STANDARDIZATION OF ULTRA-HIGH PERFORMANCE CONCRETE THE CANADIAN PESPECTIVE

Vic Perry (1) and Katrin Habel (2)

(1) V.iConsult Inc., Calgary, AB, Canada

(2) Associated Engineering, Vancouver, BC, Canada.

Abstract:

While Ultra-High Performance Concrete (UHPC) has been under research and development for more than 20 years, it is still a relatively new material technology compared to conventional concrete. The use of this technology is slowly increasing and gaining acceptance in numerous applications, such as bridges, architectural products, security, water / waste-water, building elements and others. It is the superior mechanical properties of UHPC, particularly durability and tensile ductility that provide the benefits and reason for potential users of the technology, irrespective of the challenges of deploying this technology. The challenge of the lack of codes and standards is one major factor in slowing the implementation of UHPC. Several jurisdictions have commenced the process of writing standards for UHPC, such as the American Concrete Institute (USA), the American Society of Testing and Materials (USA), the Swiss Institute of Engineers and Architects (Switzerland), the French Society of Civil Engineers (France), the Japanese Society of Civil Engineers (Japan) and others. Early in 2016 the Canadian Standards Association formed two Task Groups to develop guidelines for the standardization of UHPC and fibre-reinforced concrete. The first Task Group is drafting the Materials and Methods Standard for UHPC and the second Task Group is drafting a Structural Design Guideline for Bridges for tension softening and hardening fibre reinforced concretes.

This paper covers the Canadian approach to standardizing UHPC including the background, a brief outline and the main points of the new materials, methods and the structural design of bridges with fibre-reinforced concretes, including UHPC.

Résumé :

Alors que le béton à ultra-hautes performances (BUHP) fait l'objet de recherches et de développement depuis plus de 20 ans, c'est encore un matériau relativement nouveau en comparaison du béton traditionnel. Son utilisation est en croissance progressive et devient de mieux en mieux acceptée dans de nombreuses applications comme les ponts, les produits architecturaux, la sécurité, l'eau / les eaux usées, les composants de bâtiment etc. Ce sont les propriétés mécaniques élevées des BUHP, particulièrement leur durabilité et leur ductilité en traction, qui constituent les avantages et les raisons d'utiliser cette technologie, quels que soient les défis à relever pour la déployer. Le problème du manque de codes et de normes est critique pour ralentir le développement des BUHP. Plusieurs organismes ont commencé à rédiger des normes pour les BUHP, comme l'ACI (USA), l'ASTM (USA), l'Institut Suisse des Ingénieurs et Architectes (Suisse), l'Association Française de Génie Civil (AFGC - France), la Société Japonaise des Ingénieurs en Génie Civil (JSCE - Japon) et d'autres. Début 2016, l'Association Canadienne de Normalisation (CSA) a formé deux groupes de travail pour rédiger des recommandations pour la normalisation du BUHP et du béton de fibres. Le premier groupe de travail prépare les normes Matériaux et Méthodes pour le BUHP et le second groupe de travail prépare des recommandations de calcul de structure pour les ponts constitués de bétons fibrés écrouissants ou adoucissants en traction.

Le présent article traite de l'approche Canadienne pour normaliser le BUHP, en présentant le contexte, un bref aperçu et les points principaux des nouveaux matériaux, des méthodes et du calcul des ponts en béton de fibres, y compris en BUHP.

1. INTRODUCTION

In this paper Ultra-High Performance Concrete (UHPC) is defined as a cementitious, composite material that has enhanced strength, durability and ductility compared to high performance concretes. UHPC may contain fibres for post-cracking ductility, have specified compressive strength of at least 120 MPa at 28 days, and are formulated with a modified multi-scale particle packing of inorganic materials of less than 0.6 mm diameter (larger sizes maybe used) [1]. The material matrix is typically manufactured from combining fine materials such as sand (< 400 microns; larger sizes can be used), ground quartz, Portland cement and silica fume (other nonorganic mineral fillers maybe used). The matrix typically contains small fibres 12 mm x 0.2 mm diameter; (large fibers can be used) in a very high dosage rate of 2 % by volume (volume fractions can range from 1 % to 5 %). Fiber types can be high carbon steel or organic (such as PVA, glass, etc.). The high compressive and tensile properties of UHPC also facilitate a high bond stress and hence, a short bond development length for embedded reinforcing or prestressing. The use of fine materials for the matrix also provides a high aesthetic surface with the ability to closely replicate surface textures and finishes. The matrix provides a very dense and low permeability (Chloride ion diffusion less than 0.02 x 10^{-12} m^2/s) to prevent the ingress of chlorides or other aggressive agents [2]. Like conventional or High Performance Concrete (HPC), UHPC is a family of products with different formulations that are used for different applications. These formulations vary in raw material ingredient dosages, fiber types and curing regimes.

While Ultra-High Performance Concrete (UHPC) has been under research and development for more than 20 years, it is still a relatively new material technology compared to conventional concrete [3]. The use of this technology is slowly increasing and gaining acceptance in numerous applications, such as bridges, architectural products, security, water / waste-water, building elements and others. It is the superior mechanical properties of UHPC, particularly durability and tensile ductility that provide the benefits and reason for potential users of the technology, irrespective of the challenges of deploying this technology. The challenge of the lack of codes and standards is one major factor in slowing the implementation of UHPC.

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CSA has been developing standards for concrete (Materials, Methods and Design) for approximately 100 years. The CSA approach has been to develop separate concrete standards – one for materials and methods and a second for structural design. A further refinement is that a separate structural design standard is developed for bridges and for buildings. Additionally, a specific and separate standard is developed for precast concrete. This approach allows for experts in each of these areas (materials vs structural) to develop the specific standards in parallel, with a few of the experts serving on both committees to provide coordination.

2. BACKGROUND AND THE NORTH AMERICAN HISTORY OF UHPC DEVELOPMENT

In the overall history of concrete, UHPC is still a very young material, although it has been researched for over 30 years and in development for approximately 20 years. UHPC was developed in France [5] based on early research in Denmark [6]. Acceptance for UHPC has been growing at a moderate pace, with recent trends showing accelerated popularity among architects and bridge engineers, mainly for its aesthetic and durability properties. UHPC research commenced in Europe in the 1970's and late 1980's. By the early 1990's, it was recognized as a potential new "revolutionary" material for the construction industry.

Early introduction and testing of UHPC for use in North American bridge structures and marine environments began in 1994, over 20 years ago [5]. Raw material sourcing and formulating resulted in the preparation and placement of UHPC test prisms at the US Army Corps of Engineers (USACE) Long-Term Marine Exposure Station at Treat Island, Maine in 1996. Visual inspections determined that, after nearly 20 years, the prism corners are still sharp and crisp. Additionally, chloride ion penetration tests have revealed that the permeability of the UHPC samples is significantly lower (or an order of magnitude better) than High Performance Concrete (HPC) [7, 8].

The first use of UHPC in a North American bridge was in 1997, for construction of the Sherbrooke Pedestrian Bridge (Figure 1) in Quebec, Canada [9]. This 60 m clear span bridge was constructed from six precast 3-D Space Truss UHPC elements, and post-tensioned together on site. Although not a highway bridge, it has been exposed to light vehicle loadings for winter snow removal and severe freeze/thaw conditions as well as deicing salts for almost 20 years.

Figure 1: Sherbrooke Pedestrian Bridge, Quebec, Canada (1997)

In 2001, the US Federal Highway Administration (FHWA) initiated a research program to evaluate and introduce UHPC into the U.S. Highway program [10]. From 2006 through 2014 FHWA published several documents on UHPC, including a design guide for Field Cast Connections of Precast Bridge Element. Additionally, under a FHWA funded program Iowa State University published a design guide for the design of UHPC Waffle Deck Bridges [11].

As of the end of 2016, over 150 bridges utilizing UHPC have been completed in North America. These include either precast bridge elements or field-cast connections (for precast bridge elements) or, in some cases, both precast and field-cast UHPC solutions. The material has also been implemented for a range of other precast architectural and structural applications, such as cladding systems, high security products, wastewater treatment troughs, urban furnishings, underground utility products, canopies, struts and columns (for a light rail transit station), plus others.

During this same period from the late 1990's, outside of North America, UHPC was also being developed in a number of regions, such as France, Australia, Japan, Germany, Korea, China, Denmark and others. However, unlike North America, several other countries began the process of writing standards, codes and guides on UHPC. France introduced its first UHPC Design Guide in 2001 and a subsequent updated version in 2013, entitled "Scientific and Technical document on Ultra High Performance Fibre-Reinforced Concrete, Recommendations" (AFGC, 2013)[12]. In 2017 France will release two new standards NF P18-470 "Bétons fibrés à ultra-haute performances – Spécification, performance, production et conformité" and NF P 18-710 "National addition to Eurocode 2 – design of concrete structures: specific rules for Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC)" [13]. Australia introduced a structural design guide in 2000 and a code on strain-softening fibre-reinforced concrete in 2016 while in 2006 Japan issued a design guide [14, 15]. The Swiss Society of Engineers and Architects have released in 2014 a new guide prSIA 2052 "Bétons fibrés Ultra-Performant: Matériaux, dimensionnement et exécution (UHPC: Material, dimensioning and construction)" [16]. Additionally, in 2012 Germany published guidelines on "Steel Fibre Reinforced concrete" from Deutscher Ausschuss fuer Stahlbeton (DAfStb). While several countries did begin the process of introducing structural design guides to assist engineers with the design of structures, there still was a lack of standards for testing and specifying materials [17].

In 2012, the American Concrete Institute initiated a committee on UHPC, "ACI 239 – UHPC", which commenced the task of collecting a group of industry experts and defining UHPC. The committee has formed several sub-committees which are now focused on two Emerging Technology Reports, including one report on the structural design of UHPC.

In 2013 a small industry group made a presentation to the American Society for Testing and Materials (ASTM) with the intention to start developing materials test standards for UHPC. Subsequently work has started within ASTM to develop a "Standard Practice for Fabricating and Testing Specimens with UHPC".

3. CHALLENGES FACING THE RAPID DEPLOYMENT OF UHPC

Considering the superior properties of UHPC and the potential benefits of a more resilient infrastructure, it is often believed that UHPC should be adopted more rapidly. An obvious question could be, "Why don't more bridge or building engineers use UHPC in their designs?"

In 1994, when UHPC was being introduced for infrastructure projects in North America, the engineering community was not aware of the new technology and there were no existing codes or standards that supported the use of a concrete with a compressive strength of over approximately 70 MPa, nor did any code recognized the design properties of concrete in tension [18]. Also, there was only one supplier of the material in the market and the lack of competition slowed the acceptance by public agencies requiring competitive bidding. Furthermore, a structural engineer's number one priority is to protect the public, and not to encourage new technologies that don't meet the codes and standards. The bridge and building engineering community, by training and responsibility, is to be conservative and not take unnecessary risks. The lack of adequate structural design codes, material codes and test standards all contributed to a slow adoption rate for this new technology.

Structural design codes for concrete normally do not permit the use of the tensile properties of concrete for primary load carrying stresses. Due to the lack of ductility of conventional concretes, the codes and standards ignore any tensile capacity from the concrete. UHPC, unlike conventional concrete, has tensile ductility and this property can be used to increase the load capacity of elements. This concept is not commonly used by structural engineers and hence is a barrier to using the tensile capacity of UHPC in structures.

Additionally, the properties of UHPC are typically an order of magnitude superior to high performance concrete and, therefore, the lack of suitable ASTM materials testing standards makes it very difficult to provide meaningful data or in many cases the test result is within testing error, thereby rendering the result useless. As a result, materials engineers have to use *ad hoc* modified ASTM and the American Association of State Highway Transportation Organization (AASHTO) test material standards. Consequently, there is a need to develop new testing standards that provide meaningful test results for a full range of UHPC material properties. These tests are necessary in order to categorize different UHPC's and to provide reliable and reproducible material properties for structural engineers to use in the design of UHPC structures. Currently under the auspices of ASTM Sub-committee C09.61"Strength", a new standard ASTM C1856/C1856M "Standard Practice for Fabricating and Testing of Specimens from UHPC" has been developed to address the lack of available testing standards. The development and adoption of this new material specific and appropriate testing standard is the first step to writing any future design (material or structural) standards [19]. All future design standards will necessarily have to specify testing standards which will define the process to determine the material properties used in the design and construction process. For example, today the global UHPC definition includes a minimum specified compressive strength of 120 or 150 MPa and until now in North America there was no standard test for compressive strength of UHPC. The new ASTM standard practice ASTM C1856/C1856M will provide the methods to verify if a product can be defined as a UHPC.

Even though this technology uses basically the same types of raw materials and equipment as normal concrete, there are many significant differences that require a new approach to implementing the technology. These significant differences, such as the selection and proportioning of the raw materials, the batching sequence and high batching energy demands, the cost of the raw materials and the need for superior Quality Assurance/Quality Control (QA/QC) to reduce variations can only be consistently assured by the development of a new UHPC material standard.

In North America today, there does not exist an UHPC materials code or standard that provides a clear definition nor guidance on categorizing UHPC. Any high performance concrete today can claim to be UHPC and in many cases materials are being presented as UHPC without any code or standard to prove or disprove the claim.

Today there are no North American broad based materials, or methods or structural design guidelines, standards or codes that provides a complete document to an engineer on designing and building a structure with UHPC, unlike conventional concrete. For UHPC, North American structural engineers are required to use existing codes or guides from other countries, then apply conservative safety factors, then load test to validate full sized elements before proceeding with the full construction. This process of testing increases initial costs of materials, test elements, testing procedures and time delays. In many cases the use of UHPC loses to other more conventional solutions due to these added costs, even though all parties recognize the UHPC solution to be superior to the status-quo.

4. THE CSA APPROACH TO STANDARDIZING UHPC

In the fall of 2015, a number of industry leaders and UHPC experts commenced an initiative to include FRC and UHPC into the next Canadian standards cycle. Major Canadian standards are normally updated on a five-year cycle and both the concrete and bridge standard are scheduled for updating and release in 2019. Presentations to the executive committees for both the concrete materials and bridge standards resulted in an endorsement of the proposal to develop a new non-mandatory Annex in each of the standards for release in 2019.

Two Task Groups were formed with several members serving on both groups to provide liaison and coordination between the two new Annexes.

4.1 CSA A23.1/2 Annex S on UHPC, Materials and Methods for Construction

In December of 2015, under CSA A23.1, Chapter 8, the new "Working Group on UHPC" was formed, with the mandate to develop a new non-mandatory Annex on UHPC materials [20].

The Annex provides information for materials and methods of construction for the use of UHPC in cast-in-place concrete and precast concrete. All of the requirements of CSA A23.1, "Concrete Materials and Methods of Concrete Construction" apply, except as stated in the Annex. The Annex is intended to be used in its entirety. The users are cautioned against extracting individual clauses and using them in project specifications, since taking them out of context can change their meaning. The Annex was developed to provide guidance to suppliers, specifiers and users of UHPC technology. The Annex establishes boundaries on the properties of UHPC, how to characterize the material within given categories and how to batch, transport, place and cure the material. The Annex is intended to provide limits on what materials may be classified and how to use UHPC, without restricting innovation in the development of new uses or material formulations. The Annex does not provide requirements for the design of UHPC structures; or all of the required test methods for UHPC. The requirements for the structural design for bridges, is covered in CSA S6 Annex on UHPC (see section 4.2 below).

Table 1: UHPC direct tensile strength categories [1]

Property	**Parameter**	**Hardening (H)**	**Softening (S)**	**No Fibres (N)**
Tensile strength (MPa)	f_t	≥ 5.0	≥ 4.0	≥ 4.0
Hardening strength ratio	f_{tu} / f_t	≥ 1.1	< 1.1	NA
Ultimate strain (‰)	ε_{tu}	≥1.0	NA	NA
Post-cracking strength	f_{ti}	Clause S.4.1.2.2.6	Clause S.4.1.2.2.7	NA

Example: *Class H* is a UHPC with a minimum characteristic design compressive strength of 120 MPa, has a minimum characteristic design tensile strength of 5 MPa, exhibit strain hardening ratio of greater than 1.1 post cracking of the matrix, have an ultimate strain of at least 1.0 % and have a minimum post cracking strength with a corresponding specified strain.

The new Annex covers a broad scope on the use of UHPC materials such as; categorization, characterization (See Table 1 for an example on characterizing tensile properties and Figure 2 for the corresponding stress-strain values shown in Table 1), raw materials, proportioning, production, mixing, transporting, formwork, placing, finishing and QA/QC. By January 2017, the working group had already conducted two ballots on the new draft with an anticipated completed draft by May 2017. The document would then go to public comment in 2018 and target to be published in the 2019 edition of the next CSA A23.1-19.

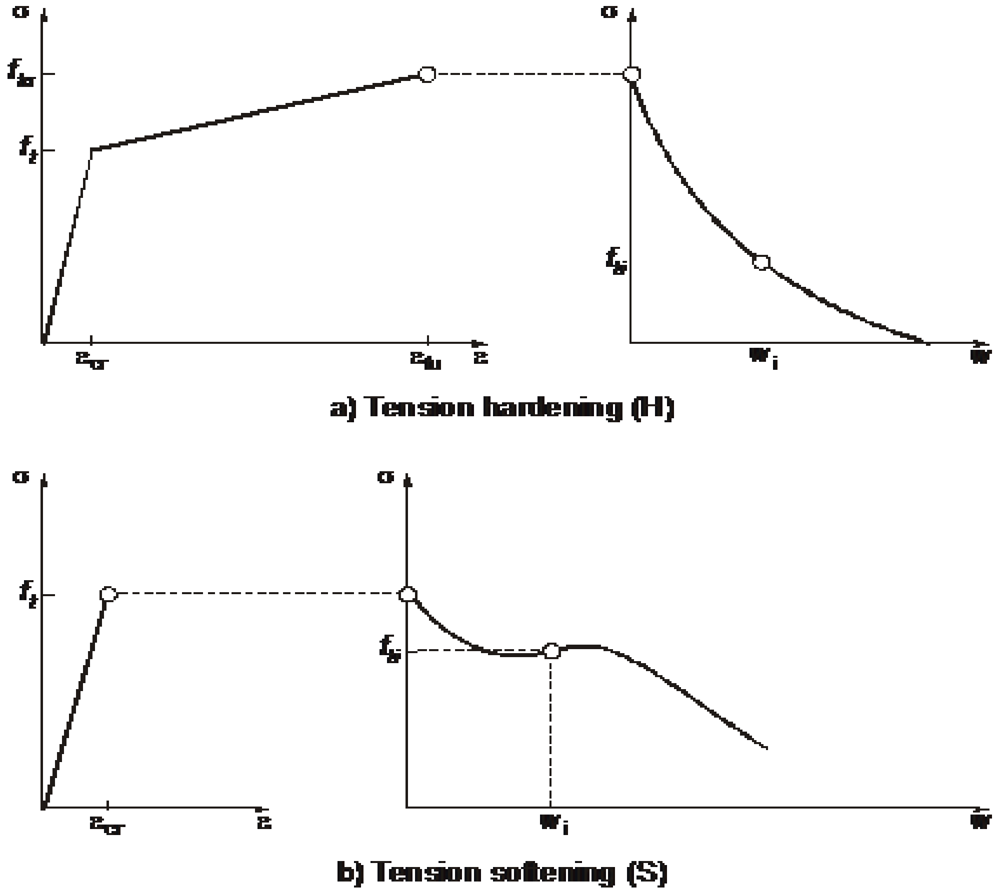

Figure 2: Stress – Strain Diagrams [1]

The Annex provides categories and methods for characterizing the following Strength and Durability properties of UHPC:
a) Mechanical Properties – compressive and tensile strength, Young's Modulus, Poisson's ratio
b) Durability – abrasion, salt-scaling, absorption, chloride ion penetration and sulphate resistance

Guidance is also provided for methods for determining the following properties:
a) consistency
b) fabricating and moulding specimens
c) curing and thermal treatments
d) fire properties
e) time dependent properties -creep, shrinkage and thermal coefficient

The Annex requires the preblend material supplier or mix designer to provide a material identity card with a minimum specified number of properties. The material identity card requires a full characterization (mean and standard deviation of the previously mention above properties) of the preblended material or mix design, plus mix components, quantity and quality of raw materials, mixing instructions and curing instructions.

The chapter on "Production and Delivery" provides requirements for raw materials, preblending equipment specifications, blending and batching precision, quality control, packaging, batching procedures, temperature control and ranges, mix adjustment and retempering and delivery.

Two additional chapters on "Formwork, Reinforcing & Prestressing " and "Placing, Finishing & Curing" provide the requirements for macro-reinforcement, formwork and tolerances, handling, depositing, consolidation, vibration, protection & curing, demoulding, surface treatments, grinding & cutting and end of life treatment.

4.2 CSA S6 Annex 8.1 on FRC/UHPC for the Structural Design of Bridges

In March 2016, a task force started work on an Annex on the structural design of FRC and UHPC under the Concrete section of the Canadian Highway Bridge Design Code (CSA S6) [21]. The aim is to develop an Annex which specifies requirements for the design of structural components that are made of precast or cast-in-place fibre-reinforced concrete (FRC) with prestressed or non-prestressed steel [22]. The document will include guidelines for the structural design of strain-hardening and strain-softening fibre reinforced materials, which include, but are not limited to UHPC. The definition of strain-hardening and strain-softening are generally in accordance with the definition in Table 1 except that the tensile strength may be lower than the values stated in the table.

The Annex is intended to become a non-mandatory Annex in the 2019 edition of CSA S6 and will be complementary to the Concrete section of CSA S6. The first edition of the Annex will be a guideline which will draw upon the existing state-of-the-art in the content development and will be limited in scope. The intent is to continue development of the guideline beyond the 2019 edition of CSA S6 with the ultimate goal to obtain a mandatory section for strain-hardening and strain-softening fibre reinforced concretes in a future edition of CSA S6.

The first edition of the Annex will include sectional design models for compression, tension, bending and shear, design considerations for the design with fibre reinforced materials at the ultimate and serviceability limit states as well as requirements specific to certain applications such as joints between precast components. Based on the current state-of-the-art, the Annex will have the following limitations:

- Fibre reinforced concrete only (i.e. without reinforcing bars or prestressing) are allowed for non-structural applications only.
- Structural applications require continuous reinforcing (mild reinforcing bars or prestressing) in addition to fibres.
- No force/moment redistribution allowed.

5. CONCLUSIONS

In the overall history of concrete, UHPC is a very young material, albeit has been researched for over 30 years and in development for approximately 20 years. Acceptance has been growing at a moderate pace, with recent trends showing an accelerated popularity among architects, bridge owners and engineers, mainly for its performance, and durability properties.

Today numerous excellent examples exist showing how the technology can provide value to the owner and end-users. These projects, with up to more than 20 years of in-service data, validates the performance of the material. There exist today hundreds of completed projects worldwide that use UHPC and perform as intended in the design. These completed projects demonstrate to the industry that the technology is working and meets the needs of the users. It also demonstrates that codes and standards are required that provide equally documented code information to all industry users in North America

Currently, structural design guides for fibre reinforced concrete have been written in countries on every continent, except Africa and North and South America. In 2013, the American Concrete Institute (ACI) established committee ACI 239 UHPC. In 2015, the American Association of Testing and Materials (ASTM) begin to write standards that recognize UHPC. In 2016 the Canadian Standards Association began writing a materials standard for UHPC. All of these organizations are in the early stages of developing codes and standards for UHPC. The demand of the material is growing and precasters / contractors are learning how to work with the technology.

The new CSA Annexes will provide much need guidance to the industry on the limits on what materials may be classified, how to use and design with FRC and UHPC, without restricting innovation in the development of new uses or material formulations.

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