Construction and Building Materials 153 (2017) 918–928

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Evaluation of modulus of elasticity of ultra-high performance concrete

Ali Alsalman [a], Canh N. Dang [b,c,*], Gary S. Prinz [a], W. Micah Hale [a]

[a] University of Arkansas, Department of Civil Engineering, 4190 Bell Engineering Center, Fayetteville, AR 72701, USA
[b] Department for Management of Science and Technology Development, Ton Duc Thang University, Ho Chi Minh City, Viet Nam
[c] Faculty of Civil Engineering, Ton Duc Thang University, Ho Chi Minh City, Viet Nam

HIGHLIGHTS

- Modulus of elasticity of ultra-high performance concrete using locally available materials was measured.
- Effects of sand gradation, binder content and type, and steel fiber were examined.
- The modulus of elasticity ranged from 36.9 GPa to 45.9 GPa.
- An equation was proposed to predict the modulus of elasticity of ultra-high performance concrete.
- The proposed equation provides a reasonable prediction for the relevant data found in the literature with an error of ±10%.

ARTICLE INFO

Article history:
Received 26 January 2017
Received in revised form 19 July 2017
Accepted 20 July 2017
Available online 28 July 2017

Keywords:
UHPC
Compressive strength
Modulus of elasticity
Fly ash
Local material

ABSTRACT

Modulus of elasticity (MOE) is a significant parameter in the design of concrete structures. The use of local materials for developing ultra-high performance concrete (UHPC) is beneficial in saving energy and reducing the concrete cost. However, this practice possibly decreases the MOE of UHPC. This study synthesized all relevant experimental data in the literature to propose a new equation for predicting the MOE at different ages. A number of UHPC mixtures were developed to verify the accuracy of the proposed equation. With an error of ±10%, the proposed equation provides a reasonable prediction for the UHPC mixtures containing local materials.

1. Introduction

Ultra-high performance concrete (UHPC) is a recent development in concrete technology. UHPC is a highly durable cement-based composite with a high compressive and tensile strength [1]. The enhanced mechanical properties lead to the increased flexural resistance, shear strength, and durability for concrete structures. Currently, UHPC is used for several concrete structures, typically including precast/prestressed bridge girders, precast waffle panels for bridge decks, and as a jointing material between precast concrete deck panels and girders [2,3]. In the United States, the use of UHPC for highway infrastructure began in 2001. The replacement of conventional concrete by UHPC also saves materials and decreases installation and labor costs [4]. However, these advantages have been not widely recognized because of special requirements in terms of material components used to produce UHPC mixtures (e.g., fibers, fine aggregates, or cementitious materials) and the high cost of UHPC.

Ductal® is a marketed premix of UHPC in the United States. Quartz powder with an average diameter of 10 μm and steel fibers with a tensile strength of 2600 MPa are essential components of Ductal® UHPC mixtures. Fine sand, with an average diameter of 150–600 μm, is used as a macro-filler component [3,5]. Currently, the UHPC premix is about 20 times more expensive than conventional concrete due to the additional costs of the proprietary blend and fiber reinforcement, and the costs associated with the development and delivery of the mentioned material [6]. The replacement of the fine sand with natural-gradation sand or fly ash can reduce the UHPC cost and widen the applications of UHPC to building, under-ground, or mass-concrete structures. Natural-gradation sand that is locally available is about $8 per ton, and fly ash is about $15–$40 per ton. The replacement of fine materials additionally reduces the required time and labor necessary to produce the fine sand with an average diameter less than 600 μm. However, the

* Corresponding author at: Department for Management of Science and Technology Development, Ton Duc Thang University, Ho Chi Minh City, Viet Nam. Faculty of Civil Engineering, Ton Duc Thang University, Ho Chi Minh City, Viet Nam.
E-mail address: canhdang@tdt.edu.vn (C.N. Dang).

http://dx.doi.org/10.1016/j.conbuildmat.2017.07.158
0950-0618/

use of natural-gradation sand or fly ash possibly affects the concrete stiffness, particularly modulus of elasticity (MOE), because of the changes in concrete microstructures.

In concrete structures, the modulus of elasticity is a necessary parameter in design. This parameter directly relates to the shortening of concrete components under compressive stress and due to creep and shrinkage. The concrete shortening causes the redistribution of internal stresses between columns, beams, or walls in reinforced concrete structures. Concrete shortening also affects prestress losses in prestressed members. Finally, MOE is necessary when estimating the deflection of members to ensure that serviceability requirements are met. MOE can be determined through laboratory testing, or most often it is estimated based on compressive strength. Regardless of a number of MOE equations were developed for normal-strength and high-strength concrete, it is necessary to develop a new MOE equation which is applicable for UHPC mixtures consisting of various material components.

The objective of this study is to propose a relationship between compressive strength and MOE of UHPC based on the data collected from the literature, and to evaluate the MOE of UHPC mixtures that use locally available materials as a filler material. The replacement of fine sand with natural-gradation sand or fly ash can minimize the UHPC cost, but possibly affect the concrete stiffness. Understanding the effect of these local materials on the behavior of UHPC is a preliminary step to widen the applications of UHPC to different types of concrete structures. It has been expected that the superior mechanical properties of UHPC can extend the service life of concrete structures with a minimal maintenance cost [3].

2. Literature review

A number of equations have been proposed to estimate the MOE of concrete as summarized in Table 1. Since the measurement of the MOE requires specific expertise, a correlation between the MOE (E_c) and compressive strength f'_c has been developed to assist engineers with the design of concrete structures when the MOE test data are not always available. The equation proposed by ACI Committee 318–14 [7] is widely used to estimate the MOE of concrete. However, test data indicates that this equation overestimates the MOE of high-strength concrete [8]. When the compressive strength increases, the MOE also increases, but not at the same rate as normal-strength concrete. Therefore, the ACI Committee 363 [8] proposed a new equation to predict the MOE of high-strength concrete. It has been anticipated that a new equation is necessary for UHPC since the compressive strength of UHPC is larger and the concrete components are different when comparing to high-strength concrete.

Table 1 lists typical MOE equations found in the literature since 2000s. For example, Graybeal [16] developed an equation that is in a similar form to the ACI 318–14 equation based on the test data of four curing regimens: (1) steam at 90 °C and 95% of relative humidity (RH), (2) untreated laboratory control conditions, (3) tempered steam at 60 °C and 95% RH, and (4) delayed steam at 90 °C and 95% RH. This equation was revised when additional data was used to derive the fitting curve [17]. In other words, the accuracy of the proposed equations is dependent on the size of the collected or tested data. In this study, the authors collected relevant test data from the literature to derive a new MOE equation and conduct necessary tests to evaluate its accuracy.

The MOE of the UHPC premix available in current markets varies from 55 to 59 GPa at 28 days of age [3]. Bonneau et al. [18], however, reported a lower MOE of 46 GPa for non-fibered UHPC. The addition of 2.0% of steel fibers by fraction volume increased the MOE by 6%. The MOE is anticipated to be decreased when the fine sand used to develop the UHPC premix is replaced by natural-gradation sand or fly ash. Therefore, the existing equations or reported MOE values may not accurately represent UHPC mixtures containing natural sand or fly ash as a fine material.

In this study, the authors measure the MOE of a number of UHPC mixtures that contain locally available materials and different contents of steel fibers. A new MOE equation is derived from all relevant test data found in the literature to minimize the inaccuracy due to inconsistent sample size. The accuracy of the derived equation is verified based on the measured MOE values.

3. Experimental investigation

3.1. Relationship between compressive strength and modulus of elasticity

Concrete compressive strength has a strong correlation to the MOE. Researchers have proposed a number of equations to represent this correlation as discussed in previous sections. These equations were mainly developed based on the test results of an individual study or combined with the collected data of similar studies. The

Table 1
Proposed MOE equations.

Committee or Researcher(s)	Equation	Note
ACI Committee 318–14 [7]	$E_c = 4,730\sqrt{f'_c}$	Normal-strength concrete $f'_c \leqslant 41.4$ MPa and $1440 \leq \omega \leq 2480$ kg/m^3
ACI Committee 363–10 [8]	$E_c = 3,320\sqrt{f'_c} + 6900$	High-strength concrete, $f'_c \leq 83$ MPa
FIP-CEB [9]	$E_c = 21,500\alpha_\beta\left[\frac{f_{ck}}{8}\right]^{\frac{1}{3}}$	$f'_c < 80$ MPa; α_β is a variable for the aggregate type, f_{ck} is the characteristic compressive strength of 150 × 300 mm cylinders
	$E_c = 21,500\alpha_\beta\left[\frac{f_{cm}}{10}\right]^{\frac{1}{3}}$	$f'_c < 80$ MPa; α_β is a variable for the aggregate type, f_{cm} is the compressive strength at 28 days of 150x300 mm cylinders
Norwegian Standard NS 3473 [10]	$E_c = 9,500(f'_c)^{0.3}$	$25 \leq f'_c \leq 85$ MPa
Ma et al. [11]	$E_c = 19,000(\frac{f'_c}{10})^{\frac{1}{3}}$	UHPC without coarse aggregates, $150 \leq f'_c \leq 180$ MPa
	$E_c = 21,902(\frac{f'_c}{10})^{\frac{1}{3}}$	UHPC with basalt coarse aggregates, $150 \leq f'_c \leq 180$ MPa
Association Française de Génie Civil (AFGC) [12]	$E_c = 9,500(f'_c)^{\frac{1}{3}}$	Heat-cured UHPC, $f'_c \geq 140$ MPa
Sritharan et al. [13]	$E_c = 4,150\sqrt{f'_c}$	UHPC, f'_c = 177 MPa (on average)
Ma and Schneider [14]	$E_c = 16,365\ln(f'_c) - 34,828$	UHPC, $f'_c \geq 140$ MPa
Kollmorgen [15]	$E_c = 11,800(f'_c)^{\frac{1}{3.14}}$	$34 \leq f'_c \leq 207$ MPa
Graybeal [16]	$E_c = 3,840\sqrt{f'_c}$	$126 \leq f'_c \leq 193$ MPa
Graybeal [17]	$E_c = 4,069\sqrt{f'_c}$	$97 \leq f'_c \leq 179$ MPa

Note: f'_c = compressive strength (MPa); E_c = modulus of elasticity (MPa); ω = unit weight of concrete (kg/m^3).

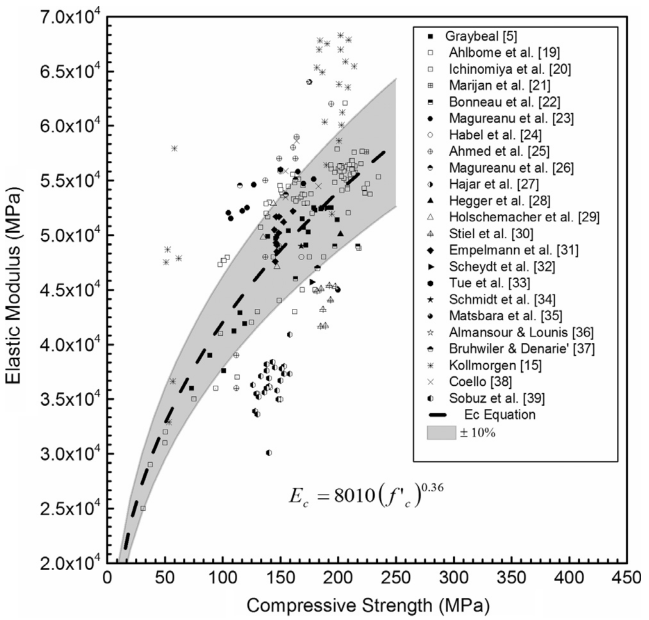

Fig. 1. Relationship between concrete compressive strength and modulus of elasticity.

deviation of the proposed equations depends on the size and diversity of the collected samples. In this study, the authors collected 223 data points of compressive strength and MOE of UHPC from a number of studies in the literature [5,15,19–39]. These data points are summarized in Appendix A. The compressive strength and MOE range from 31 to 235 MPa and 25.0 to 68.3 GPa, respectively. The data points represent the concrete properties at different ages, and the lower bounds represent the properties at early ages. Fig. 1 illustrates the collected data and the best fitting curve that represents the correlation between the compressive strength and the MOE. The best fitting curve is expressed in Eq. (1).

$$E_c = 8,010(f'_c)^{0.36} \quad f'_c \text{ and } E_c \text{ in MPa)} \tag{1}$$

Eq. (1) has a similar form to the ACI 318–14 equation. However, the exponent of 0.36 indicates that the correlation between compressive strength and MOE of UHPC does not follow the same trend as normal-strength or high-strength concrete. This deviation is expected since the microstructure of UHPC is different from normal- and high-strength concrete. For normal- and high-strength concrete, the type and stiffness of coarse aggregates are significant parameters affecting to the MOE [40]. The behavior of the concrete matrix is complex and relies on the interaction between three phases of materials: cement matrix, coarse aggregate, and interfacial transition zone –a weak link between the cement matrix and the coarse aggregate. For UHPC, however, the coarse aggregate is generally excluded, and the interfacial transition zone may not exist in UHPC. The incorporation of steel fibers additionally changes UHPC behavior. All of these factors attribute to differences in the behavior of UHPC from the normal- and high-strength concrete.

The coefficient of determination R^2 of Eq. (1) is 0.37 because of a high scatter of the reported experimental data. Given an error of ±10%, 56% of the data is in the expected range while 24% and 20% of the experimental data is under- and over-estimated, respectively. The use of special curing techniques (e.g., a combination of pressure and heat curing), which dramatically change the UHPC microstructure at the early ages, is the main reason attributing to the under-estimation of the derived equation. The derived equation, however, over-estimates the MOE of several UHPC mixtures that use locally available materials. It should be noted that the over-estimation of the MOE can result in problems when estimating the performance of UHPC structures. For example, the concrete structures may experience a deflection larger than expected, or prestressed concrete structures may experience prestress losses larger than the predicted values using existing codes.

3.2. Materials

For the UHPC developed in this study, the binder consisted of Portland cement (Type I) and condensed silica fume. Two types of fine aggregates were used in the UHPC mixtures as shown in Fig. 2. Fine-1 is the Arkansas River sand that has a natural gradation with 90% of the particles less than 1 mm as illustrated in Fig. 3a. The researchers additionally used Class C fly ash, which had an average particle size less than 75 μm, as the other fine aggregate (Fig. 3b). The fly ash identified as Fine-2 in this study. Fly ash is a by-product from the coal combustion process. The use of fly ash can improve the workability, reduce internal temperatures during hydration process, and enhance the long-term durability of concrete structures. Fly ash reacts with calcium hydroxide, which is the most soluble hydration product and has a negative effect on the concrete mechanical properties [41]. The properties of cement, fly ash, and silica fume are presented in Table 2.

Fig. 2. Two types of fine materials used in the experimental program. Fine-1 is Arkansas River sand, and Fine-2 is Class C fly ash.

Steel fibers used in this study had a diameter of 0.2 mm and a length of 12.7 mm. The steel fibers were incorporated at 2%, 4%, and 6% by fraction volume in the UHPC mixtures to investigate its effect on the compressive strength and MOE. With the given fiber content, UHPC is expected to have high compressive strength and stiffness and a longer linear portion in the stress–strain curve. Hegger and Rauscher [42] indicated that the measured UHPC stress–strain curves are linear up to 90% of the ultimate compressive strength. This property is particularly beneficial in reducing and predicting the deflection of UHPC structures. For example, the MOE of conventional concrete decreases nonlinearly when the compressive stress is larger than 45% of the ultimate compressive strength [40]. For UHPC, the MOE may stay constant until 90% of the ultimate compressive strength, which allows for a better estimate of deflection when compared to the structures cast with conventional concrete.

3.3. UHPC mixture proportions

Sixteen UHPC mixtures were developed and investigated in this study. The mixture proportions are summarized in Table 3. The *w/b* ratio and silica fume replacement are constant in the testing matrix while the binder, steel fibers, HRWRA, and fine aggregates are variables. A 20% replacement of cement by silica fume satisfies the requirement of pozzolanic reactions and packing factor of UHPC mixture proportions [5]. Two binder contents were used. A high binder content is necessary to achieve a high compressive strength by accelerating hydration reactions using heat curing regimen. In the current practice, the typical binder content in UHPC mixture proportions ranges from 1230 to 1422 kg/m^3 [24,43–46]. The binder content can be as high as 1620 kg/m^3 [47]. It was observed that increasing the cement content increased the UHPC compressive strength; however, beyond a cement content of approximately 1700 kg/m^3, the compressive strength tends to decline likely due to limited participation of aggregates [48].

For the last 4 mixtures (Group D in Table 3), class C fly ash (Fine-2) was used as a fine aggregate. A number of advantages can be recognized from this replacement. The use of fly ash can reduce the cost of producing fine sand, which has an average diameter from 150 to 600 μm. Fly ash additionally contributes to reducing the calcium hydroxide content through the pozzolanic reactions. However, fly ash reduces the heat of hydration and consequently affects the strength development at early ages. The use of heat curing can overcome this issue and accelerate the development of compressive strength.

The first 8 mixtures (Groups A and B in Table 3) had the same amount of HRWRA (dosage per 100 kg of binder) to investigate the effect of binder content (from 1365 to 1600 kg/m^3) on compressive strength and MOE. The amount of HRWRA for Group C was higher to increase the concrete flowability. The HRWRA content for last 4 mixtures (Group D), which contained a larger binder content than the first 4 mixtures, was reduced in order to maintain the same flow as the other mixtures.

3.4. Fresh concrete

The concrete was mixed using a laboratory Hobart 19L (20 quart) pan mixer. Cement, fine aggregate, and silica fume were mixed for 10 min, and then water and HRWRA were incrementally introduced to the mixture. Steel fibers were then added slowly to the UHPC. After the fibers were added, the mixing continued for approximately 3 min to ensure that the fibers were well-dispersed. The mixing time was 15 to 20 min for all mixes due to the low *w/b* ratio and high binder content.

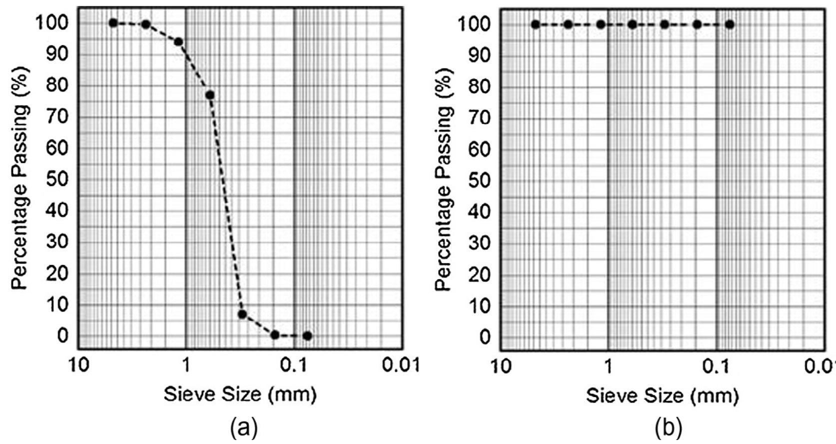

Fig. 3. The gradation of Fine–1 (left) and Fine-2 (right).

The rheology of the UHPC mixtures was evaluated through the flowability of the fresh UHPC mixtures. The flow test was conducted in accordance to ASTM C1437 [49]. This test is proposed for use with the mortar that presents plastic to flowable performance, and therefore, it is generally applicable for the fresh UHPC mixtures [6]. A fresh UHPC mixture was first placed in a short steel cone on an impact table as shown in Fig. 4a. The cone was then lifted off slowly to allow the concrete to flow evenly about the table. The average of the initial diameter D_i of the flow was taken at equally spaced locations. Next, the flow table was dropped 20 times for 20 s that allowed the concrete to settle as shown in Fig. 4b. The average final diameter D_f was recorded. The flow of the fresh UHPC mixture is calculated using Eq. (2).

$$Flow = \left(\frac{D_f - D_i}{D_i}\right) \times 100 \quad (2)$$

3.5. Hardened concrete

Cylindrical specimens, 75 × 150 mm, were cast to measure the compressive strength and MOE. The samples were demolded at 1 day of age, and were then placed into an end-grinder to remove any surface irregularities (Fig. 5a) which was necessary when measuring compressive strength. The cylinders were then heat-cured at 100% relative humidity for five days (Fig. 5b); two days at 60 °C and three days at 90 °C. The graphical cycles for the curing regimen are presented in Fig. 6. The cylinders used to measure the MOE were also sulfur capped to ensure the planeness of the specimens (Fig. 5c) [50]. The authors measured the compressive strength at 6 and 28 days of age. The 6-day and 28-day strengths are almost identical. Hydration reactions begin after casting concrete and are accelerated by the heat-curing regimen for the first 5 days. Therefore, there are no expected reactions after the heat-curing period when the concrete samples were cured in an environmental chamber. In the following sections, the authors simply report the compressive strength and MOE at 28 days of age.

The compressive test was conducted according to ASTM C109 [51]. The applied load rate was 1.0 MPa/s due to the high compressive strength of UHPC [16]. The MOE test was performed according to ASTM C469 [52] with slight adjustments (Fig. 7). Two extensometers were attached to the sample, and two strain measurements were recorded. The average strain from the two extensometers was used in determining the MOE. Three uni-directional strain gauges were attached randomly to several cylinders to compare with the strains obtained from the extensometers. Typical stress–strain curves of the two methods are presented in Appendix B.

4. Experimental results and discussion

4.1. Fresh concrete

The measured flows of the UHPC mixtures are summarized in Table 4. Fig. 8 illustrates the measured flows for the 16 UHPC mixtures. Group A and B had the same amount of HRWRA per 100 kg of binder materials, but the total HRWRA content of group B was higher because of the larger binder content. For a given fiber content, the flow increases when the binder content increases. For example, the flow of groups B and C are 2% and 4% larger than group A, respectively. The possible reason is that the binder lubricates the fine aggregate, and concrete with high cement content shows high cohesiveness.

When comparing the test results of groups B and C, the measured flows slightly increase when the amount of HRWRA increases. For example, the flows of mixtures UHPC-9 and UHPC-12 are 1% and 3% larger than those of mixtures UHPC-5 and UHPC-8, respectively. In fresh UHPC mixtures, HRWRA molecules tend to align themselves around cement particles to form a watery shell. These molecules instruct a strong negative charge that reduces the surface tension of the surrounding water; and therefore enhances the fluidity of the system and reduces the plastic viscosity of the mixture [40].

For a specific group, the measured flows decrease when the fiber content increases (Fig. 8). On average, the use of 2%, 4%, and 6% of steel fibers by fraction volume decreased concrete flowability. The increase in fiber content increases the specific surface area, which produces higher cohesive forces between the fibers and concrete matrix. In addition, the inter-connection of steel fibers within the paste matrix creates a stiff skeleton that inhibits the flowability of the UHPC mixtures [53,54]. These findings are consistent with those stated in the literature. Milan et al. [55] determined that the fiber content affects the workability of UHPC mixtures, in which the measured flows possibly reduce 10% when 4% of steel fibers by fraction volume are incorporated.

When comparing the test results of group B and D, the measured flows decrease due to the use of fly ash as a fine material, regardless of a minor difference in the HRWRA content. For example, the flows of mixtures UHPC-13 and UHPC-16 are 3% less than those of mixtures UHPC-5 and UHPC-8. The use of fly ash increases the surface area within the paste matrix and magnifies the cohesive forces between particles, which leads to a reduction in the measured flows.

4.2. Hardened concrete properties

The compressive strengths and MOE results of UHPC-1 to UHPC-16 are summarized in Table 5. Each value presented in the table is an average of three samples. The measured compressive strengths vary from 124 to 162 MPa, and the MOE ranges from 37 to 46 GPa. These values are lower than the reported results of UHPC premix. In UHPC premix, the use of fine quartz powder (average particle size = 1.7 μm) and ultra-fine sand (average particle size = 0.80 mm) produces a denser cement matrix with a minimum void ratio when comparing to the UHPC mixtures containing local materials [3]. This effect is particularly apparent in the compressive strength and MOE since these mechanical properties directly relate to the solidification of the concrete mixtures.

Table 2
Properties of cement, fly ash, and silica fume.

2a – Cement properties	
Item	Description
Chemical	
SiO_2	20.11%
Al_2O_3	5.07%
Fe_2O_3	3.80%
CaO	64.15
MgO	0.98
SO_3	3.23
Loss on ignition	2.39%
Na_2O	0.18%
K_2O	0.56%
Insoluble Residue	0.40%
CO_2	1.09%
Limestone	2.80%
$CaCO_3$	88.23%
Potential compounds	
C_3S	55%
C_2S	14%
C_3A	7%
C_4AF	11%
C_3S+4.75 C_3A	88%
Physical	
Air content of mortar (volume)	8%
Fineness	4.5 m^2/g
Autoclave expansion	−0.01%
Mortar Bar Expansion	0.00%
Specific gravity	3.15
2b – Fly ash properties	
Item	Description
SiO_2	36.73%
Al_2O_3	21.49
Fe_2O_3	5.68%
CaO	22.70%
Na_2O	1.48%
K_2O	0.57%
MgO	4.30%
∑Oxides	63.90%
∑Alkalis	29.05%
Specific gravity	2.5
2c – Silica fume properties	
Item	Description
Chemical	
SiO_2	95.25%
SO_3	0.08%
Cl	0.11%
Total Alkali	0.42%
Moisture Content	0.52%
Loss on Ignition	1.88%
pH	8.06%
Physical	
% retained on 45 μm sieve (wet sieved)	0.49%
Density - (specific gravity)	2.24
Bulk Density - (per ASTM)	696.71 kg/m^3
Specific Surface Area	24.49 m^2/g
Accelerated Pozzolanic Activity Index - with Portland Cement	124.44%

Fig. 9 illustrates the test results presented in Table 5. For all groups, the use of 2% of steel fibers has a minimal effect on compressive strength and MOE. On average, the compressive strength increases from 1 to 8% while the MOE increases from 3 to 7%. Similar results are obtained for a fiber content of 4%. These results confirm the findings in the literature. It has been reported that steel fibers affect tensile strength while it is insignificant to the compressive strength [23,42,56]. When a concrete matrix is subjected to tensile stresses, steel fibers effectively prevent the propagation of micro-cracks and transfer the stresses across the cracks. With a higher fiber content of 6%, the compressive strength and MOE are improved by 8–20% and 6–15%, respectively. However, steel fiber content is one of the main contributors to UHPC cost. Therefore, a large amount of steel fibers (≥4% by fraction volume) is used for special requirements for concrete toughness but seldom for concrete stiffness. In the current practice, a fiber content of 2.5% is generally recommended to reduce the brittleness and increase the ductility of UHPC structures [3,16].

In comparison to group A, the binder of group B was increased from 1365 to 1600 kg/m^3 to evaluate the effect of binder content on concrete properties. As shown in Fig. 9, the increase in binder content has minimal effect on compressive strength. In UHPC mixture, the water-cement ratio is low, and the mixing water is usually lower than the amount necessary for complete hydration. Therefore, a portion of binder gets hydrated that produces calcium silicate hydrate (C-S-H) –the main contributor to compressive strength. The un-hydrated binder cement particles serve as a filler material in the hardened concrete matrix. The MOE of group B, however, is slightly lower than group A. For the UHPC mixtures containing a higher binder content, the sand content is lower. In the hardened UHPC matrix, sand particles act as a skeleton that has a larger stiffness than the hardened cement matrix. Under compressive stress, this sand skeleton restrains the deformation of the concrete matrix, which results in the improved MOE of group A [57].

When comparing the test results of groups B and C, the increase in HRWRA has a negative effect on the compressive strength and minimal effect on the MOE. For example, the compressive strength of mixture UHPC-11 is 11% lower the UHPC-7. The increase in HRWRA increases the porosity of the hardened concrete matrix. The HRWRA used in this study contains 50% of water. Therefore, while HRWRA reduces the surface tension of water, which increases the concrete flowability as discussed previously, HRWRA also increases the water content in the UHPC mixture proportions. In addition, HRWRA generally tends to add entrained air during mixing process, which also increases to the porosity of the concrete mixtures [58]. According to the manufacture of the HRWRA used in this research, it adds approximately 2% of air compared to the mixture without HRWRA.

The behavior of UHPC mixtures containing fly ash as a fine material is possibly different from those containing natural sand. Technically, chemical reactions between the aggregate particles and cement matrix are not expected. Fly ash, however, engages in a number of pozzolanic reactions with cement hydration products, typically with calcium hydroxide and additionally generates C-S-H. The secondary C-S-H can strengthen the concrete matrix and improve the compressive strength and MOE, while the primary C-S-H generated during the cement hydration process is the main contributor to these concrete properties. However, the experimental results of groups B and D indicate that the use of fly ash as a fine material in the UHPC mixture proportions has no effect on compressive strength and MOE. The test results of mixtures UHPC-13 to 15 are almost identical to mixtures UHPC-5 to 7. These results are a combination of two phenomena. The compressive strength and MOE of group D is improved because of the strengthening of the secondary C-S-H. However, the remaining un-hydrated fly ash particles possibly lessen the positive effect of the secondary C-S-H. The amount of the un-hydrated fly ash depends on the amount of generated calcium hydroxide from the hydration process of cement. In the UHPC mixture proportions, the amount of calcium hydroxide is limited since the entire cement content is not involved in the hydration process as discussed previously. In summary, the use of a large volume of fly ash in a UHPC mixture

Table 3
UHPC mixture proportions.

Mixture	Binder (kg/m^3)	*w/b*	Silica Fume (%) by Mass of Binder	Steel fiber (%)	HRWRA (kg/m^3)	Fine Aggregate	Aggregate (kg/m^3)	Group
UHPC-1	1365	0.2	20	0	30.26	Fine-1	647	A
UHPC-2	1365	0.2	20	2	30.26	Fine-1	647	
UHPC-3	1365	0.2	20	4	30.26	Fine-1	647	
UHPC-4	1365	0.2	20	6	30.26	Fine-1	647	
UHPC-5	1600	0.2	20	0	38.22	Fine-1	310	B
UHPC-6	1600	0.2	20	2	38.22	Fine-1	310	
UHPC-7	1600	0.2	20	4	38.22	Fine-1	310	
UHPC-8	1600	0.2	20	6	38.22	Fine-1	310	
UHPC-9	1600	0.2	20	0	77.22	Fine-1	310	C
UHPC-10	1600	0.2	20	2	77.22	Fine-1	310	
UHPC-11	1600	0.2	20	4	77.22	Fine-1	310	
UHPC-12	1600	0.2	20	6	77.22	Fine-1	310	
UHPC-13	1600	0.2	20	0	35.37	Fine-2	292	D
UHPC-14	1600	0.2	20	2	35.37	Fine-2	292	
UHPC-15	1600	0.2	20	4	35.37	Fine-2	292	
UHPC-16	1600	0.2	20	6	35.37	Fine-2	292	

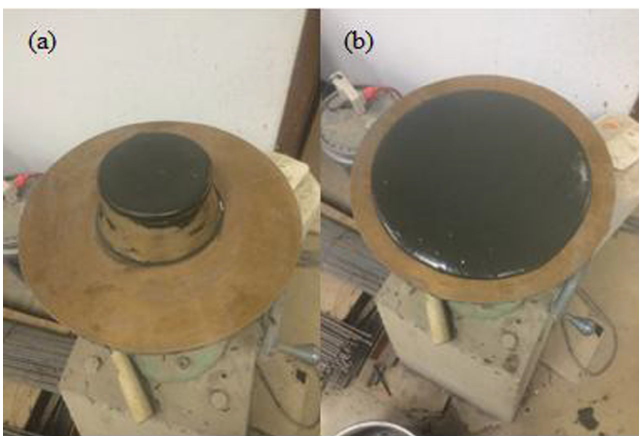

Fig. 4. Flow test.

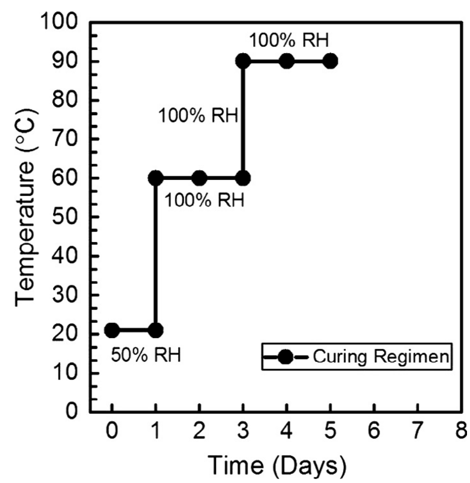

Fig. 6. Curing regimen cycle. (Note: RH = relative humidity).

proportions has minimal effect on the compressive strength and MOE.

4.3. Validation of proposed equation

Fig. 10 plots the proposed equation with an error of ±10% and experimental data achieved in this study. About 31% of the data are within the limits. This result indicates the over-estimation of the proposed MOE equation for the UHPC mixtures containing local materials in this study. The use of local materials can weaken the microstructure of the UHPC mixtures. In this study, natural sand was used in the UHPC mixture proportions without any kind of pretreatment or washing. Therefore, the concrete matrix may contain soft particles and different minerals on the

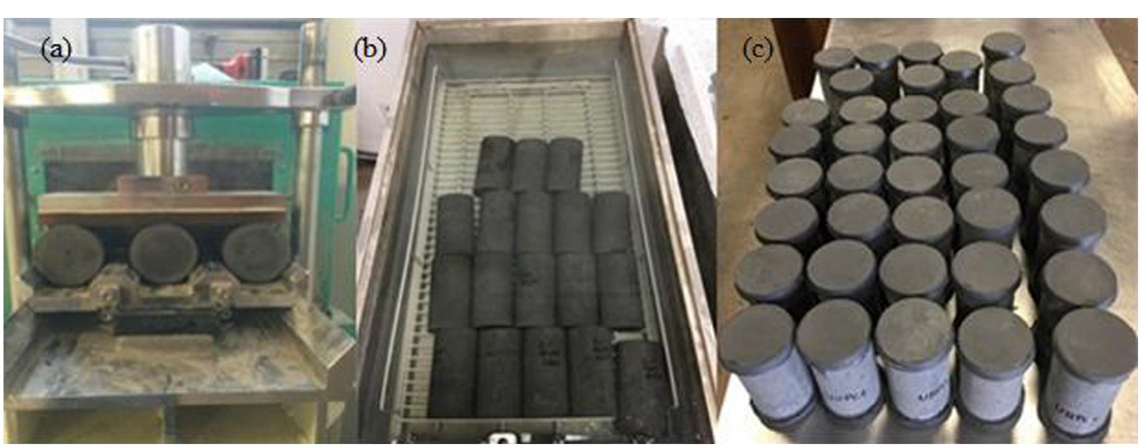

Fig. 5. The end-grinding machine (5a), water bath (5 b), and the sulfur capped cylinders (5c).

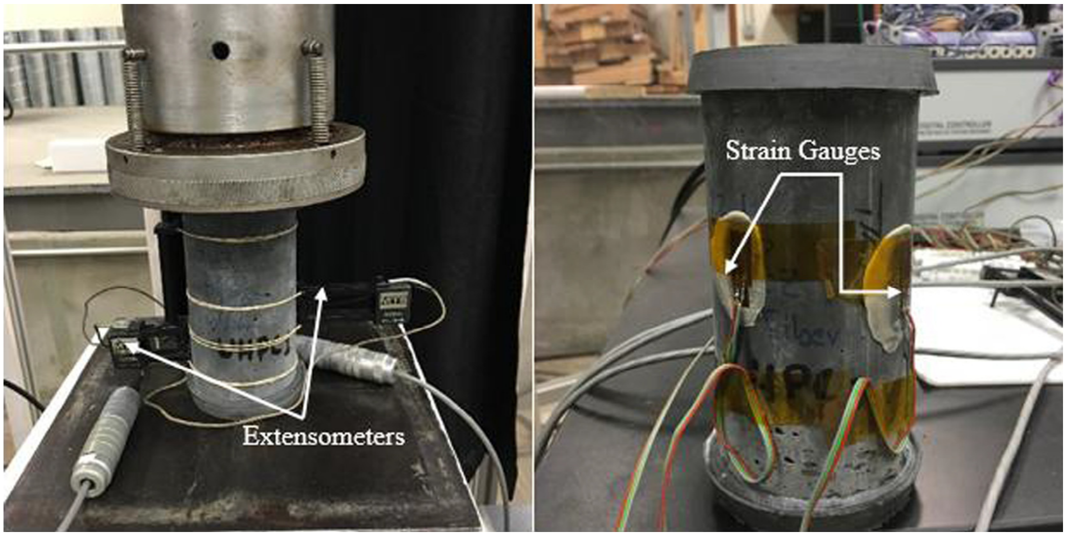

Fig. 7. Modulus of elasticity test procedure.

Table 4
Measured flows of UHPC mixtures.

Mixture	Initial Diameter D_i (mm)	Final Diameter D_f (mm)	Flow (%)	Group
UHPC-1	165	195	18	A
UHPC-2	160	185	16	
UHPC-3	155	175	13	
UHPC-4	155	170	10	
UHPC-5	175	210	20	B
UHPC-6	170	200	18	
UHPC-7	170	195	15	
UHPC-8	165	185	12	
UHPC-9	190	230	21	C
UHPC-10	185	220	19	
UHPC-11	180	210	17	
UHPC-12	170	195	15	
UHPC-13	175	205	17	D
UHPC-14	175	200	14	
UHPC-15	175	195	11	
UHPC-16	165	180	9	

Table 5
Measured compressive strength and modulus of elasticity.

Mixture	Compressive strength (MPa)	Modulus of elasticity (GPa)	Group
UHPC-1	136.4	43.4	A
UHPC-2	137.9	44.5	
UHPC-3	140.8	45.9	
UHPC-4	155.3	45.9	
UHPC-5	135.0	37.6	B
UHPC-6	135.9	40.3	
UHPC-7	143.2	41.0	
UHPC-8	145.7	43.4	
UHPC-9	124.1	37.2	C
UHPC-10	128.3	37.9	
UHPC-11	127.6	40.0	
UHPC-12	144.1	42.7	
UHPC-13	135.5	36.9	D
UHPC-14	146.8	38.3	
UHPC-15	144.7	39.3	
UHPC-16	162.4	43.1	

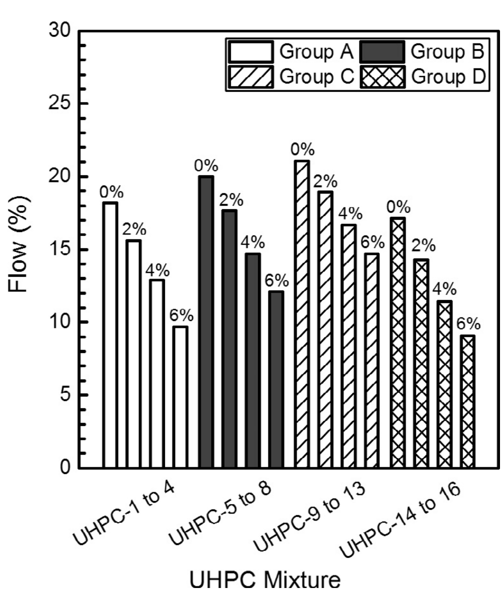

Fig. 8. Measured flows of 4 UHPC groups. (Note: The values above columns indicate the steel fiber content).

particle's surface, which creates weak links in the matrix. When concrete is subjected to tensile stresses, cracks tend to form at the weak links and propagate to adjacent regions that reduce concrete stiffness. The sand used in premix UHPC generally contains less soft particles and minerals than the natural sand. In addition, the premix sand has smaller particle sizes, which scatters possible weak links and delays the interconnection of cracks when the concrete resists external tensile stresses. Therefore, the measured MOE of premix UHPC is larger than the mixtures containing local materials.

In this study, there is no proposed equation for the modulus of elasticity of UHPC containing local materials. The achieved experimental data distribute in a limit range, which does not warrant the reliability of the proposed equation. Therefore, the authors used two typical equations proposed by Ma et al. [11] and Graybeal [16] to verify the experimental data. Fig. 10 also shows the overestimation of these equations. About 69% of data points are in the lower region of the curves. These data show a trend similar to those reported by Sobuz et al. [39]. The use of conventional materials for developing mixture proportions in Sobuz et al.'s study possibly attribute to this similarity.

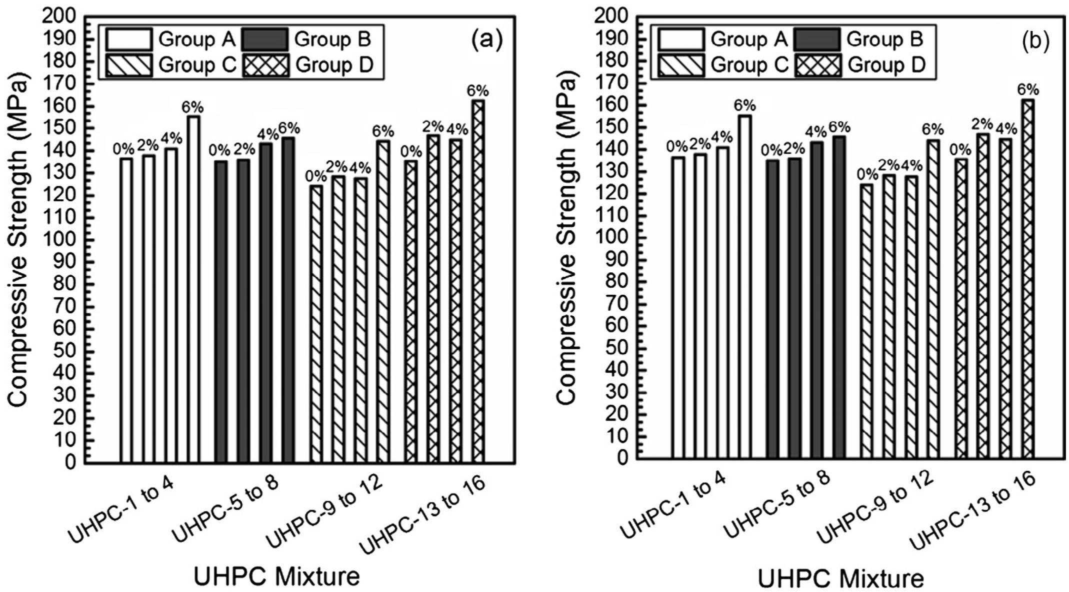

Fig. 9. Measured compressive strengths and elastic modulus. (Note: The values above columns indicate the steel fiber content).

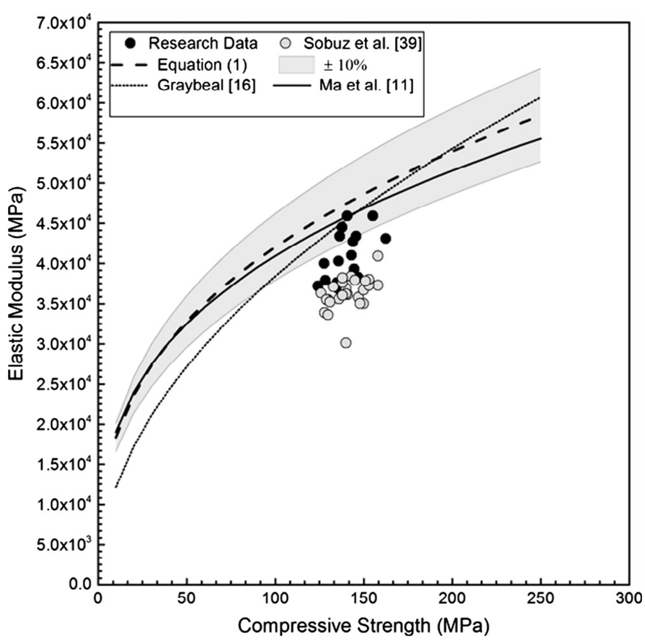

Fig. 10. Modulus of Elasticity and Compressive Strength Relationship.

5. Conclusions

Based on the results of this experimental investigation, the following conclusions are drawn:

- A new equation is proposed to predict the MOE of UHPC. With an error of ±10%, the proposed equation provides a reasonable prediction for the relevant data found in the literature.
- Steel fiber content affects the flowability of the fresh UHPC mixtures. The flows decrease by about 2% as a fiber content increases of 2%. When fly ash is used as a natural fine material, the flowability decreases when compared to mixtures containing natural sand.
- The use of natural sand or fly ash can reduce the MOE when comparing to a UHPC premix. The proposed equation overestimates the measured MOE for the UHPC mixtures using local materials in this study.
- The use of fly ash as a fine material has little effect on compressive strength and modulus of elasticity at 28 days of age in comparison to natural sand.

Acknowledgments

This research is supported by the University of Arkansas at Fayetteville, Ton Duc Thang University, and The Higher Committee for Education Development in Iraq (HCED). The authors are thank-

Table A1
Collected concrete compressive strengths and modulus of elasticity.

Author(s)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)
Graybeal [5]	169	51.5
	179	52.5
	180	52.3
	186	52.5
	185	52.4
	193	52.5
	199	51.4
	194	52.5
	73	36.0
	89	39.0
	101	37.6
	110	41.2
	119	41.9
	125	42.0
	139	49.9
	146	49.7
	147	49.9
	157	50.4
	115	42.9
	174	50.3
	170	50.7
	172	49.1

(continued on next page)

Table A1 (*continued*)

Author(s)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)
Michigan Tech [19]	98	47.3
	101	47.7
	104	48.0
	101	47.7
	141	53.0
	139	51.7
	138	52.9
	138	52.0
	133	50.7
	152	53.6
	157	54.5
	150	54.5
	152	53.9
	150	54.1
	162	54.8
	170	54.5
	161	53.3
	161	55.6
	166	55.1
	165	53.4
	168	53.5
	176	53.8
	169	53.7
	177	52.0
	171	52.9
	174	52.9
	164	53.1
	210	55.5
	215	55.7
	208	54.3
	197	54.8
	211	56.2
	212	56.8
	208	56.4
	221	57.7
	207	56.2
	194	56.1
	200	56.1
	214	57.6
	214	56.3
	213	55.7
	212	56.0
	214	55.5
	220	56.5
	213	55.6
	228	53.8
	203	54.1
	208	54.2
	225	54.7
	235	55.3
	206	62.1
	205	55.9
	197	55.7
	199	57.9
	212	56.4
	212	56.1
	210	56.4
	203	56.4
	201	55.8
	203	56.2
	210	56.1
	212	56.8
	171	53.7
	223	53.8
	223	54.3
	209	52.0
	207	55.0
	194	56.4
	212	56.0
	201	56.3
	205	55.2
	203	55.4
Ichinomiya et al. [20]	31	25.0
	38	29.0
	50	31.0
	50	32.0
	75	35.0
	94	36.0
	98	41.0
	112	37.0
	125	42.0
	130	43.0
	144	48.0
	149	44.0
	162	43.0
	169	45.0
	175	48.0
	180	45
	188	48
Marijan et al. [21]	218	49
	224	58
Bonneau et al. [22]	163	46
	217	49
	197	49
Magureanu et al. [23]	121	53
	105	52
	117	52
	107	52
	179	55
	170	55
	165	56
	127	55
Habel et al. [24]	168	48
Ahmed et al. [25]	149	49
	137	48
	112	36
	149	57
	137	55
	112	39
	163	57
	164	59
	161	58
	194	62
Magureanu et al. [26]	163	55
	155	54
	150	56
	115	55
Hajar et al. [27]	175	64
Hegger et al. [28]	202	50
Holschemacher et al. [29]	135	50
	147	47
	144	53
Stiel et al. [30]	192	45
	193	44
	197	45
	185	42
	185	45
	187	43
	182	45
	189	42
Empelmann et al. [31]	161	52
	146	49
	145	51
	146	52
	149	52
	148	50
	147	49
	147	49
	153	51
	146	48
Scheydt et al. [32]	190	53
	177	46
Tue et al. [33]	150	56

Table A1 (*continued*)

Author(s)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)
Schmidt et al. [34]	168	49
Matsbara et al. [35]	200	45
Almansour and Lounis [36]	175	64
Bruhwiler and Denarie' [37]	182	47
Kollmorgen [15]	57	37
	58	58
	53	33
	51	48
	62	48
	52	49
	186	65
	188	60
	202	68
	201	64
	214	65
	190	56
	184	68
	209	68
	194	52
	201	59
	190	68
	203	60
	183	67
	181	65
	203	61
	208	64
	206	66
	202	67
Coello [38]	183	54
	164	59
	154	56
	154	53
Sobuz [39]	141	36
	147	36
	150	35
	140	30
	148	35
	158	37
	143	38
	140	37
	140	36
	136	36
	150	37
	158	41
	153	37
	153	38
	138	38
	151	38
	145	38
	126	36
	130	36
	128	34
	129	36
	130	34
	131	35
	133	37
	138	36
	138	38

ful to Griffith, F., Deschenes, R., and Casillas, B. for their help during the experimental program. The first author is thankful for Mr. Adnan Alsalman for his engorgement.

Appendix A

Table A1

Appendix B

Figs. B1 and B1

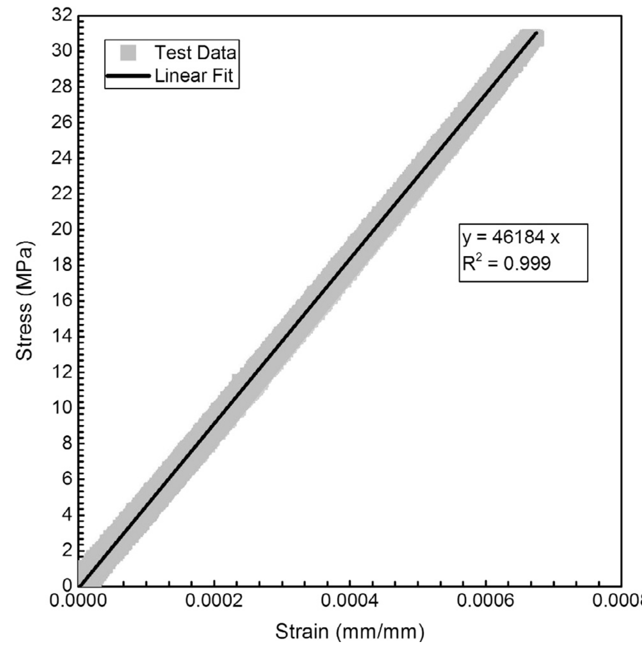

Fig. B1. Stress–strain curve for UHPC-3 with two extensometers.

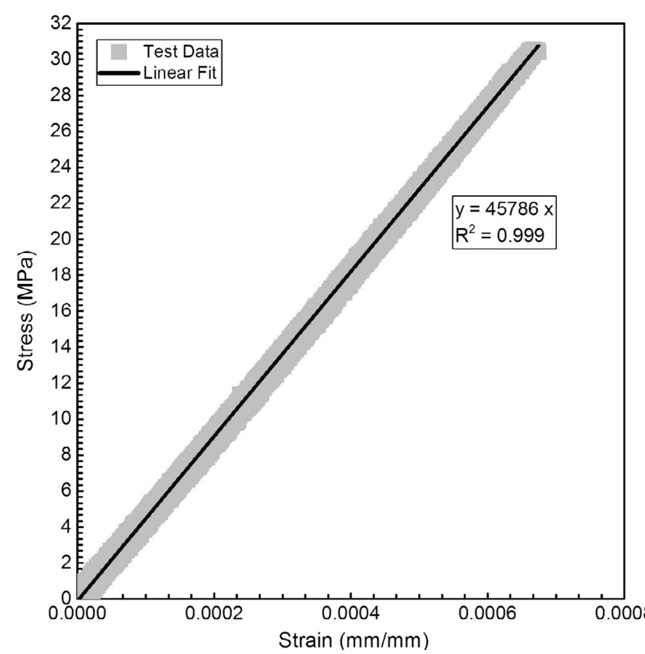

Fig. B2. Stress–strain curve for UHPC-3 with three uni-directional strain gauges.

References

[1] K. Wille, A. Naaman, Ultra-high performance concrete and fiber reinforced concrete: achieving strength and ductility without heat curing, Mater. Struct. 45 (3) (2012) 309–324.
[2] B. Graybeal, "Ultra-High Performance Concrete," TechNote, FHWA-HRT-11-038, Federal Highway Administration, McLean, VA, 2011, 1 pp.
[3] B. Graybeal, "Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community," FHWA-HRT-13-060, 2013, 1, 4, 5, pp. 19.
[4] C. Tang, "High Performance Concrete – Past, Present and Future," in: Proceedings of the 1st International Symposium on Ultra-High Performance Concrete, Kassel, Germany, 2004, pp. 3 – 9.
[5] B. Graybeal, "Material Property Characterization of Ultra-High Performance Concrete," FHWA-HRT-06-103, Federal Highway Administration, Washington, DC, 2006, 3, 35, 36 pp.

[6] B. Graybeal, "Development of Non-Proprietary Ultra-High Performance Concrete for Use in the Highway Bridge Sector," FHWA-HRT-13-100, Federal Highway Administration, McLean, VA 2013, 2, 4 pp.
[7] Building Code Requirements for Structural Concrete (ACI 318-14) "Commentary on Building Code Requirements for Structural Concrete (ACI 318R-14)," Farmington Hills, MI, 317 pp.
[8] ACI Committee 363, "Report on High-Strength Concrete (ACI 363R – 10)," ACI, Farmington Hills, MI, 27 pp.
[9] FIP-CEB, 1990, "High Strength Concrete: State-of-the-Art Report," Bulletin d'Information No. 197, Lausanne, Switzerland, 91 pp.
[10] Norges Standardiseringsfund, 1992, "Concrete Structures—Design Rules," NS 3473, Oslo, Norway.
[11] J. Ma, F. Dehn, N.V. Tue, M. Orgass, D. Schmidt, "Comparative Investigations on Ultra-High Performance Concrete with and without Coarse Aggregates," in: Proceedings of the 1st International Symposium on Ultra-High Performance Concrete, Kassel, Germany, 2004, pp. 205 – 212.
[12] SETRA (Service d'études techniques des routes et autoroutes), and AFGC (Association Française de Génie Civil), "Ultra High Performance Fiber – Reinforced Concretes- Interim Recommendations," (Bétons Fibrés à Ultra-Hautes Performacnes – Recommandations Provisoires), France, 2002.
[13] S. Sritharan, B.J. Bristow, V.H. Perry, Characterizing an ultra high performance material for bridge applications under extreme loads, 3rd International Symposium on High Performance Concrete, PCI, Orlando, Florida, 2003.
[14] J. Ma, H. Schneider, Properties of ultra-high-performance concrete, LACER 7 (2002) 25–32.
[15] G.A. Kollmorgen, Impact of Age and Size on the Mechanical Behavior of an Ultra High Performance Concrete (Unpublished master's thesis), 2004.
[16] B. Graybeal, Compressive behavior of ultra-high-performance fiber-reinforced concrete, ACI Mater. J. 104 (2) (2007) 146–152.
[17] A.B. Graybeal, "Compression Response of a Rapid-Strengthening Ultra-High Performance Concrete Formulation," FHWA-HRT-12-064, Federal Highway Administration, 2012, 6 pp.
[18] O. Bonneau, C. Poulin, J. Dugat, P. Richard, P.C. Aïtcin, Reactive powder concretes: from theory to practice, Concr. Int. 18 (4) (1996) 47–49.
[19] Center for Structural Durability Michigan Tech Transportation Institute, "Ultra High Performance Concrete for Michigan Bridges Material Performance – Phase I Final Report," 2008, Appendix A.
[20] T. Ichinomiya, Y. Hishiki, T. Ohno, Y. Morita, K. Takada, "Experimental Study on Mechanical Properties of Ultra-High-Strength Concrete with Low-Autogenous-Shrinkage," in: Seventh International Symposium on the Utilization of High-Strength/High-Performance Concrete, V. II, Publication No. SP-228, Ed., Russell, H.G., ACI, Farmington Hills, MI, 2005, pp. 1341 – 1352.
[21] S. Marijan, B. Dubravka, S. Zeljana, "Acoustic Emission Response and Mechanical Characterization of Ultra High-Performance Concrete Types," in: Seventh International Symposium on the Utilization of High-Strength/High-Performance Concrete, V. II, Publication No. SP-228, Ed., Russell, H.G., ACI, Farmington Hills, MI, 2005, pp. 1207–1220.
[22] O. Bonneau, M. Lachemi, D. Dallaire, J. Dugat, P.C. Aitcin, Mechanical properties and durability of two industrial reactive powder concretes, ACI Mater. J. 94 (4) (1997) 286–290.
[23] C. Magureanu, I. Sosa, C. Negrutiu, B. Heghes, Mechanical properties and durability of ultra-high-performance concrete, ACI Mater. J. 109 (2) (2012) 177–183.
[24] K. Habel, E. Denarié, E. Brühwiler, Experimental investigation of composite ultra-high-performance fiber-reinforced concrete and conventional concrete members, ACI Structural Journal 104 (1) (2007) 93–101.
[25] S. Ahmad, A. Hakeem, A. Azad, Effect of curing, fiber content and exposures on compressive strength and elasticity of UHPC, Adv. Cem. Res. 27 (4) (2015) 233–239.
[26] C. Magureanu, I. Sosa, C. Negrutiu, B. Heghes, "Physical and mechanical properties of ultra-high strength fiber reinforced cementitious composites," in: Proceedings of FraMCoS-7, 2010, pp. 23-28.
[27] Z. Hajar, A. Simon, D. Lecointre, J. Petitjean, "Design and Construction of the world first Ultra-High Performance Concrete road bridges," in: Proceedings of the 1st International Symposium on Ultra High Performance Concrete, Kassel, Germany, pp. 39 – 48.
[28] J. Hegger, B. Kommer, D. Tunchlinski, "Bond Anchorage Behavior and Shear Capacity of Ultra High Performance Concrete Beams," in: Proceedings of the 1st International Symposium on Ultra High Performance Concrete, Kassel, Germany, 2004, pp. 351 – 360.
[29] K. Holschemacher, D. Weiße, S. Klotz, "Bond of Reinforcement in Ultra High Strength Concrete," in: Proceedings of the 1st International Symposium on Ultra High Performance Concrete, Kassel, Germany, 2004, pp. 375 – 388.
[30] T. Stiel, E. Fehling, B. Karihaloo, "Effect of Casting Direction on the Mechanical Properties of CARDIFRC®," in: Proceedings of the 1st International Symposium on Ultra High Performance Concrete, Kassel, Germany, 2004, pp. 481 – 493.
[31] M. Empelmann, G. Steven, M. Teutsch, "Improvement of the post fracture behavior of UHPC by fibers," in: Proceedings of the 2nd International Symposium on Ultra High Performance Concrete, Kassel, Germany, 2008, pp. 177 – 184.
[32] J. Scheydt, H. Müller, G. Herold, "Long term behavior of Ultra High Performance Concrete under the attack of Chlorides and Aggressive Waters," in: Proceedings of the 2nd International Symposium on Ultra High Performance Concrete, Kassel, Germany, 2008, pp. 231 – 239.
[33] N. Tue, M. Küchler, "Load and Deformation Behavior of Confined Ultra High Performance Concrete Dowels," in: Proceedings of the 2nd International Symposium on Ultra High Performance Concrete, Kassel, Germany, pp. 553 – 560.
[34] C. Schmidt, S. Reiddl, "Strengthening and Rehabilitation of Pavements Applying Thin Layers of Reinforced Ultra- High Performance Concrete (UHPC-White topping)," in: Proceedings of the 2nd International Symposium on Ultra High Performance Concrete, Kassel, Germany, pp. 655 – 662.
[35] N. Matsubara, G. Sakai, S. Ishii, T. Ohno, Y. Watanabe, M. Ashida, "Application of a New Type of Ultra-High Strength Fiber Reinforced Concrete to a Prestressed Concrete Bridge," in: Second International Symposium on Ultra High Performance Concrete, Kassel, Germany, pp. 787 – 794.
[36] H. Almansour, Z. Lounis, "Structural performance of precast prestressed bridge girders built with Ultra High Performance Concrete," in: Proceedings of the 2nd International Symposium on Ultra High Performance Concrete, Kassel, Germany, pp. 823 – 830.
[37] E. Bruhwiler, Denariĕ, "Rehabilitation of concrete structures using Ultra- High Performance Fiber Reinforced Concrete.," in: Proceedings of the 2nd International Symposium on Ultra High Performance Concrete, Kassel, Germany, pp. 895 – 902.
[38] E.D. Ruiz Coello. "Prestress Losses and Development Length in Pretensioned Ultra High Performance Concrete Beams," Ph.D. Dissertation in Civil Engineering, University of Arkansas, 2007.
[39] H.R. Sobuz, P. Visintin, M.S. Mohamed Ali, M. Singh, M.C. Griffith, A.H. Sheikh, "Manufacturing Ultra-High Performance Concrete Utilizing Conventional Materials and Production Methods," Construction and Building Materials, 111, pp. 251 – 261.
[40] P.K. Mehta, P.J.M. Monteiro, Concrete Microstructure, Properties, and Materials, The McGraw-Hill Companies, Inc., New York, NY, 2006. 86, 93, 288 p..
[41] T. Naik, B. Ramme, R. Kraus, R. Siddique, Long-term performance of high-volume fly ash concrete pavements, ACI Mater. J. 100 (2) (2003) 150–155.
[42] J. Hegger, S. Rauscher, "UHPC in Composite Construction," in: Proceedings of the 2nd International Symposium on Ultra High-Performance Concrete, Kassel, Germany, 2008, pp. 545 – 552.
[43] B. Graybeal, M. Davis, Cylinder or Cube: strength testing of 80 to 200 MPa (11.6 to 29 ksi) ultra-high-performance fiber-reinforced concrete, ACI Mater. J. 105 (6) (2008) 603–609.
[44] M. Reda, N. Shrive, J. Gillott, Microstructural investigation of innovative UHPC, Cem. Concr. Res. 29 (1999) 323–329.
[45] P.S. Ambily, C. Umarani, K. Ravisankar, Prabhat Ranjan Prem, B.H. Bharatkumar, Nagesh R. Iyer, Studies on Ultra high performance concrete incorporating copper slag as fine aggregate, Constr. Build. Mater. 77 (2015) 233–240.
[46] P. Rossi, A. Arcab, E. Paranta, P. Fakhri, Bending and compressive behaviors of a new cement composite, Cem. Concr. Res. 35 (1) (2005) 27–33.
[47] P. Richard, M. Cheyrez, Composition of Reactive Powder Concretes, Cem. Concr. Res. 25 (7) (1995) 1501–1511.
[48] I. Talebinejad, A. Iranmanesh, S. Bassam, M. Shekarchizadeh, "Optimizing mix proportions of normal weight reactive powder concrete with strengths of 200–350 MPa," in: Proceedings of the 1st International Symposium on UHPC, Kassel, Germany, 2004, pp. 133–141.
[49] ASTM C1437, "Standard Test Method for Flow of Hydraulic Cement Mortar," American Society for Testing and Materials Standard Practice C1437, Philadelphia, PA, 2015.
[50] ASTM C617/C617M-15, "Standard Practice for Capping Cylindrical Concrete Specimens," American Society for Testing and Materials Standard Practice C617, Philadelphia, PA, 2015.
[51] ASTM C39/C39M-10, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2010.
[52] ASTM C 469, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression", 2002.
[53] Z. Wua, C. Shia, W. Hea, L. Wu, Effects of steel fiber content and shape on mechanical properties of ultra-high performance concrete, Constr. Build. Mater. 103 (2016) 8–14.
[54] R. Yu, P. Spiesz, H.J.H. Brouwers, Mix design and properties assessment of Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC), Cem. Concr. Res. 56 (2014) 29–39.
[55] R. Milan, B. Tomáš, K. Jiří, "Impact of steel fibers on workability and properties of UHPC", Diff. Defect Data Pt B Solid State Phenomena J. 249 (2016) 57–61.
[56] S. Kazemi, A.S. Lubell, Influence of specimen size and fiber content on mechanical properties of ultra-high-performance fiber-reinforced concrete, ACI Mater. J. 109 (6) (2012) 657–684.
[57] S. Harsh, Z. Shen, D. Darwin, Strain-rate sensitive behavior of cement paste and mortar in compression, ACI Mater. J. 87 (5) (1990) 508–516.
[58] Y. Yamamoto, S. Kobayashi, Effect of temperature on the properties of superplasticized concrete, ACI J. 83 (1) (1986) 80–87.