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

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 $1440 \le \omega \le 2480$ kg/m^3
ACI Committee 363–10 [8]	$E_c = 3,320\sqrt{f'_c} + 6900$	High-strength concrete, $f'_c \le 83$ 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]	$E_c = 9,500(f'_c)^{0.3}$	$25 \le f'_c \le 85$ MPa
Ma et al. [11]	$E_c = 19,000(\frac{f'_c}{10})^{\frac{1}{3}}$	UHPC without coarse aggregates, $150 \le f'_c \le 180$ MPa
	$E_c = 21,902(\frac{f'_c}{10})^{\frac{1}{3}}$	UHPC with basalt coarse aggregates, $150 \le f'_c \le 180$ MPa
Association Française de Génie Civil (AFGC) [12]	$E_c = 9,500(f'_c)^{\frac{1}{3}}$	Heat-cured UHPC, $f'_c \ge 140$ 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, $f'_c \ge 140$ MPa
Kollmorgen [15]	$E_c = 11,800(f'_c)^{\frac{1}{3.14}}$	$34 \le f'_c \le 207$ MPa
Graybeal [16]	$E_c = 3,840\sqrt{f'_c}$	$126 \le f'_c \le 193$ MPa
Graybeal [17]	$E_c = 4,069\sqrt{f'_c}$	$97 \le f'_c \le 179$ MPa

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