Impact of mixing and curing temperatures on UHPFRC properties

Authors & Affiliation:

Jean-Philippe Charron, Research Center on Concrete Infras. (CRIB), Polytechnique Montreal
Cédric Androuët, Research Center on Concrete Infras. (CRIB), Polytechnique Montreal
Olivier Deaux, Research Center on Concrete Infras. (CRIB), Polytechnique Montreal

Abstract:

First structural applications in ultra-high performances fiber reinforced concretes (UHPFRC) were mainly precast solutions, such as bridge components and architectural panels. In that context, most studies concerning the impact of temperature on UHPFRC properties concerned high curing temperatures feasible in precast industry where a high control of the production process can be obtained. More recent applications of UHPFRC concerned also cast-in-place solutions involving field-cast joints and thin repairs. Limited data is available on the impact of low to moderate mixing and curing temperatures found on construction sites. This paper describes a research project focused on the evaluation of fresh state and hardened properties of UHPFRC in realistic cast-in-place conditions. UHPFRC were produced between 10 to 30 °C and cured between 10 to 35 °C, measurements of slump flow, air content, density, compressive and bending strengths are presented and discussed.

Keywords:

Mixing temperature, Curing temperature, Slump flow, Air content, Compressive strength, Flexural strength.

1. Introduction

In the last decades, structural applications in ultra-high performances fiber reinforced concretes (UHPFRC) gained in interest. First applications of the materials were mainly precast solutions, such as bridge components and architectural panels (Lachance et al 2016). In that context, most research projects concerning the impact of temperature on UHPFRC properties concerned high curing temperatures feasible in precast industry where a high control of the production process can be obtained. More recent applications of the materials concerned also cast-in-place solutions involving field-cast joints and thin repairs (Bastien-Masse and Brühwiler 2016, Graybeal 2014). Limited data is available on the impact of low to moderate mixing and curing temperatures found on construction sites.

Besides, upcoming Canadian standards and a new American standard for concrete and bridges (CSA A23.1-19, CSA S6-19, ASTM C1856) now provides guidelines for the design, production, curing, material characterization and installation of UHPFRC on structures. Although new standards are available in North America, Europe and Asia, many discrepancies exist between codes. For example, loading rate applied on specimens may vary depending on the geometry and the standard used to perform the compressive tests. It is important to assess if specimen types and the range of loading rates proposed are adequate.

2. Background

Knowledge on the properties of UHPFRC produced under field conditions is limited. Many studies were dedicated on the effects of high curing temperatures (above 60 °C) such as steam or autoclave curing used in precast industry for UHPFRC (Ahlborn et al. 2008, Yang et al. 2009). However, the influence of mixing and curing temperatures between 10 and 40 °C encountered in field conditions have been poorly studied for UHPRC so far. Literature found on the subject mainly concern normal strength concretes (NSC) (Neville 2011, Burg 1996). For NSC, when mixing temperature increases, both workability and setting time decrease (Neville 2011), while compressive strength increases at early age and decreases in the long term (Neville 2011, Burg 1996) in comparison to results obtained with a production at 20°C. When curing temperature increases, setting time of NSC generally decreases, while its compressive strength increases at early age and decreases in the long term in comparison to results measured with a curing at 20°C (Neville 2011, Termkhajornkit and Barbarulo 2012). Confirmation of these trends is needed for UHPFRC to allow a better prediction of their on-site properties.

Loading rate applied on specimens may vary depending on the geometry and the standard used to perform the compressive tests. CSA A23.2-9C as well as ASTM C39 standards indicate to use an average loading rate of 0.25 MPa/s, whereas CSA A23.1 Annex U as well as ASTM C1856 specify an average loading rate of 1.0 MPa/s, and ASTM C109 recommends minimum value of 0.35 MPa/s for tests on cubes. In order to compare the requirements of these standards, compressive tests should be conducted on both cubes and cylinders within the range of loading rate detailed previously.

This paper describes a research project focused on the evaluation of fresh state and hardened properties of UHPFRC in realistic cast-in-place conditions. UHPFRC were produced between 10 to 30 °C and cured between 10 to 35 °C, slump flow, air content, density, compressive and bending strengths results are presented and discussed, specimen type and loading rate are analyzed on compressive strength of one testing condition. Experimental data of this paper have been collected from Deaux' thesis (Deaux 2018).

3. Testing Methods

3.1. Experimental program

Impact of three mixing temperatures and three curing temperatures were studied on a UHPFRC properties. Mixing temperatures were set respectively at 10, 20 and 30°C and curing temperatures were fixed at 10, 23 and 35°C. Intermediate temperatures are the ones usually found in laboratories while extreme temperatures are the boundaries allowed in CSA A23.1-19 standard. Only realistic combinations have been studied, thus improbable ones such as a mixing temperature of 10°C and a curing temperature of 35°C or a mixing temperature of 30°C and a curing temperature of 10°C were not considered.

3.2. Material

The experimental program was completed with a commercially available UHPFRC distributed by King Packaged Materials Company. The product name is UP-F3 Poly, it has a water/binder ratio of 0.2 and a volumetric dosage of 13 mm steel fibers of 3%. Its nominal compressive strength at 28 days is 120 MPa. The mix design is shown in Table 1.

Table 1. UHPFRC mix design

Component	Quantity (kg/m^3)
Premix	1890
Water	221
Superplasticizer	50
Steel fibers	234

3.3. Experimental procedures

3.3.1. Mixing and curing procedures

The mixing procedure used in this study consists of mixing the premix (dry materials) one minute, adding water and admixtures during a mixing period of three minutes, adding fibers during a mixing period of three minutes and a last mixing stage of three minutes. This method allows to get a homogeneous and self-levelling UHPFRC. Mixing temperatures at 30°C was obtained with tap water at 23°C, this is the normal fresh state temperature in ambient condition (23 °C). Mixing temperatures at 20°C and 10°C were obtained by replacing water of the mix by respectively 50% and 100% of ice.

Three different curing temperatures were applied on specimens in different controlled boxes set at 10, 23 and 35°C, Three different curing temperatures were applied on specimens in different controlled boxes set at 10, 23 and 35°C, maximal temperature variation of ±2 °C was measured with thermocouples in the boxes along the curing period. No humidity control was available in these boxes. The drying condition imposed during curing reduced the mechanical properties measured for the UHPFRC. All testing conditions were submitted to the same drying during curing, thus trends observed for various mixing and curing temperatures stay applicable.

3.3.2. Testing procedures

Fresh state properties were evaluated by slump flow test (ASTM C1611), air content and density measurement (ASTM C231 and ASTM C138 respectively), temperature of fresh concrete (ASTM C1064). One measurement was made on each mix produced.

Hardened state properties were also evaluated. Compressive test was conducted accordingly to ASTM C39 at 2, 3, 7 and 28 days on 75-mm diameter cylinders for all combinations of mixing and curing temperatures. The loading rate was 0.25 MPa/s.

Impacts of the specimen type (75-mm side cube versus 75-mm diameter cylinder) and loading rate (0.25, 0.35 and 1.0 MPa/s) were evaluated with tests at 28 days at a mixing temperature of 20°C and curing temperature of 23°C. Three specimens per conditions were tested.

Elastic modulus and Poisson ratio tests were conducted accordingly to ASTM C469 at 28 days on 100-mm diameter cylinders for all combinations of mixing and curing temperatures. One specimen per condition was tested, the average value obtained for the three loading cycles is provided.

Flexural tests were conducted following CSA A23.1-19-Annex U as well as ASTM C1856, except that prism dimensions were different (50 mm-height, 150 mm-width and 400 mm-length with a span of 300 mm), at 28 days for all combinations of mixing and curing temperatures. Three specimens per conditions were tested.

Steel fiber orientation was analyzed by an in-house image analysis program (Delsol and Charron 2013). A slice of each flexural prisms tested is extracted and polished to obtain smooth and straight analyzing surfaces. This surface is painted to highlight the steel fibers in concrete and then digitalized with a scanner. Finally, the image is processed by the program which identify accurately fiber outline and calculate the fiber density (ρ) and the fiber angle (θ) according to the normal direction of the analyzed surface.

4. Results and discussion

4.1. Impact of mixing temperature on fresh state properties

Table 2 summarizes the fresh state properties measured for UHPFRC production at 10, 20 and 30°C, values shown are the average results obtained on 2 or 3 mixes produced at each mixing temperature. Table 2 shows an increase in workability with the decrease of mixing temperature, which is in agreement with NSC relevant literature (Neville 2011, Burg 1996). As expected, air content and mass density did not present any significant variation. Mixing temperature does not affect significantly the hardened state properties of the UHPFRC studied. Consequently, these results are not presented.

Table 2. Fresh state properties

Mixing temperature (°C)	Slump flow (mm)	Air content (%)	Mass density (kg/m^3)
10	790	3.7	2403
20	745	3.3	2402
30	670	3.3	2411

4.2. Impact of curing temperature on hardened state properties

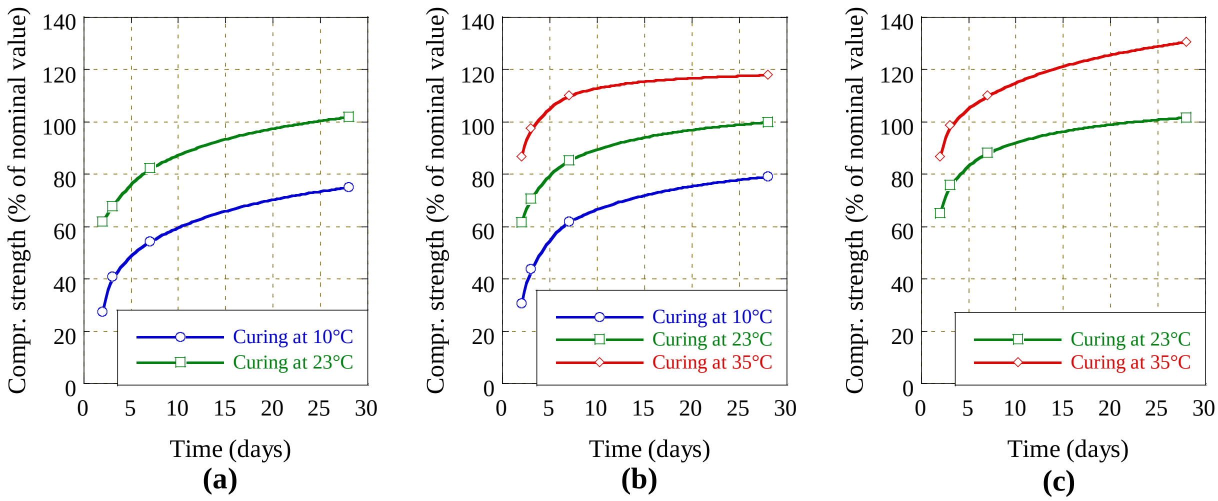
4.2.1. Compressive strength

Figure 1 presents the impact of curing temperatures on compressive strength (3 specimens per conditions) at various mixing temperatures. The results are shown in percentage of the 28 days nominal value obtained at mixing and curing temperatures of 20 °C and 23 °C, respectively. As stated previously, 28 days compressive strength was lower than the expected nominal value of 120 MPa since the drying condition imposed during curing reduced mechanical properties. This presentation was preferred instead of value in MPa to facilitate evaluation of the impact of mixing and curing temperatures on results.

For a mixing temperature of 10°C, the higher the curing temperature, the stronger the compressive strength for all terms tested (Figure 1a). More specifically, when the UHPFRC is produced at 10°C, the compressive strength is always at least 28% higher when cured at 23°C than at 10°C.

For a mixing temperature of 20°C, an increase in curing temperature leads to a faster increase of early-age compressive strengths and a faster stabilization of compressive strengths development (Figure 1b). As a practical information, when produced at 20°C, compressive strength is in average 29% higher when the UHPFRC is cured at 35°C than at 23°C, itself 48% higher than when UHPFRC is cured at 10°C.

For a mixing temperature of 30°C, an increase in curing temperature also provides a faster increase of early-age compressive strengths (Figure 1c). More specifically, when concrete is produced at 30°C, compressive strength is always at least 17% higher when cured at 35°C than at 23°C.



a) Mixing temperature 10°C b) Mixing temperature 20°C c) Mixing temperature 30°C

Figure 1. Impact of curing temperatures on compressive strength

As a general trend, the higher the curing temperature, the higher the compressive strength and the quicker the compressive strength reaches a high value. High early strengths can be related to an accelerated hydration kinetics. This trend is consistent with relevant literature for NSC and UHPFRC (Park et al. 2015, Kamen et al. 2007), which indicates that high curing temperatures resulted in higher hydration rates and higher compressive strengths at younger ages.

The impact of the specimen type (75 mm-side cube and 75 mm-diameter cylinders) and loading rate (0.25, 0.35 and 1 MPa/s) were studied at a mixing temperature of 20 °C and a curing temperature of 23 °C. The 28 days compressive strength results are summarized in Figure 2, extreme values measured are also shown with brackets. The results obtained with cubes and cylinders are nearly equivalent, it means that the specimen types studied don't have an impact on measurement. Besides, a very slight increase in the average compressive strength of cubes and cylinders can be noted for the higher loading speed in comparison to the lower one (5% and 8% respectively for cubes and cylinders). This trend is in agreement with the general observation that increasing the loading rate leads to higher compressive strength (Bischoff and Perry 1991). It may indicate that using the CSA A23.1 Annex U loading rate of 1.0 MPa/s could lead to a slight overestimation of UHPFRC strength. However, given the inherent variability of compression tests showed with brackets in Figure 2, this observation should be verified by a complimentary program with a higher number of specimens.

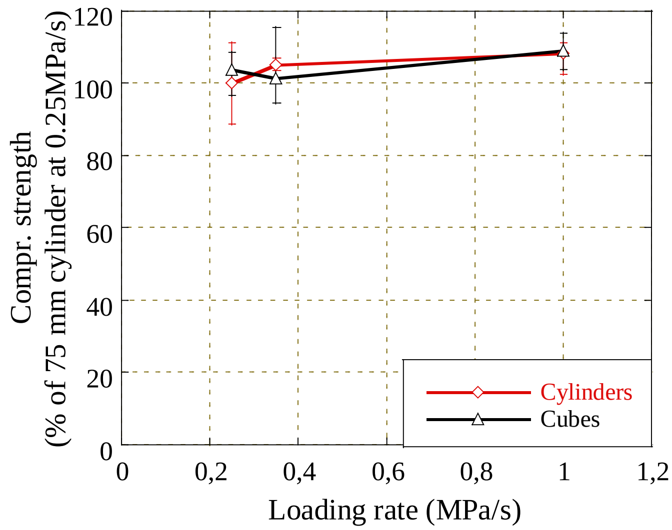


Figure 2. Impact of specimen type and loading rate on compressive strength at mixing temperature of 20°C and curing temperature of 23°C

4.2.1. Elastic modulus and Poisson's ratio

Table 3 summarizes the 28-days elastic modulus and Poisson's ratio values for the various testing conditions studied. Overall, only conditions involving curing temperature at 10°C reduce the elastic modulus of the UHPFRC studied (decrease between 13 and 19%). Other combinations of mixing and curing temperatures do not affect significantly the elastic modulus. No trend is detectable for Poisson's ratio, which presents values of the same magnitude for all mixing and curing temperatures considered.

Table 3. Impact of mixing and curing temperatures on elastic modulus and Poisson's ratio

Mixing temperature (°C)	Curing temperature (°C)	E (GPa)	υ (-)
10	10	29.3	0.21
	23	36.0	0.23
20	10	31.6	0.23
	23	36.3	0.24
	35	35.3	0.22
30	23	35.3	0.23
	35	35.8	0.21

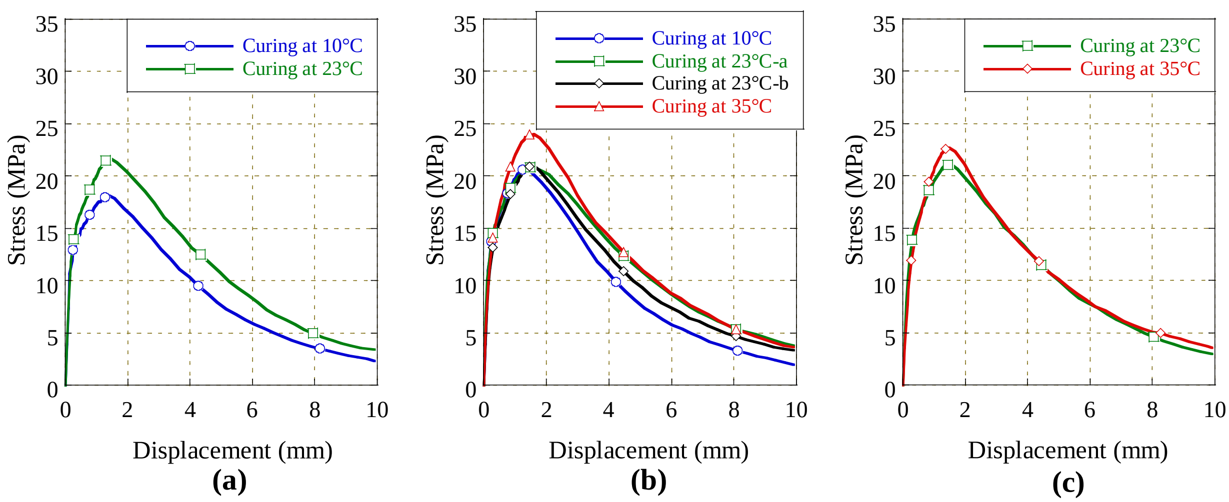
4.2.1. Flexural behavior

The bending behavior of fiber reinforced concretes is highly influenced by fiber orientation and fiber density within specimens (Ferrara et al. 2012). Although the casting procedure of flexural specimens was made carefully and with reproducibility, variations of fiber density and orientation were measured at failure plan in specimens. In this context, the appropriate analysis of flexural test results has required to consider the variation of these parameters.

The flexural test results were adjusted according to a reference fiber density and fiber orientation. The references values selected was the mean fiber orientation angle (θ_m) and the mean fiber density (ρ_m) measured in all testing specimens. The impact of orientation and density of the fibers on flexural behavior of UHPFRC has been considered of the same magnitude, as suggested by (Nunes et al. 2017), thus the weighting coefficients applied to results has been defined as the square root of the product of orientation and density coefficients. The weighting coefficient γ_i is presented in Equation 1, where θ_i and ρ_i are the average orientation angle and fiber density measured for a testing condition *i* (for example the combination of mixing and curing temperatures of 20 °C and 23 °C), θ_m and ρ_m are the mean orientation angle and fiber density measured for all testing conditions. The methodology for determining the weighting coefficients is detailed in (Deaux 2018).

$$\gamma_i = \sqrt{\frac{\theta_i}{\theta_m} \times \frac{\rho_m}{\rho_i}} \tag{1}$$

The stress values of each bending curve were multiplied by the weighting coefficient γ_i of each condition studied. Weighted average results of flexural tests conducted at 28 days at various mixing temperatures are presented in Figure 3.



a) Mixing temperature 10°C   b) Mixing temperature 20°C   c) Mixing temperature 30°C

Figure 3. Impact of curing temperatures on flexural strength

For mixing temperature of 10°C, maximum flexural strengths are higher when concrete is cured at 23°C than 10°C. For mixing temperature of 20°C, maximum flexural strengths are more than 14% higher for UHPFRC cured at 35°C than at 10°C or 23°C, between which difference is less than 1%. For mixing temperature of 30°C, maximum flexural strengths are higher when UHPFRC is cured at 35°C than at 23°C by 7%.

It can be concluded that an increase in curing temperature is accompanied by an increase in flexural strengths. This trend is both consistent with the one observed in compressive tests and with relevant literature both about NSC and UHPFRC (Yang et al. 2009, Kim et al. 2002), which reveals that an increase in curing temperature generally leads to an increase in flexural strength. The increase of flexural strength with higher curing temperature can be firstly explained by the same reasons detailed for the compressive strength as the upper surface of the flexural prisms is subjected to compressive forces. In addition to this effect, a higher curing temperature also improves the fiber adhesion with the surrounding matrix, itself linked to the compressive strength of the fiber reinforced matrix (Wu et al. 2016).

5. Conclusions

The paper focuses on the evaluation of the impact of mixing and curing temperatures on fresh and hardened states properties of UHPFRC. The following conclusions can be drawn:

- Increasing UHPFRC mixing temperature between 10 to 30 °C leads to a reduction of its workability up to 15%.
- Mixing temperature does not modify the mass density and air content.
- Increasing UHPFRC curing temperature between 10 to 35 °C provides higher compressive strengths and a quicker stabilization of the compressive strength. For example, when produced at 20 °C, compressive strength is in average 29% higher when the UHPFRC is cured at 35 °C than at 23 °C, itself 48% higher than when UHPFRC is cured at 10 °C.
- Conducting compressive tests with 75-mm side cube or 75-mm diameter cylinders provide equivalent results.
- Conducting compressive tests with loading rate of 1.0 MPa/s versus 0.25 MPa/s may lead to a slight overestimation of compressive strength.
- Increasing UHPFRC curing temperature between 10 to 35 °C provides higher flexural strength. For example, when produced at 20 °C, maximum flexural strength is more than 14% higher for UHPFRC cured at 35 °C than at 10°C or 23 °C.

The results of this experimental campaign can help engineers to plan the UHPFRC curing duration and formwork removal.

6. References

Ahlborn, T. M., Misson, D. L., Peuse, E. J., Gilbertson, C. G. "Durability and Strength Characterization of Ultra-High Performance Concrete under Variable Curing Regimes, " presented at the Second International Symposium on Ultra High Performance Concrete, Kassel, Germany, 2008.

ASTM C1856 "Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete," ASTM Standards 2017.

Bastien-Masse, M. Brühwiler, E. "Experimental investigation on punching resistance of R-UHPFRC–RC composite slabs," Materials and Structures, vol. 49, 2016, pp. 1573–1590

Bischoff, P. H., Perry, S. H. "Compressive behaviour of concrete at high strain rates," Materials and Structures, Vol. 24, 1991, pp. 425-450.

Burg, R. G. "The influence of casting and curing temperature on the properties of fresh and hardened concrete," in "Research and Development Bulletin RD113T " Portland Cement Association, Skokie, Illinois, U.S.A. 1996.

CSA A23.1-19/A23.2-19 "Concrete materials and methods of concrete construction / Test methods and standard practices for concrete," CSA Standards, 2019.

CSA S6-19 "Canadian Highway Bridge Design Code," CSA Standards, 2019.

Deaux, O. "Optimisation de bétons fibrés à ultra-hautes performances et caractérisation de leurs propriétés en contexte industriel," M.Sc.A., Polytechnique Montreal, Canada, 2018.

Delsol, S., Charron, J.-P. "Numerical modeling of UHPFRC mechanical behavior based on fibre orientation," presented at the RILEM-fib-AFGC International Symposium on Ultra-High Performance Fibre-Reinforced Concrete UHPFRC 2013, Marseille, France, 2013.

Ferrara, L., Caverzan, A., Muhaxheri, M., di Prisco, M. "Identification of tensile behaviour of SFR-SCC: direct vs. indirect tests," in 8th RILEM International Symposium on Fibre Reinforced Concrete (BEFIB 2012) - Challenges and Opportunities, Guimaraes, Portugal, 2012, vol. Pro 88, pp. 209-221.

Graybeal, B. "Design and Construction of Field-Cast UHPC Connections," FHWA Publication, Report No: FHWA-HRT-14-084., 2014, 36 pages.

Kamen, A., Denarie, E., Brühwiler, E. "Thermal effects on physico-mechanical properties of ultra-high-performance fiber-reinforced concrete, " ACI materials journal, vol. 104, no. 4, 2007, pp. 415-423.

Kim, J.-K. , Han, S. H., Song, Y. C. "Effect of temperature and aging on the mechanical properties of concrete: Part I. Experimental results," Cement and Concrete Research, vol. 32, no. 7, 2002, pp. 1087-1094.

Lachance, F., Charron, J.-P., Massicotte, B. "Development of Precast Bridge Slabs in High and Ultra-High Performance Fiber Reinforced Concretes," ACI Structural Journal, V. 113, No. 5, September-October 2016. pp. 929-939.

Neville, A. M. "Properties of concrete," 5th ed. Pearson United Kingdom 2011, 872 pages.

Nunes, S., Pimentel, M., Ribeiro, F., Milheiro-Oliveira, P., Carvalho, A. "Estimation of the tensile strength of UHPFRC layers based on non-destructive assessment of the fibre content and orientation," Cement and Concrete Composites, vol. 83, 2017, pp. 222-238.

Park, Kim, Y. J., Cho, J.-R., Jeon, and S.-J. "Early-Age Strength of Ultra-High Performance Concrete in Various Curing Conditions," Materials, vol. 8, no. 8, 2015, pp. 5537-5553.

Termkhajornkit, P., Barbarulo, R. "Modeling the coupled effects of temperature and fineness of Portland cement on the hydration kinetics in cement paste," Cement and Concrete Research, vol. 42, no. 3, pp. 526-538, 2012.

Wu, Z., Shi, C., Khayat, K. H. "Influence of silica fume content on microstructure development and bond to steel fiber in ultra-high strength cement-based materials (UHSC)," Cement and Concrete Composites, vol. 71, 2016, pp. 97-109.

Yang, S. L., Millard, S. G., Soutsos, M. N., Barnett, S. J., Le, T.T. "Influence of aggregate and curing regime on the mechanical properties of ultra-high performance fibre reinforced concrete (UHPFRC)," Construction and Building Materials, vol. 23, no. 6, pp. 2291-2298, 2009.

7. Acknowledgements

This research project was financially supported by MITACS and King Packaged Materials Cie. Authors would like to acknowledge King Packaged Materials Cie and Euclid Canada for graciously providing materials and the technical staff of Polytechnique Montreal for their contribution to this project.