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Effect of temperature and aging on the mechanical properties of concrete Part I. Experimental results

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Abstract

This paper reports the results of curing temperature and aging on the strength and elastic modulus and the Part II paper suggests a prediction model based on these experimental results. Tests of 480 cylinders made of Types I, V, and V cement + fly ash concretes, cured in isothermal conditions of 10, 23, 35, and 50 °C and tested at the ages of 1, 3, 7, and 28 days are reported. According to the experimental results, concretes subjected to high temperatures at early ages attain higher early-age compressive and splitting tensile strengths but lower later-age compressive and splitting tensile strengths than concretes subjected to normal temperature. Even though the elastic modulus has the same tendency, the variation of elastic modulus with curing temperature is not so obvious as compressive strength. Based on the experimental result, the relationships among compressive strength, elastic modulus, and splitting tensile strength are analyzed, considering the effects of curing temperature, aging, and cement type.

Keywords: Temperature; Aging; Compressive strength; Elastic moduli; Splitting tensile strength

1. Introduction

Temperature variation caused by the heat of hydration in mass concrete or the change of external environment has a large influence on the mechanical properties of early-age concrete. Mechanical properties such as compressive strength, elastic modulus, and splitting tensile strength are factors to be considered in the design and construction of concrete structures. Specifically, evaluation of the thermal cracking of mass concrete structure requires estimation of the elastic modulus and tensile strength of early-age concrete with temperature. Therefore, effects of temperature and aging on the mechanical properties must be studied and quantified [1–6].

Most of the code relationships between compressive strength and elastic modulus or splitting tensile strength were developed based on experimental data on concrete cured at normal temperature and tested at 28 days. To apply the relationship to concretes cured at other curing temperatures or tested at different ages, it is necessary to examine the validity of the relationships at different temperatures and ages [7–11].

The objectives of this study are to produce a data inventory of the early-age mechanical properties of concrete with temperature and to investigate the validity of the relationships between compressive strength and elastic modulus or splitting tensile strength according to temperature and aging.

2. Experimental program

2.1. Experimental variables

Experimental variables consisted of cement type, water–binder ratio, and curing temperature. Details are provided in Table 1.

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Table 1
Test variables

Cement type	Water–binder ratio (w/b)	Binder (kg/m^3)		Curing temperature (°C)
		Cement	Fly ash	
Types I and V	0.40	452	–	10, 23, 35, 50
	0.50	362	–	10, 23, 35, 50
Type V + fly ash	0.40	385	38	10, 23, 35, 50

2.2. Materials

The material properties of cement, sand, coarse aggregate, and fly ash are shown in Table 2 and the chemical properties of cements and fly ash are provided in Table 3.

2.3. Mixture proportions

Table 4 shows basic mixture proportions. Fly ash–binder ratio of Type V cement + fly ash concrete is 15% and fine aggregate–aggregate ratio is from 0.38 to 0.42. Cement content is from 362 to 452 kg/m^3 according to water–binder ratio and water content of all mixes is 181 kg/m^3. The quantities of AE (air-entraining) agent and superplasticizer are given as the ratio of binder content.

2.4. Test methods

After mixing, cylinders were cast in 100 × 200-mm paper mold and put into the chamber within 30 min. Subsequently, cylinders including paper molds were cured in the chambers, which were set at 100% humidity and target temperatures of 10, 23, 35, and 50 °C. Paper molds were removed after 24 h and specimens were cured in the chamber to the test ages of 1, 3, 7, and 28 days. The upper and lower surfaces of the specimens were ground before testing. The experimental results of three identical specimens were averaged. Compressive strength was tested according to ASTM C 39, splitting tensile strength according to ASTM C 496, and elastic modulus according to ASTM C 469.

Table 2
Material properties

	Type I cement	Type V cement	Fly ash	Fine aggregate	Coarse aggregate
Type	–	–	–	river sand	crushed stone (granite) (maximum size: 19 mm)
Specific surface (cm^2/g)	3315	3210	4300	–	–
Specific gravity	3.15	3.15	2.10	2.55	2.58
Fineness modulus	–	–	–	2.95	7.23
28-day compressive strength (MPa)	40	35	–	–	–

Table 3
Chemical properties of cements and fly ash

	Type I cement (%)	Type V cement (%)	Fly ash (%)
Calcium oxide, CaO	63.03	63.53	2.61
Silicon dioxide, SiO_2	20.57	21.74	61.20
Aluminum oxide, Al_2O	5.48	3.18	20.13
Magnesium oxide, MgO	3.41	3.11	1.37
Ferric oxide, Fe_2O_3	3.18	4.71	10.34
Sulfur trioxide, SO_3	2.23	1.87	0.06
Potassium oxide, K_2O	0.80	0.59	1.27
Loss on ignition	1.24	0.53	3.02

3. Experimental results

3.1. Type I cement concrete

Fig. 1(a) shows the experimental results of Type I cement concrete. As shown in Fig. 1(a), the 1- and 3-day compressive strengths increased with increasing curing temperature. However, this tendency was reversed with aging. The 28-day compressive strength of concrete with 0.40 w/c cured at 10 °C is the largest and that cured at 50 °C the smallest. These results suggest that concrete subjected to high temperature at an early age attains higher early-age compressive strength but lower later-age compressive strength. Alexander and Taplin [1] referred to this phenomenon as the "crossover effect." The same phenomenon also appears in the splitting tensile strength and elastic modulus with increasing curing temperature. However, the crossover effect of elastic modulus is not so obvious as that of compressive strength. This is due to the difference between the rate of increase of compressive strength and elastic modulus. The 3-day compressive strength of concrete cured at normal temperature is about 50–60% of the 28-day compressive strength, but the 3-day elastic modulus is about 80–90% of the 28-day elastic modulus. As the difference in elastic modulus between early and later age is smaller than that of compressive strength, the crossover effect of elastic modulus at a later age is not so obvious as that of compressive strength. Table 5 provides the experimental results for compressive strength, splitting tensile strength, and elastic modulus of concretes with 0.40 and 0.50 w/c.

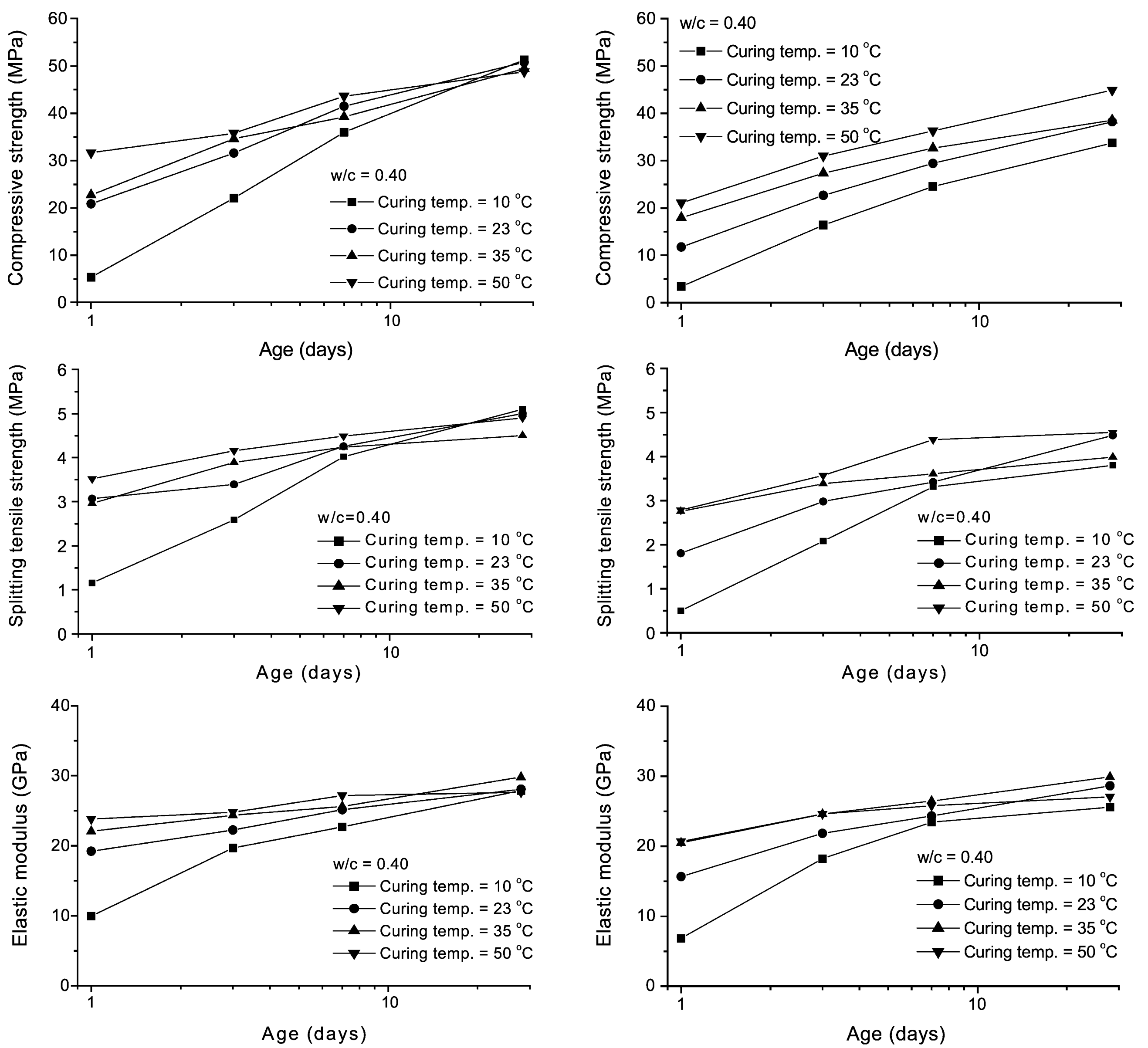
3.2. Type V cement and Type V cement + fly ash concrete

Fig. 1(b) and (c) show the experimental results for Type V cement and Type V cement + fly ash concretes. As shown in Fig. 1(b), the strength and elastic modulus between 1 and 7 days increase with increasing curing temperature. But the rate of increase of 28-day strength and elastic modulus of concretes cured at 23 °C is greater than those cured at 35 °C. Compared with Type I cement concretes, the crossover effect

Table 4
Basic mixture proportions

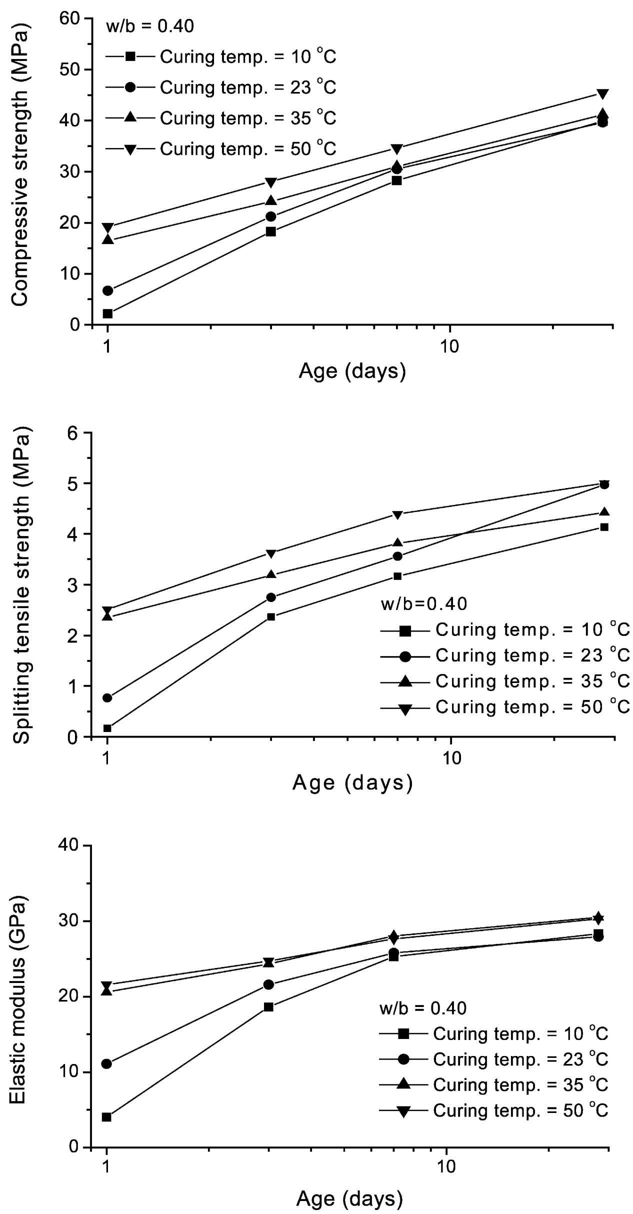
Cement type	Water–binder ratio (w/b)	Sand–aggregate ratio (s/a)	Unit weight (kg/m^3)						
			Water (w)	Binder (b)		Sand (s)	Gravel (g)	Admixture	
				Cement (c)	Fly ash (f)			AE agent (b × %)	Superplasticizer (b × %)
Types I and V	0.40	0.39	181	452	–	630	989	0.005	0.5
Types I and V	0.50	0.42	181	362	–	707	989	0.005	0.5
Type V + fly ash	0.40	0.38	181	385	68	608	989	0.005	0.5

of Type V cement concretes is not so obvious, due to the difference in the hydration rate with cement type. Because the hydration rate of Type V cement concrete is slower than that of Type I cement concrete, the crossover effect of Type V cement concrete is delayed. Therefore, the crossover effect of Type V cement concrete at testing ages is not so obvious as Type I cement concrete. Tables 6 and 7 give the experimental results for Type V cement and Type V cement + fly ash



(a) Type I cement (b) Type V cement

Fig. 1. Experimental compressive strength and elastic modulus.



(c) Type V cement + fly ash

Fig. 1. (*continued*)

concretes with water–binder ratios of 0.40 and 0.50, respectively. As shown in Tables 6 and 7, concretes with water–binder ratio of 0.50 have the same tendency as concretes with water–binder ratio of 0.40.

4. Analysis of experimental results

4.1. Relationship between elastic modulus and compressive strength

Elastic modulus is generally estimated using a relationship between compressive strength and elastic modulus. Most relationships are developed based on experimental data of concrete cured at normal temperature and tested at 28 days. If the relationship is to be applied to concretes cured at different curing temperatures or tested at different ages, it is necessary to evaluate the validity or the applicability of the relationship for the given conditions. This paper investigates the effect of curing temperature, aging, and cement type on the relationship.

Fig. 2 shows the relationship between elastic modulus and compressive strength according to cement type, curing

Table 5
Experimental results of Type I cement concrete

	Compressive strength (MPa)				Splitting tensile strength (MPa)				Elastic modulus (GPa)			
	1 day	3 days	7 days	28 days	1 day	3 days	7 days	28 days	1 day	3 days	7 days	28 days
w/c = 0.40												
10 °C	5.4	22.1	36.0	51.3	1.2	2.6	4.0	5.1	10.7	21.2	24.4	30.0
23 °C	20.9	31.6	41.5	50.8	3.0	3.4	4.2	5.0	20.7	23.9	27.1	30.2
35 °C	22.8	34.6	39.2	49.4	2.9	3.9	4.2	4.5	23.7	26.2	27.6	32.1
50 °C	31.7	35.8	43.6	48.7	3.5	4.1	4.5	4.9	25.6	26.7	29.2	29.7
w/c = 0.50												
10 °C	3.5	14.3	24.7	36.9	0.6	2.2	3.1	4.2	9.1	19.2	23.4	27.6
23 °C	9.4	23.4	31.5	42.4	1.8	2.9	3.8	4.7	16.9	25.0	26.4	28.8
35 °C	17.1	24.2	33.1	41.3	2.5	3.4	3.9	4.2	20.7	24.5	26.5	29.1
50 °C	19.8	28.1	34.6	39.3	2.6	3.5	3.9	4.4	22.3	24.9	27.0	30.1

Table 6
Experimental results of Type V cement concrete

	Compressive strength (MPa)				Splitting tensile strength (MPa)				Elastic modulus (GPa)			
	1 day	3 days	7 days	28 days	1 day	3 days	7 days	28 days	1 day	3 days	7 days	28 days
w/c = 0.40												
10 °C	3.4	16.4	24.5	33.8	0.5	2.1	3.3	3.9	6.9	18.2	23.4	25.6
23 °C	11.8	22.7	29.4	38.2	1.8	2.9	3.4	4.5	15.7	21.9	24.3	28.6
35 °C	17.9	29.4	32.7	38.5	2.8	3.4	3.6	4.0	20.5	24.6	26.5	29.9
50 °C	21.0	38.2	36.3	44.9	2.8	3.5	4.4	4.5	20.7	24.6	25.8	27.1
w/c = 0.50												
10 °C	2.3	10.9	17.2	24.7	0.3	1.5	2.2	2.9	3.5	14.1	18.4	22.5
23 °C	7.1	17.2	22.3	30.7	1.1	2.5	3.0	3.9	12.5	19.8	23.5	26.8
35 °C	10.2	17.3	21.9	28.6	1.8	2.5	2.8	3.6	14.2	19.9	22.3	27.9
50 °C	10.3	17.4	22.5	27.1	1.6	2.6	3.0	3.5	16.0	19.2	22.9	24.6

Table 7
Experimental results of Type V cement + fly ash concrete

	Compressive strength (MPa)				Splitting tensile strength (MPa)				Elastic modulus (GPa)			
	1 day	3 days	7 days	28 days	1 day	3 days	7 days	28 days	1 day	3 days	7 days	28 days
w/c = 0.40												
10 °C	2.2	18.2	28.2	39.9	0.2	2.4	3.1	4.1	4.0	18.6	25.3	28.3
23 °C	6.7	21.1	30.5	39.6	0.8	2.8	3.5	5.0	11.1	21.6	25.8	28.0
35 °C	16.5	24.1	31.0	41.2	2.4	3.2	3.8	4.4	20.6	24.3	28.0	30.5
50 °C	19.2	28.1	34.6	45.4	2.6	3.6	4.4	5.0	21.6	24.7	27.7	30.3

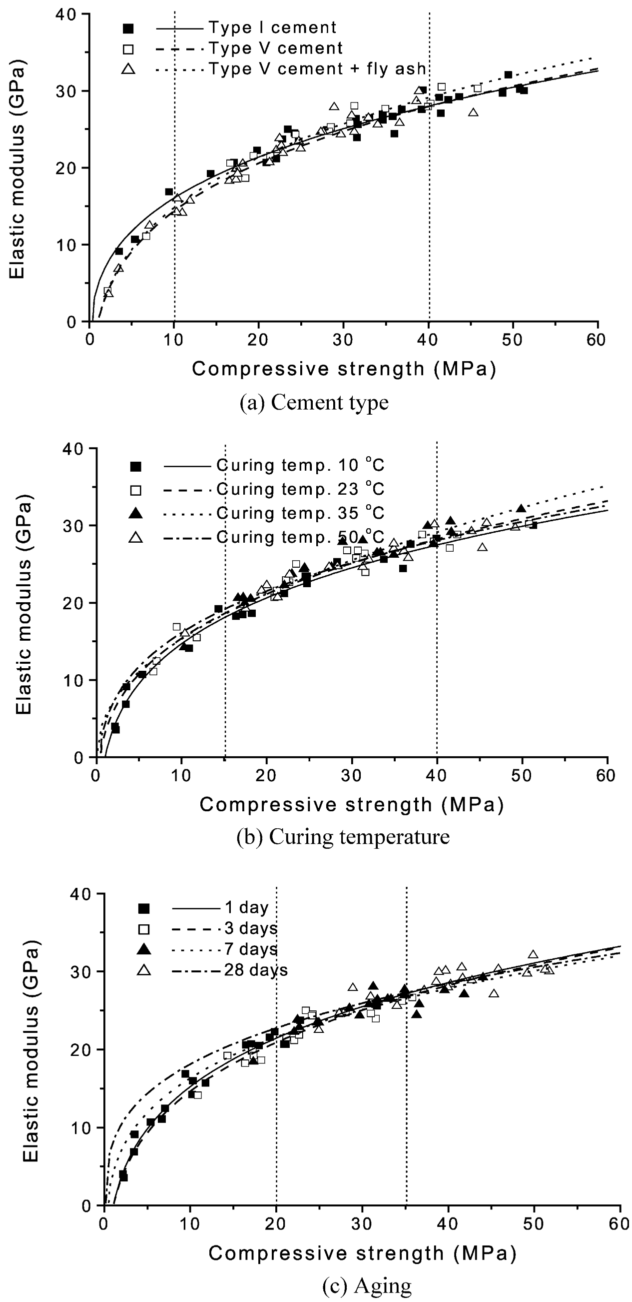


Fig. 2. Comparison of elastic modulus and compressive strength.

temperature, and aging. The experimental data were analyzed using Eq. (1):

$$E_c = a(f_c')^b \tag{1}$$

where E_c is the elastic modulus of concrete, f_c' is the compressive strength of concrete, and a and b are constants. For the properties that fall within the interval indicated by the two dotted lines, the regression curves in Fig. 2(a) should be compared with each other. The difference in elastic modulus at the same compressive strength by cement type is less than ±5% in the interval considered. This suggests that cement type hardly affects the relationship between compressive strength and elastic modulus. Fig. 2(b) presents the relationships between compressive strength and elastic modulus with curing temperature. The regression curves, except the case cured at 35 °C, are similar and the difference between the regression curve of concrete cured at 35 °C and other curves is less than ±5% in the interval considered. The regression curves illustrated in Fig. 2(c) consider concrete aging. These curves are similar in the interval considered. Therefore, it is safe to conclude that cement type, curing temperature, and aging do not substantially affect the relationship between elastic modulus and compressive strength.

Eq. (2) is formulated based on the experimental data of compressive strength and elastic modulus:

$$E_c = 5250(f_c')^{0.46}. \tag{2}$$

Eq. (2) was compared with the equations of ACI [8,9] and CEB-FIP 1990 [7] models. The compressive strength used in the ACI model is the specified compressive strength and that used in the CEB-FIP 1990 model is the mean value of compressive strength associated with the specific characteristic compressive strength. The modification coefficient of CEB-FIP 1990 model for E_c is 1.0 because the granite used in this paper corresponds to quartzitic aggregates. The ACI and CEB-FIP 1990 model curves of Fig. 3 were estimated based on experimental data on compressive strength in order to compare the proposed equation with the equations of ACI and CEB-FIP 1990 models. As shown in Fig. 3, the ACI 318 model [$E_c = 4700\sqrt{f_c'}$] (*Building Code Requirements for Reinforced Concrete and Commentary*) [8] accurately estimates the elastic modulus for concretes with compressive strengths under 30 MPa. The ACI 363 model [$E_c = 3300\sqrt{f_c'} + 6900$] (*State-of-the Art Report on High-Strength Concrete*) [9] accurately estimates those over 30 MPa. The proposed equation fits the experimental data rather well. The CEB-FIP 1990 model [$E_c = 1828[f_c']^{1/3}$] overestimates the elastic modulus for concretes with compressive strengths under 30 MPa. Therefore, it is safe to assume that the ACI 318 model for concretes with compressive strength under 30 MPa and the ACI 363 model for concretes with compressive strength over 30 MPa

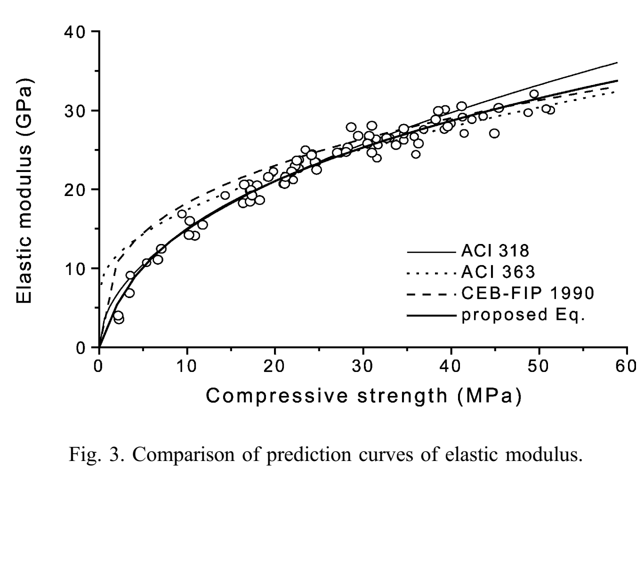
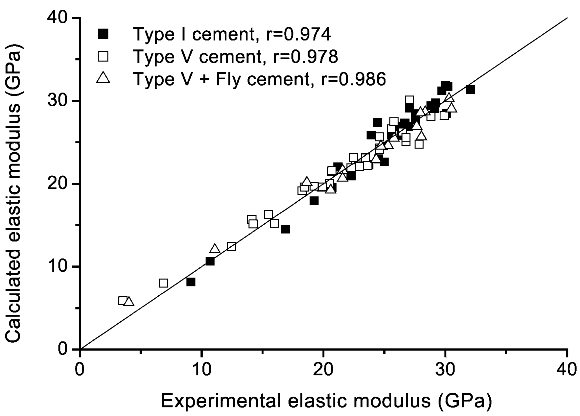
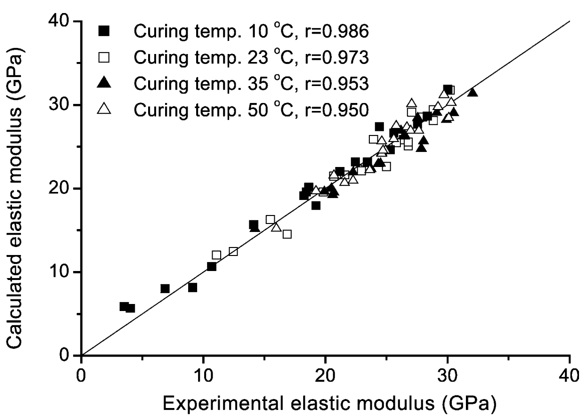


Fig. 3. Comparison of prediction curves of elastic modulus.

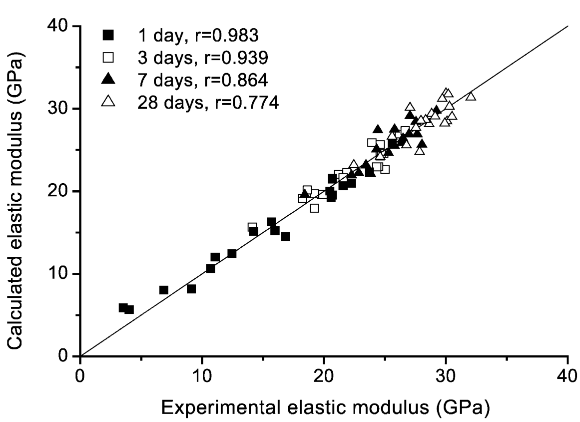
accurately estimate the relationship between compressive strength and elastic modulus, and that the models can be used regardless of curing temperature and aging. If the proposed equation is used, the same results as the two ACI models can be obtained with one equation. Fig. 4 compares the values estimated using the proposed equation with the experimental results, according to cement type, curing temperature, and aging. As shown in Fig. 4(a) and (b), the difference between estimated values and experimental results is very small for cement type and for curing temperature. Though the coefficient of determination shown in Fig. 4(c) decreases with aging, this does not mean that the equation underestimates or overestimates the elastic modulus because the difference between calculated and experimental values is not oriented to one direction. It seems that the deviation of the coefficient of determination is due to the scatter of experimental elastic modulus with compressive strength.



(a) Cement type

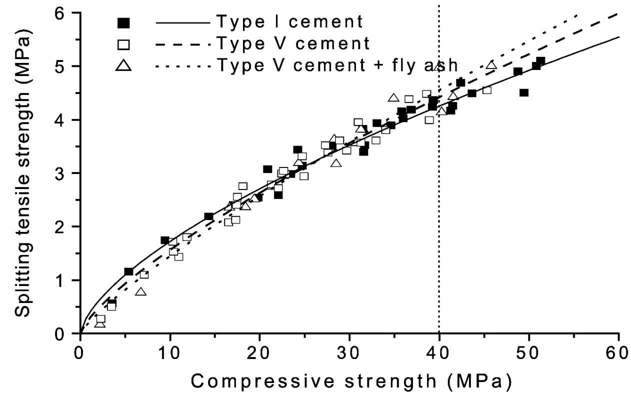


(b) Curing temperature

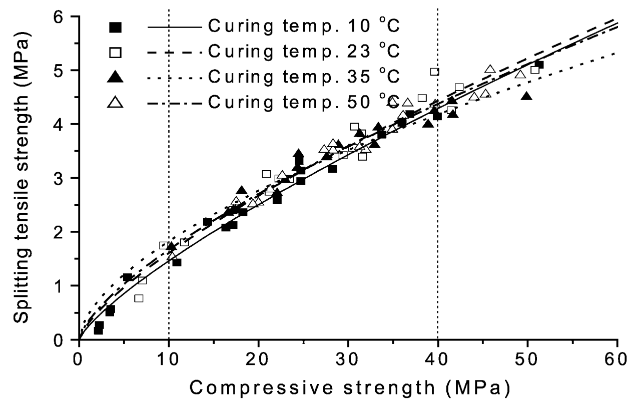


(c) Aging

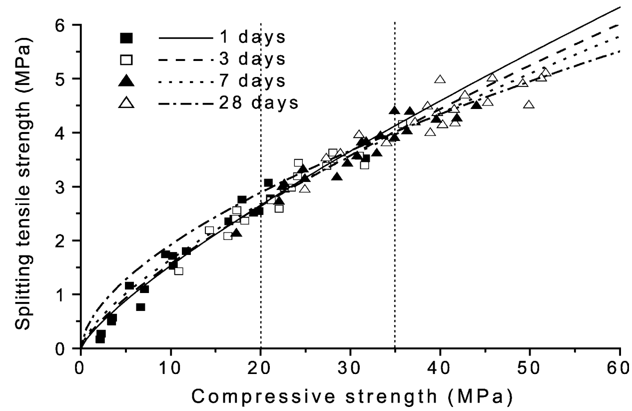
Fig. 4. Experimental and calculated elastic modulus.



(a) Cement type



(b) Curing temperature



(c) Aging

Fig. 5. Comparison of splitting tensile strength and compressive strength.

4.2. Relationship between splitting tensile strength and compressive strength

Fig. 5 shows the experimental results of splitting tensile strength and compressive strength according to cement type, curing temperature, and aging, and the regression curves based on Eq. (3):

$$f_{ct} = a(f_c')^b \tag{3}$$

where f_{ct} is the splitting tensile strength of concrete, f_c' is the compressive strength of concrete, and a and b are constants. For the properties that fall within the interval indicated by the dotted line, the regression curves in Fig. 5(a) should be compared with each other. As shown in Fig. 5(a), the difference in splitting tensile strengths at the same compressive strength by cement type is less than $\pm 5\%$ in the interval considered. So, it seems that cement type does not have a large effect on the relationship between splitting tensile strength and compressive strength. Fig. 5(b) and (c) show the variation of the relationships with curing temperature and aging. The difference between the regression curves for curing temperature and for aging is not large for the intervals considered. Therefore, it is reasonable to assume that cement type, curing temperature, and aging do not substantially affect the relationship between splitting tensile strength and compressive strength.

Eq. (4) is formulated based on experimental data of splitting tensile strength and compressive strength:

$$f_{ct} = 0.31(f_c')^{0.71}. \tag{4}$$

Eq. (4) was compared with equations suggested by other researchers. The compressive strength used in the ACI 318 [8] and CEB-FIP 1990 [7] models is the specified/characteristic compressive strength and in the Ahmad and Shah [10] and Oluokun [11] models is the mean compressive strength of concrete. The ACI 318 and CEB-FIP 1990 model curves of Fig. 6 were estimated on the basis of experimental compressive strength to compare the proposed equation with

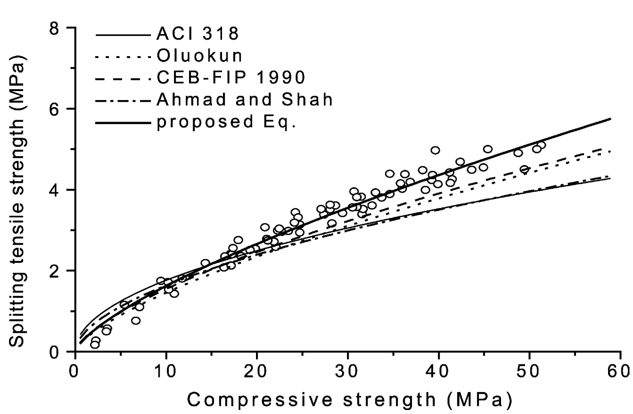


Fig. 6. Comparison of prediction curves of splitting tensile strength.

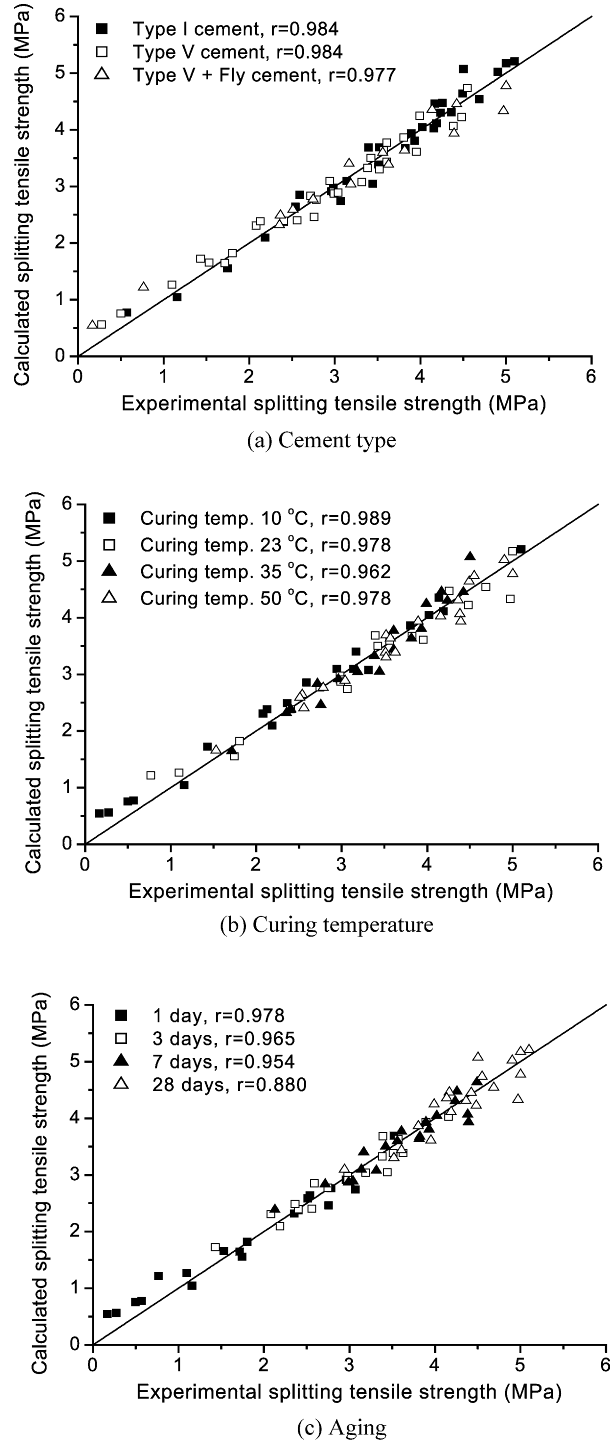


Fig. 7. Experimental and calculated splitting tensile strength.

the equations of the ACI and CEB-FIP 1990 models. As shown in Fig. 6, the ACI 318 and Ahmad and Shah equations overestimate the splitting tensile strength of concretes with low compressive strength and underestimate the splitting tensile strength of concretes with compressive strength over 20 MPa. The CEB-FIP 1990 and Oluokun equations accurately estimate the splitting tensile strength of concretes with compressive strength under 20 MPa but underestimate the splitting tensile strength of concretes with compressive strength over 20 MPa. Since the splitting tensile strength is generally used as the criterion of crack propagation, the model that underestimates the splitting tensile strength has the safety factor corresponding to the difference between estimated and experimental values. Thus, it is safe to suggest that the CEB-FIP 1990 and Oluokun models can be used in estimating the splitting tensile strength regardless of curing temperature, aging, and cement type. Fig. 7 compares the estimated values by Eq. (4) with the experimental results according to cement type, curing temperature, and aging. As shown in Fig. 7(a) and (b), the difference between estimated values and experimental results is very small for cement type and for curing temperature. Though the coefficient of determination in Fig. 7(c) decreases with aging, this does not mean that the equation underestimate or overestimate the splitting tensile strength because the differences between estimated and experimental values are not oriented to one direction. The reason of the deviation is estimated as the scatter of the experimental splitting tensile strength with compressive strength like elastic modulus.

5. Conclusions

This study has investigated the mechanical properties according to curing temperature, aging, and cement type, and proposed the relationships between compressive strength and splitting tensile strength or elastic modulus. Based on this study, the following conclusions have been made:

1. Concrete subjected to high temperature at early ages attains higher early-age compressive and splitting tensile strengths but lower later-age compressive and splitting tensile strength. Elastic modulus has the same tendency; the crossover effect of curing temperature on elastic modulus is not so obvious as compressive strength.

2. Cement type (Types I and V cement), curing temperature (from 10 to 50 °C), and aging (less than 28 days) have no large effects on the relationship between elastic modulus and compressive strength and the relationship between splitting tensile strength and compressive strength.

3. The best-fit equation between elastic modulus and compressive strength is in good agreement with the experimental data and estimates the same values as ACI models. Also, based on the experimental data, the equation of the relationship between splitting tensile strength and compressive strength is proposed. The equation properly estimates splitting tensile strength.

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