Empirical Models for Modulus of Elasticity of HSC Considering the Effect of In Situ Curing Conditions

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Abstract: This paper aims to predict the modulus of elasticity E_c of high-strength concrete (HSC) under different in situ curing conditions. Because of the effect of the hydration temperature and the curing condition, the E_c value of HSC measured on moist-cured specimens may not be able to sufficiently represent that of HSC in structures and precast concrete components. This issue is not adequately taken into account in current codes of practice. Equations based on moist-cured specimens may result in a large discrepancy when used to estimate the in situ E_c of HSC. In this study, measured E_c of HSC on member-cured, temperature match–cured, on-site-cured specimens, and drilled cores from large structural members are gathered. The accuracy of selected equations is investigated using the collected data. Based on the investigations, new empirical relations for estimating the E_c of HSC considering the effect of the in situ curing conditions are proposed. **DOI: 10.1061/(ASCE)MT.1943-5533.0000950.**

Author keywords: High-strength concrete (HSC); Modulus of elasticity; In situ curing condition.

Introduction

A number of empirical equations for estimating the modulus of elasticity E_c of high-strength concrete (HSC) are available, such as in Mokhtarzadeh and French (2000). In current codes of practice, empirical equations for the E_c of HSC are recommended for design purposes. Most of the existing equations were derived based on the measured E_c on moist-cured specimens.

Because the temperature profiles and humidity within a member and structure can differ greatly from the standard moist conditions, the HSC in structures and precast components is subjected to a distinct curing condition in comparison with moist-cured specimens. Many tests (e.g., Burg and Ost 1994; Cetin 1995; Mokhtarzadeh and French 2000) have shown that the curing condition in HSC, especially in the early stages, has a considerable influence on its strength and E_c. The effect of the curing condition on the development of the E_c of HSC was recently highlighted by ACI Committee 363 (2010).

Because of the influence of the curing condition that is associated with changes in hydration temperature, moist-cured specimens cannot adequately represent the in situ HSC. Therefore, equations based on moisture-cured specimens may not be applicable for estimating the in situ E_c of HSC. The main objectives of this paper are (1) to find out the effect of the in situ curing condition on the E_c of HSC by collecting available test data on the compressive strength f'_c and E_c in the literature; (2) to evaluate the applicability of selected code relations for describing the time effects and predicting the magnitude of the in situ E_c of HSC; and (3) to select and/or develop equations that can predict the in situ E_c of HSC with more reasonable accuracy considering the effect of the curing condition.

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Database Collection

Over 200 test data for the in situ E_c of HSC were collected. The details of the data are presented in Table 1. The data were measured according to four types of specimens:

1. Member-cured specimens, which are cast in precast plants during concrete placement for producing members and then stored continuously alongside the members on the cast bed until test. These specimens are intended to represent the concrete in members by being subjected to a curing condition that has a similar temperature profile as that of the members. They are traditionally used to verify the required concrete release strength;
2. Temperature match-cured specimens, which are produced in the same way as member-cured specimens. Until the release of the prestressing force (typically one day after casting), the specimens are cured at the exact temperature profiles as the members through a match-curing system. The temperature in the members is monitored and the temperature of the specimens is matched to that of the members through heating elements in the mold. The specimens are then stored adjacent to the members until test, and are often recommended for use to represent the concrete within a member;
3. On-site-cured specimens, which are produced during the in situ concrete placement for casting at jobsites and are left exposed to ambient weather conditions along the cast-in situ members and structures until test; and
4. Drilled cores, which are extracted from large structural components and are commonly used to determine the in situ concrete f'_c.

Previous findings on the in situ E_c of HSC were reported by Hester and Cook (Russell 1990); Myers and Carrasquillo (1998); Burg and Fiorato (1999); Glover and Stallings (2000); Roller et al. (2003), Al-Omaishi (2001), Ozylidrim (2002), Myers and

Table 1. Database Properties of Modulus of Elasticity of HSC

Source	Projects/mixture	w/b	Cement	Binder	Coarse aggregate	Specimen (mm)	Curing[a]	$f'_{c,28}$[b]	Age (days)
Myers and Carrasquillo (1998)	Louetta HPC precast beams	0.25	C-III	Fly ash	Limestone	100 × 200	MC	87	Release, 28, 56
							TMC	89	
	S.A HPC precast beams	0.25	C-III	Fly ash	Limestone	100 × 200	MC	92	Release, 7, 28, 56
							TMC	93	
	Louetta HPC precast deck panels	0.31	A-III	Fly ash	Gravel	100 × 200	MC	64	7, 28, 56
	S.A precast deck panels	0.38	C-III		Limestone			63	7, 28, 56
	Louetta HPC precast column	0.31	A-III		Gravel			89	28, 56
	S.A HPC piers	0.33–0.36	LS-II	Fly ash	Gravel	100 × 200	On site	60–63	28, 56
	S.A HPC pier caps	0.36–0.38						56–67	28, 56
	Field trial	0.29–0.35						56–72	28, 56
	S.A HPC decks	0.25–0.27						56–60	3, 7, 14, 28, 56
Glover and Stallings (2000)	HPC precast girders	0.30	III	Fly ash	Limestone	100 × 200	MC	68	Release, 7, 28, 56
							TMC	79	
Ozylidrim (2002)	HPC beams B1, B2	0.32	I	Silica fume	Limestone	150 × 300	MC	67	28, 56
	HPC beam B3	0.32					MC	68	28, 56
	HPC beam B4	0.33					MC	63	28, 56
Roller et al. (2003)	C.C bridge HPC girders	0.25	III	Fly ash	Limestone	150 × 300	MC	66	Release, 7, 28, 56, 90
						100 × 200	TMC	73	
Al-Omaishi (2001)	NE09G	0.35	III	—	Limestone	100 × 200	MC	62	7, 14, 28, 56
	NH10G	0.29	II	Silica fume	Gravel			69	3, 7, 14, 28, 56
	TX09G	0.34	III	—	Limestone			77	3, 6, 11, 21, 28
	WA10G	0.31	III	—	Gravel			79	1, 3, 7, 14, 28, 56
Myers and Yang (2005)	Mi.HPC girders	0.25	I	Silica fume	Rock	100 × 200	MC	86[c]	Release, 56
Hughs et al. (2005)	L.C bridge	0.33[d]	I-II	Fly ash silica fume	—	100 × 200	On site	69	3, 28
Burg and Fiorato (1999)	High strength	0.23	I	Fly ash silica fume	Dolomite	100 × 200	Drilled cores	90	35, 84, 277, 400
	Low-heat mix	0.28	I					71	

[a]MC = member-cured; TMC = temperature match–cured.
[b]$f'_{c,28}$ in MPa.
[c]Compressive strength at an age of 56 days.
[d]w/c (water/cement ratio).

Yang (2005), and Hughs et al. (2005). Empirical relations for predicting the in situ E_c of HSC were proposed by Myers and Carrasquillo (1998) based on their measured data; however, there is uncertainty about whether their equations can provide satisfactory predictions in other cases.

Evaluation of Existing Equations and New Proposals

Development of In Situ Modulus of Elasticity of HSC with Time

Data Measured on Member-Cured Specimens

Fig. 1(a) shows the test data by Myers and Carrasquillo (1998), Glover and Stallings (2000), Al-Omaishi (2001), and Roller et al. (2003) for the development of the E_c of HSC with time measured on member-cured specimens that were produced with two types of cement. It is evident that the measured E_c increases with time, for both types of cement. In the case of HSC produced with Type III cement, the one-day E_c reaches approximately 90% of the 28-day value, whereas the HSC with Type II cement shows a slower increase of the E_c before 28 days. The measured data are compared with the ACI Committee 209 (2008) and the fib (2011) equation ($s = 0.20$), in addition to the ACI Committee 209 (1992) equation presented in Table 2. For data measured on HSC mixed with Type II cement, only the equation by ACI Committee 209 (2008) and fib (2011) is compared with the test data.

Fig. 1(a) shows that for HSC specimens with Type III cement, the ACI Committee 209 (2008) and fib (2011) equation underestimates the development of the E_c before 7 days, and the ACI Committee 209 (1992) equation for moist-cured HSC exhibits a similar performance. However, the ACI Committee 209 (1992) equation for heat-cured HSC specimens tends to overestimate the measured E_c values before 7 days ($R^2 = 0.327$). Therefore, they are not necessarily applicable for member-cured HSC. However, the ACI Committee 209 (2008) and fib (2011) equation seems to provide a reasonable prediction of the time effect on the E_c of member-cured HSC specimens with Type II cement ($R^2 = 0.858$).

In this paper, the equation by ACI Committee 209 (2008) and fib (2011) with an alternative value for the coefficient s, which is 0.055 based on regression analysis using the least-squares method, is proposed to describe the time-dependent E_c of member-cured HSC specimens with Type III cement ($R^2 = 0.462$). The predictions with the proposed s are also shown in Fig. 1(a).

Data Measured on Temperature Match–Cured Specimens

The collected test data for the E_c of HSC measured on temperature match-cured specimens by Myers and Carrasquillo (1998), Glover and Stallings (2000), and Roller et al. (2003) are shown in Fig. 1(b). All specimens were mixed with Type III cement. As observed. the ACI Committee 209 (2008) and fib (2011) equation and the ACI Committee 209 (1992) equation for moist-cured HSC underestimates the development of the E_c before an age of 7 days by 10–35% and 7–28%, respectively, whereas the ACI Committee 209 (1992) equation for heat-cured specimens provides a reasonable description of the increase in the E_c with time ($R^2 = 0.398$). This indicates that the development of the E_c of temperature match–cured HSC specimens is comparable to that of heat-cured specimens. However, the heat-cured specimens used by Mokhtarzadeh and French (2000) to determine the constants a and b were not *steam-cured,* as specified in ACI Committee 209 (1992); instead, they were cured under a condition that emulated the fabrication of precast products and the used curing regime was more or less similar to that of the temperature match–cured specimens. A more accurate prediction of the time-dependent E_c of temperature match–cured HSC specimens is achieved through optimizing the coefficient s based on regression analysis of data. The optimal value is identified as 0.03 ($R^2 = 0.613$). Fig. 1(b) presents the predictions with the proposed s values.

Data Measured on On-Site-Cured Specimens

The measured data by Myers and Carrasquillo (1998) for the E_c at different ages measured on on-site-cured HSC specimens mixed with Type II cement are shown in Fig. 1(c). Only the ACI Committee 209 (1992) and fib (2011) equation was evaluated against the test data. The equation is in good agreement with the test data except for before 7 days ($R^2 = 0.361$). However, the measured data for this period are rather limited.

A more precise description of the time effects on the E_c of on-site-cured HSC can also be derived by optimizing the coefficient s through regression analysis, whose optimal value is determined as 0.14 ($R^2 = 0.433$). In Fig. 1(c), the estimations with $s = 0.14$ are also presented.

Measured data for the E_c of HSC-drilled cores at early ages are so far still too limited; therefore, the applicably of the code equations are not evaluated for this type of specimen.

Prediction of In Situ Modulus of Elasticity of HSC

Because most of the collected data were measured on 100×200 mm specimens and the 150×300 mm cylinder is the standard specimen according to ASTM C 469 (ASTM 1994), the code equations presented in Table 2 were developed based on a 150×300 mm cylinder, so the size effect on the E_c should be taken into account. In this study, the proposals by Rashid et al. (2002) were used to convert the data for 150×300 mm cylinders from those measured on 100×200 mm cylinders.

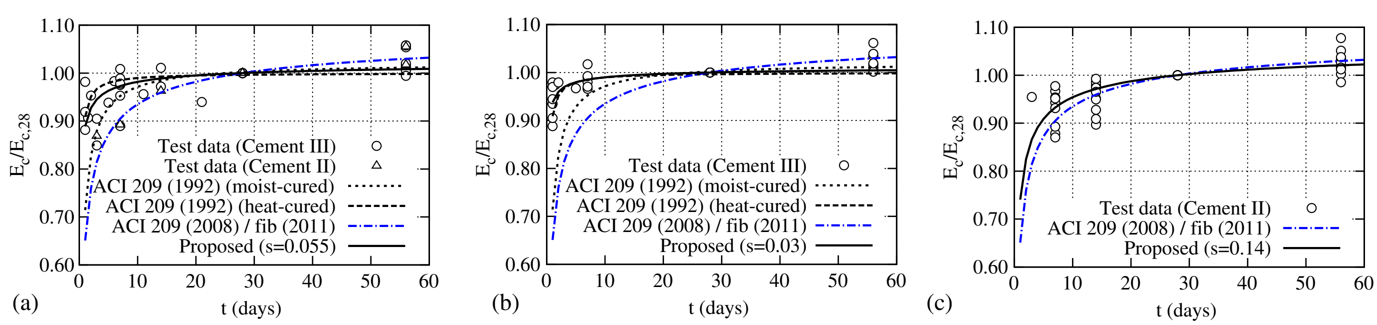

Fig. 1. Modulus of elasticity of HSC versus time: (a) data measured on member-cured specimens; (b) data measured on temperature match–cured specimens; (c) data measured on on-site-cured specimens

Table 2. Selected Code Equations for *Ec* of HSC

Time effect	ACI Committee 209 (1992)	$E_c = \sqrt{t/a + bt} E_{c,28}$[b]
	ACI Committee 209 (2008) fib (2011)	$E_c = \beta_e E_{c,28}$, $\beta_e = \exp[s/2 \cdot (1 - \sqrt{28/t})]$[a]
Magnitude	ACI Committee 318 (2011)	$E_c = 4{,}730\sqrt{f'_c}$ (in MPa)
	ACI Committee 363 (1992)	$E_c = 3{,}320\sqrt{f'_c} + 6{,}900$ (in MPa)
	fib (2011)	$E_c = \alpha_E 9{,}500 f_c'^{1/3} \beta_e^{1/3}$ (in MPa)[c]

[a] s = coefficient depending on the cement type and concrete compressive strength. If $f'_{c,28} > 60$ MPa (8,700 psi), then $s = 0.20$, irrespective of the cement type and concrete strength.
[b] The a and b magnitudes by ACI Committee 209 (1992) are valid only for normal-strength concrete (NSC). Suitable values for HSC were proposed by Mokhtarzadeh and French (2000). In the case of HSC with Type III cement, $a = 1.00$, $b = 0.96$ for moist-cured specimens, whereas $a = 0.21$, $b = 1.00$ for heat-cured specimens.
[c] α_E = coefficient depending on the coarse aggregate, which ranges from 0.7 to 1.2. In this study, α_E is assumed to be 1.0 because of the limit-measured data.

Data Measured on Member-Cured Specimens

The measured E_c on member-cured HSC specimens, at an age ranging from 1 to 90 days, reported by Myers and Carrasquillo (1998), Glover and Stallings (2000), Al-Omaishi (2001), Ozyldirim (2002), Roller et al. (2003), and Myers and Yang (2005), are presented in Fig. 2. Each point represents the mean value of two or more specimens. The measured data are compared with the equations by ACI Committee 318 (2011), ACI Committee 363 (1992), and Myers and Carrasquillo (1998). The fib (2011) equation is absent from Fig. 2 because it also includes the influence of time ($\beta_e^{1/3}$). It is observed that the ACI Committee 363 (1992) equation generally underestimates the measured E_c, especially for HSC with f'_c exceeding 70 MPa, whereas the equation by Myers and Carrasquillo (1998) without the zero intercept tends to overestimate the measured data for that strength range. The ACI Committee 318 (2011) equation and that by Myers and Carrasquillo (1998) with the zero intercept provide satisfactory descriptions of the test data. The fib (2011) equation exhibits a similar accuracy ($R^2 = 0.333$). Among these equations, the ACI Committee 318 (2011) equation exhibits the highest accuracy.

A more accurate equation for estimating the E_c of member-cured HSC specimens is developed in this study through regression analysis using the square root model by ACI Committee 318 (2011) and ACI Committee 363 (1992), which is expressed as

$$E_c = 4{,}603\sqrt{f'_c} \text{ (in MPa)} \tag{1}$$

Fig. 2 reveals that the predictions of Eq. (1) represent approximately the average value of the measured data, and most of the data fall within ±15% of the predicted values. Eq. (1) is only slightly more accurate than the ACI Committee 318 (2011) equation and that of Myers and Carrasquillo (1998) with the zero intercept, with minimal difference.

Data Measured on Temperature Match–Cured Specimens

Fig. 3 presents the collected data for the E_c of HSC on temperature match–cured specimens at ages between 1 and 90 days. The data were reported by Myers and Carrasquillo (1998), Glover and Stallings (2000), and Roller et al. (2003). The ACI Committee 318 (2011) equation and those by Myers and Carrasquillo (1998) are found to overestimate substantially the measured E_c, whereas the ACI Committee 363 (1992) equation yields underestimations. The fib (2011) equation is also found to provide significantly higher predictions.

Eq. (2) is proposed to predict the E_c of temperature match–cured HSC specimens based on regression analysis. The mean absolute error (MAE) and root mean square error (RMSE) of this equation are 1,109 and 1,282, respectively. The measured data are found to fall within ±10% of the predicted values by Eq. (2)

$$E_c = 853\sqrt{f'_c} + 31{,}221 \text{ (in MPa)} \tag{2}$$

Data Measured on On-Site-Cured Specimens

Available test data on the E_c of HSC measured on on-site-cured specimens, reported by Myers and Carrasquillo (1998) and Hughs et al. (2005), are shown in Fig. 4. The equation by ACI Committee 318 (2011) tends to overestimate the measured E_c value when $f'_c > 60$ MPa, whereas the ACI Committee 363 (1992) equation underestimates the measured E_c. A similar performance to the ACI Committee 318 (2011) model is found for the fib (2011) equation ($R^2 = 0.336$). Eq. (3) is proposed to predict the E_c of on-site-cured HSC based on regression analysis. As shown, Eq. (3) provides more accurate predictions than existing models

$$E_c = 3{,}042\sqrt{f'_c} + 12{,}611 \text{ (in MPa)} \tag{3}$$

Data Measured on Drilled Cores

Rather limited data for the E_c of HSC measured on cores drilled from structural members is available. In this study, only the data by Burg and Fiorato (1999), which were measured on two different HSC mixes at an age of 35–400 days, are included. As shown

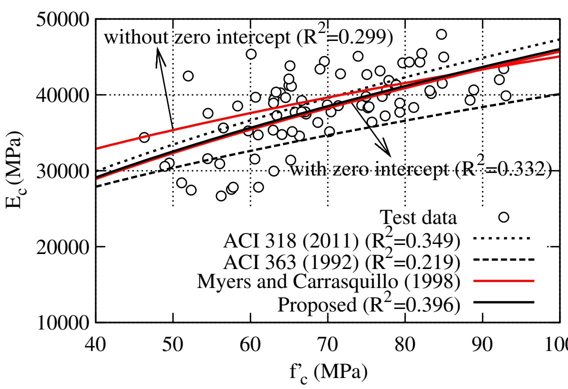

Fig. 2. Modulus of elasticity of HSC measured on member-cured specimens

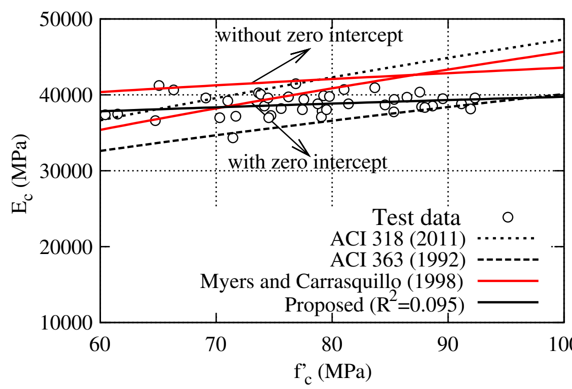

Fig. 3. Modulus of elasticity of HSC measured on temperature match–cured specimens

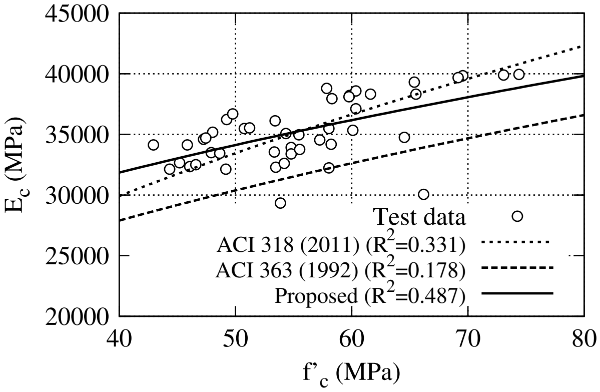

Fig. 4. Modulus of elasticity of HSC measured on on-site-cured specimens

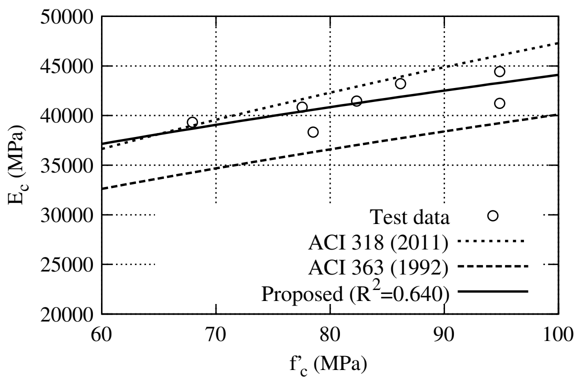

Fig. 5. Modulus of elasticity of HSC measured on drilled cores

in Fig. 5, the ACI Committee 318 (2011) and ACI Committee 363 (1992) equations appear approximately in the upper and lower boundaries of the measured data. However, the fib (2011) equation (without considering the time factor, because its influence is quite small for later age) leads to a better agreement with the test data ($R^2 = 0.423$). A more accurate equation [i.e., Eq. (4)] is proposed in this paper based on regression analysis of the test data. Because the data measured on drilled cores are quite limited, more data are needed

$$E_c = 3{,}083\sqrt{f_c'} + 13{,}266\,(\text{MPa}) \tag{4}$$

A comparison of the proposed equations in this study with those of ACI Committee 318 (2011) and ACI Committee 363 (1992) leads to the following interesting findings:

1. The proposed equations for the in situ E_c of HSC generally fall within the two code relations by ACI Committee 318 (2011) and ACI Committee 363 (1992);
2. When $f_c' > 70$ MPa, the predictions of Eq. (1) for member-cured specimens exceed those of Eq. (2) for temperature match–cured specimens. This implies that the former may overestimate the E_c of HSC in structures and precast concrete components because temperature match–cured specimens are usually more representative of the in situ HSC. This is consistent with the observations of Roller et al. (2003) if the size effect of the specimen is considered; however more validations are needed; and
3. The equation for temperature match–cured specimens [i.e., Eq. (2)] seems to be less sensitive to f_c' than other equations because its slope is flatter than that of other models. This might be the result of the effect of this type of curing condition, but can also result from the scatter of the test data.

Conclusions

The in situ curing condition has a remarkable influence on the development of the E_c of HSC with time (particularly at early ages) and the relation between E_c and f_c'. Existing code equations based on moist-cured specimens are generally inadequate for describing the in situ E_c of HSC. Based on available test data, new proposals for describing the E_c of HSC considering the effect of the in situ curing conditions are presented in this paper.

The proposed equations are based on available test data in the literature and are able to estimate the concrete properties in the range of those data. However, for HSC outside of that range, the reliability and applicability of the equations need to be evaluated further. Moreover, more measured data—especially on drilled cores—are required to acquire more knowledge about the in situ Ec of HSC and to examine the reliability of the code and the proposed equations.

Notation

The following symbols are used in this paper:

a, b = constants for estimation of the time-dependent compressive strength;
E_c = modulus of elasticity at any age of curing;
$E_{c,28}$ = modulus of elasticity at an age of 28 days;
f_c' = compressive strength at any age of curing;
$f_{c,28}'$ = compressive strength at an age of 28 days;
R^2 = coefficient of determination;
s = coefficient for description the time-dependent modulus of elasticity; and
t = curing age.

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