidelines for the use of UHPC exterior wall cladding materials, producing an acceptance criteria, AC458 (ICC-ES, 2016), with the purpose of establishing requirements for UHPC used to form exterior thin wall cladding panels and being recognized under the 2015, 2012, and 2009 International Building Code® (IBC). The goal of these criteria was to provide guidelines for the evaluation of UHPC thin wall cladding (<25.4 mm) panels, since the IBC and documents referenced by the IBC did not specify requirements for the testing and use of UHPC panel products. In these acceptance criteria, different codes and references standards from ASTM, ACI, AASHTO, FHWA, NFPA, etc. are used for evaluation, specification, and design purposes. However, the AC458 acceptance criteria still requires revision or modification in order to include the use of composite UHPC (A|UHPC®) wall panels and elements in which extended deflection (high strain) after the first fracture is produced through the presence of reinforcing 2D textiles. For example, in AC458, it is established that flexural cracking shall be conducted according to the ASTM C1609 (beam sample), observing flexural hardening or non-brittle behavior. Also, it is established that a significant amount of post cracking load-carrying capacity, documented by bending stress-deflection curves should be observed, post cracking peak strength (P_p) shall be greater than the first peak strength (P_1), see Fig. 3a. As is established and illustrated by the French evaluation report on UHPC with organic fibers (CSTB report, 2005), such behavior can only be obtained in UHPC with a high amount of fibers (>2.0 vol.%). Another disadvantage of the procedure proposed is that it evaluates the base UHPC matrix (Fig. 3a) and not the final product (Fig. 3b for a panel). This makes the evaluation of composite UHPC out of the scope of this acceptance criteria – testing the mix behavior rather than the panel behavior. Contrary to a standard UHPC,, A|UHPC® uses less fiber (<2.0 vol.%) and presents extended deflection after the first fracture (P_1) as illustrated in Fig 3b. when tested with textile reinforcement and tested in the form of use.

Another issue with the AC458 is the test method and performance requirements for out-of-plane transverse load related to panel anchor evaluation. Section 4 of this acceptance criteria says that post-installed concrete anchors supporting UHPC panels shall be tested in accordance with Test No. 4 (tension, for leeward wind) and Test No. 17 (shear) of Table 4.2 in the ICC-ES Acceptance Criteria for Mechanical Anchors in Concrete-AC193 (ICC-ES, 2012). AC193 states that testing shall be conducted in cracked UHPC panels with 0.203 mm (0.008 in.) crack width, allowing some exceptions to the minimum "slab" thickness and embedded depth requirements of anchors in AC193. However, reviewing the methodologies described in AC193 and the respective ACI anchor design load and qualification testing (ACI 318 and ACI 355.2), the methods to produce a control crack width are applicable to thick concrete slabs, not typical UHPC façade panels of 16 mm thickness with embedded undercut anchors of 10 mm in length. Additionally, the failure criteria showed in ACI 318 consider a brittle failure for the structural analysis and not a ductility behavior and high deflection normally found in standard and composite UHPC panels. Thus, more collaboration between manufacturers and ACI, PCI, ASTM, and IBC is still needed to develop new evaluation and constitutive law for structural analysis and design of architectural façade panels elements manufactured with UHPC and its composites.

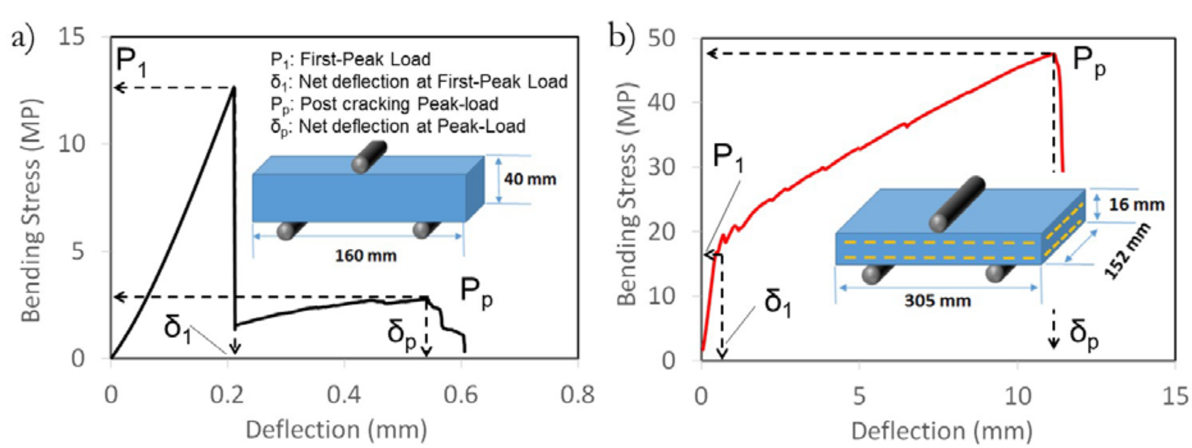

Figure 3 Typical bending stress-deflection curves for, a) 40x40x160 mm UHPC prisms (2.0 vol.% inorganic fibers) and b) 305x152x16 mm composite UHPC cladding panels with 2D mesh reinforcements and 1.5 vol.% or inorganic fibers.

CONCLUSIONS

In the present study, architectural UHPC and its composites (A|UHPC®) basic material properties, classification, performance capabilities, and limitations were summarized and compared with other traditional building façade materials. Furthermore, an explanation of the relevant emerging codes, testing requirements, manufacturers' accreditations and specifications for UHPC in architectural applications was presented. Finally, a discussion of opportunities for continued development of specifications, codes, and design guidelines for the practical use of A|UHPC® applications in the built environment was included. The successful application of A|UHPC® in architectural cladding has been demonstrated by more than 250 projects executed and on-going in North America, creating the path for long-lasting, resilient building envelopes that require less material and draw from a large palette of textures, patterns, colors and geometries. The analysis performed also leave open the debate to develop and accelerate the adaptation of the existing standards and emerging design codes for the safe and efficient utilization of UHPC in the architectural field.

ACKNOWLEDGMENTS

The authors would like to thank Charles Rosenblum and Dino Misetic from the TAKTL Communications Department for their editorial and the graphic work.

REFERENCES

ACI. 2007. ACI 355.2-07. *Qualification of Post-Installed Mechanical Anchors in Concrete & Commentary*, American Concrete Institute, Farmington Hills, MI. on-line committee documents.

ACI. 2014. ACI 318-14. *Building Code Requirements for Structural Concrete and Commentary*. ACI Committee 318, American Concrete Institute, Farmington Hills, MI.

ACI. 2017. ACI 239C. *ETR on the Structural Design of Ultra-High Performance Concrete*. ACI Committee 239, American Concrete Institute, Farmington Hills, MI. on-line committee documents.

ASTM. 2014. ASTM C230/C230M-14, *Standard Specification for Flow Table for Use in Tests of Hydraulic Cement*. Philadelphia: American Society for Testing and Materials.

ASTM. 2015. ASTM C1437-15, *Standard Test Method for Flow of Hydraulic Cement Mortar*. Philadelphia: American Society for Testing and Materials.

ASTM. 2016. ASTM C1185-08 (2016), *Standard Test Methods for Sampling and Testing Non-Asbestos Fiber-Cement Flat Sheet, Roofing and Siding Shingles, and Clapboards*. Philadelphia: American Society for Testing and Materials.

ASTM. 2016. ASTM C1186-08 (2016), *Standard Specification for Flat Fiber-Cement Sheets*. Philadelphia: American Society for Testing and Materials.

ASTM. 2017. ASTM C1856/C1856M-17-87, *Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete*. Philadelphia: American Society for Testing and Materials.

Bache, H.H. 1970. Model for strength of Brittle Materials built up of particles joined at point of contact. *Journal of the American Ceramic Society* 53 (12):654-658.

Bache, H.H. 1981. Densified cement/ultra-fine particle-based materials. *The second International conference on superplasticizers in Concrete*. Ottawa, Ontario, Canada, June 10-12.

Bache, H.H. 1987. Compact Reinforced Composite Basic Principles. *CBL Report N°41*, Cement and Concrete Lab, Aalborg Portland, Denmark.

Bache, H.H. 1991. Principles of similitude in design of reinforced brittle matrix compistes. *International Workshop on High Performance Fiber Reinforced Cement Composites*, Mainz, Germany.

Batoz, J.F., Behloul, M., Fonollosa, M. Concrete Compositions. United States Patent, US7,901,504 B2, March 8: 1-8.

Berry, M., Snidarich, R., Wood Camylle. D. 2017. Development of Non-Proprietary Ultra-High Performance Concrete. Final report FHWA/MT-17-010/8237-001. DOT Montana: 1-128.

Buitelaar, P. 1992. Densit mortars for very strong and dense concrete. Development and applications of cement based mortars with ultra-high strength. *Dutch Journal Cement*, November.

Buitelaar, P. 2004. Ultra-High Performance Concrete: Developments and Applications during 25 years. Plenary session of *First International Symposium on Ultra High Performance Concrete*. September 14th - 15th, Kassel, Germany: 1-28.

Cladia. 2017. Cladia Cladding System brochure. Zanette Srl, Italy: 1-16. (www.cladia.it).

CSTB Report. Ultra-High Performance Fiber-Reinforced Concrete (UHPFRC). Technical Evaluation Ductal®-FO. *CSTB Safety, Structures, and Fire Performance Department*: 1-31.

Dialog. 2012. The Atrium, Victoria BC. Canadian Consulting Engineering Awards 2012. *Association of Consulting Engineering Companies Canada-Canadian Consulting Engineer*: 1-33.

Ductal. 2017. Ductal® Rainscreen Cladding Solutions. (www.ductal.com/en/architecture/rainscreen-cladding-solutions).

Eklips. 2016. Entrez dans l'ère du revêtement haute performance. Panneaus Eklips Panels:1-16. (www.panneauxeklips.com).

Engberts, E. 2006. Large-size façade elements of Textile Reinforced Concrete. *Proceedings of international RILEM symposium textile reinforced concrete*. Aachen, Germany: 309-318.

Envel. 2016. Envel Create Brochure. Envel Inc.: 1-8. (www.envelfacade.com).

Fib. 2009. Structural Concrete - Textbook on behavior, design, and performance. Bulletin 51. Vol. 1. 2009, Lausanne: *fédération internationale du béton (fib)*: 95-149.

Ghoneim, G., El-Hacha, R., Carson, G. and Zakariasen, D. 2010. Precast Ultra High Performance Fiber Reinforced Concrete Replaces Stone and Granite on Building Façade. *Proceedings of the 3rd Fib International Congress*: 1–15.

Gilbert, G. GFRC - 30 Years of High Fiber Cement Composite Applications Worldwide. *International Concrete*. Special Publication ACI 224:1-19.

GRCA. 2016. GRCA Practical Design Guide for Glass Reinforced Concrete Using Limit State Theory. International GRCA Technical Committee: 1-98. (www.grca.org.uk/grc-technical/publications.php).

Hegger, J. and Voss, S. 2008. Investigations on the load-bearing behavior and application of textile reinforced concrete. *Eng. Struct*. 30: 2050–2056.

ICC. 2009. International Building Code®, 2009 Edition. International Code Council Inc. (ICC).

ICC. 2012. International Building Code®, 2012 Edition. International Code Council Inc. (ICC).

ICC. 2015. International Building Code®, 2015 Edition. International Code Council Inc. (ICC).

ICC-ES. AC193. 2012. *Acceptance Criteria for Mechanical Anchors in Concrete Elements*. ICC Evaluation Service, LLC. Subsidiary of International Building Code®: 1-49.

ICC-ES. AC458. 2016. *Acceptance Criteria for Exterior Ultra-High Performance Concrete Thin Wall Cladding Panels*. ICC Evaluation Service, LLC. Subsidiary of International Building Code®: 1-6.

Larrard, F. and Sedran, T. 1994. Optimization of Ultra-High Performance Concrete by the Use of a Packing Model. *Cement and Concrete Research* 24 (6): 997–1009.

Mueller, U., Portal, N.W., Chozas, V., Flansbjer, M., Larraza, I., Da Silva, N., Malaga, K. 2015. Reactive powder concrete for facade elements – A sustainable approach. *VII International Congress on Architectural Envelopes*, May 27,-29, San Sebastian-Donostia, Spain:1-8.

Müller, U., Meng, B., Kühne, H.-C., Nemecek, J. and Fontana, P. 2008. Micro texture and mechanical properties of heat treated and autoclaved Ultra High Performance Concrete (UHPC). *2nd International Symposium on Ultra High Performance Concrete*. Kassel, Germany. Kassel University Press: 213-220.

NBK™. 2016. Architectural Terra Cotta Brochure. NBK North America Inc. Marblehead, MA, USA:1-24. (www.nbkusa.com).

Neville, A.M. .2002. Properties of Concrete, 4th ed., Prentice Hall/Pearson, Harlow,

NPCA. 2013. Ultra-High Performance Concrete (UHPC). Guide to Manufacturing Architectural Precast UHPC Elements. National Precast Concrete Association. NPCA Carmel, In. :1-19. (www.precast.org).

PCI. 2007. Architectural Precast Concrete. Third Edition. *Precast/Prestressed Institute*. PCI. Chicago:1-609.

Rebentrost, M., Wight, G., Fehling, E. 2008. Experience and Applications of Ultra-High Performance Concrete in Asia. *2nd International Symposium on Ultra High Performance Concrete*. Kassel University Press, Kassel, Germany: 19–30.

Richard, P. and Cheyrezy, M. 1995. Composition of Reactive Powder Concrete. *Cement and Concrete Research*. 25 (7):1501–1511.

Rigaud, S. Fonollosa, Ph., Chanvillard, G. Concrete Composition. *United States Patent*, US8,303,708 B2, March 8: 1-8.

Stovall, T., Larrard, D., Buil, M. 1986. Linear Packing Density Model of Grain Mixtures. *Powder Technol.* 48, (1):1–12.

Swisspearl. 2017. Ventilated façade system brochure. SWISSPEARL GROUP AG: 1-37. (www.swisspearl.com).

TAKTL. 2018. TAKTL® Certified Test Results (SI). Doc. T2-1-2 Rev. 11.16. TAKTL LLC.: 1. (www.taktl-llc.com).

TerraClad™. 2017. TerraCladTM General Specifications. Boston Valley Terra Cotta 6860 S. Abbott Road Orchard Park, NY: 1-8. (www.terraclad.com).

Toutlemonde, F., Généreux, G., Delort, M., Resplendino, J. 2016. Product and Design Standards for UHPFRC in France. First International Interactive Symposium on UHPC. July 18-20. Des Moines, Iowa, USA: 1-8.

U.K., pp. 537-576.

Willie, K. and Graybeal, B. 2013. Development of Non-Proprietary Ultra-High Performance Concrete for Use in The Highway Bridge Sector. FHWA Publication No.: FHWA-HRT-13-100: 1-8.

Zargaran, M., Attari, N.K.A., Alizadeh, S., Teymouri, P. 2017. Minimum reinforcement ratio in TRC panels for deflection hardening flexural performance. *Construction and Building Materials* 137: 459–469

Zargaran, M., Attari, N.K.A., Teymouri, P. 2014. Bonding performance of Nylon tire cord in fine grain concrete, *Int. Civil Eng.* 12 (1): 104–111.