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Effects of environmental temperature and age on the elastic modulus of concrete

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Abstract. Concrete mechanical properties change constantly with age, temperature, humidity and the other environmental factors. This research studies the effects of temperature and age on the development of concrete elastic modulus by a series of prism specimens. Elastic modulus test was conducted at various temperatures and ages in the laboratory to examine the effects of temperature and age on it. The experimental results reveal that the concrete elastic modulus decreases with the rise of temperature but increases with age. Then, a temperature coefficient *K* is proposed to describe the effects of temperature and validated by existing studies. Finally, on the basis of *K*, analytical models are proposed to determine the elastic modulus of concrete at a given temperature and age. The proposed models can offer designers an approach to obtain more accurate properties of concrete structures through the elastic modulus modification based on actual age and temperature, rather than using a value merely based on laboratory testing.

Keywords: environmental temperature; age; elastic modulus; temperature coefficient

1. Introduction

Concrete is a material that is extensively used in different structures. The elastic modulus of concrete significantly affects the behavior of concrete particularly in structural elements subjected to flexure (Baalbaki *et al.* 1992). It also plays important roles in analyses and design calculations, such as evaluating stiffness of structural members and estimating creep and shrinkage in concrete structures (Ahmadi-Nedushan 2012). The mechanical properties of concrete are traditionally characterized by cylinders moist cured at (23 ± 2)°C (ASTM C192 2016) or prims cured at a temperature of (20 ± 2)°C and a relative humidity of at least 95% (ISO 1920-3 2004, GB/T 50081 2002) at the age of 28 days. However, they gain strength over a long period of time after pouring. Concrete structures are exposed to the changing environment, which influences their mechanical properties. Therefore, it is necessary to explore the variation of concrete elastic modulus relevant to age and environmental factors.

Environmental factors typically involve temperature, humidity, wind, flood, etc. Among them, temperature and humidity are key factors influencing the elastic modulus of concrete. Shoukry *et al.* (2001) studied the mechanical properties of concrete at various temperatures and humidity to examine their effects on concrete. It demonstrated that the elastic modulus increased by 0.17% with 1% increase of the moisture amount while it decreased by 0.48% with 1°C increase of temperature. Liu *et al.* (2014) found that the elastic modulus increased by 7.1% with the weight of the specimen increased by 1%. Converted to moisture amount, the elastic modulus increased by 0.28% with the moisture amount increased by 1%. In fact, the humidity does not change significantly unless the specimen is soaked in the water. Consequently, compared with temperature, the effect of humidity on the properties of concrete is relatively smaller. This research will not take the factor of humidity into consideration.

A considerable research has been conducted to explore the effects of age and curing temperature on the mechanical properties of concrete before 28 days (Gardner *et al.* 2005, Wang and Lee 2012). Large amounts of literature can be accessible on the performance of concrete under extreme high or low temperatures (Naus and Graves 2006, Shih *et al.* 1988). In fact, curing is an extremely short period during their service life and most concrete structures don't experience extreme high or low temperatures. Based on the literature above, research on the variation of elastic modulus with environmental temperature and age after curing is not done fully.

This research provides an overview of the influence of temperature and age on the elastic modulus of concrete after 28 days in the second section. Then the design of experiments is described in the third section. In the fourth section, experimental results are achieved and analyzed

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systematically. A temperature coefficient K is proposed to describe the effect of temperature on elastic modulus. Then analytical models are proposed to determine the elastic modulus of concrete at a certain temperature and age based on temperature coefficient K.

2. Literature review

2.1 Effects of environmental temperature on the concrete elastic modulus

Variations of 28-day concrete elastic modulus at temperature between -56°C and 232°C were given by Saemann and Washa (1958). It was found that the elastic modulus decreased with the increase of temperature. However, there was an exception when the temperature ranged between 121°C and 177°C; the elastic modulus exhibited an increase with the growth of temperature.

Berwanger and Sarkar (1973) explored the variation of the dynamic modulus over the temperature range of -73°C to 66°C at the age of 28 days. The dynamic modulus increased with decreasing temperature, while a sharper increase occurred below the freezing point.

Nasser (1973) studied the effect of elevated temperature (21°C, 46°C, 71°C and 96°C) on the behavior of air-entrained concrete. For concrete specimens with two different aggregate-cement ratios, group A and B, the reduction of elastic moduli was 22% to 59%.

Yamane *et al*. (1978) provided test results of the mechanical properties of several kinds of concrete mixed in the temperature range of -70°C to 20°C. Increases were found in elastic moduli under low temperatures. The increase rates were higher for the specimens with larger moisture amount and higher water to cement ratios. At low temperatures, concrete under wet conditions or with high water to cement ratios showed the elastic moduli of 1.5 times of that at room temperature.

Lee *et al*. (1988) conducted laboratory studies on concrete elastic modulus at a temperature range of -70°C to 20°C. All specimens were moist cured at a temperature of (23 ± 1.7)°C and tested under normal temperature (+20°C), -10°C, -30°C, -50°C and -70°C at the age of 23 to 27 days. The mean values of elastic moduli at different lower temperatures were expressed in percentage ratio to properties at normal temperature. The elastic moduli increased by 3%~56%. Besides normal concrete, Lee *et al*. (1989) also studied the mechanical properties of high-strength concrete at low temperatures. The elastic moduli increased by -2%~23%. It was obvious that the elastic modulus of high-strength concrete was less sensitive to temperatures.

Lu (1989) obtained the evaluation of elastic modulus in the temperature range of 0°C to 200°C as shown in Eq. (1)

$$E(T)=(1-0.0015T)E(0°\mathrm{C}) \tag{1}$$

where $E(T)$ is elastic modulus of concrete, T is temperature (°C).

Jiao *et al*. (2014) investigated the elastic modulus of concrete at temperature range of -20°C to 60°C. Their relationship is listed in the following equation

$$E(T)=-0.125T+29.13 \qquad R^2=0.985 \tag{2}$$

Zheng (2015) tested the elastic modulus of C30 concrete at temperature varying from -20°C to 60°C. The evaluation of elastic modulus was provided in the following equation

$$E(T)=-0.1022T+29.729 \tag{3}$$

2.2 Effects of age on the concrete elastic modulus

Washa and Fluck (1950) presented the elastic moduli changes of concrete specimens which were made of three different cements and had three different water-cement ratios over 10.5 years. It was observed that the elastic moduli increased by 2%~33.2%, except specimens made with one specific kind of cement exhibiting a decrease in elastic moduli. Mazzotti and Savoia (2012) fabricated several conventional vibration C50 concrete specimens and found that elastic moduli grew with time. Elastic moduli at 120 and 180 days increased by 11% and 2% respectively compared with that at 28 days. ACI Committee 209 (1997) proposed the following formula to estimate elastic modulus of concrete at the age of t days according to the value of 28 days:

$$E(t)=\left(\frac{t}{\alpha+\beta t}\right)^{1/2}E(28) \tag{4}$$

where α and β are constants, they are functions of both the type of cement and the type of curing employed. The range of α and β for normal weight, sand lightweight and all lightweight concrete (using both moist and steam curing and Types Ⅰ and Ⅲ cement) are: α=0.05 to 9.25, β=0.67 to 0.98. The cement type is referred to ASTM C150 (2012).

The authors' former work (Yang *et al*. 2018) explored the development of elastic modulus of C30 concrete up to 975 days. In air conditions, the elastic modulus of concrete rapidly increased with age during the initial 150 days and then exhibited a slower increase. At the age of 975 days, the elastic modulus showed an increase of 16.6% compared with that of 28 days.

2.3 Combined effects of environmental temperature and age on the concrete elastic modulus

A number of empirical equations were proposed in CEB-FIP model code 2010 (2013) to estimate the elastic modulus of concrete at an age of t and a temperature T. For a mean temperature of 20°C and curing in accordance with ISO 1920-3 (2004), the elastic modulus of concrete at an age of t days were estimated as below:

$$E(t)=\beta_E(t)E(28) \tag{5}$$

with

$$\beta_E(t)=[\beta_{cc}(t)]^{0.5}=\sqrt{\exp\left\{s\cdot\left[1-\left(\frac{28}{t}\right)^{0.5}\right]\right\}} \tag{6}$$

where $\beta_E(t)$ is a coefficient which depends on the age of concrete in t days,

$\beta_{cc}(t)$ is a function to describe the strength development with time,

Table 1 Coefficients to be used in Eq. (6) for different types of cement

f_{cm} (MPa)	Strength class of cement	s
≤60	32.5 N	0.38
	32.5 R, 42.5N	0.25
	42.5 R, 52.5 N, 52.5 R	0.20
>60	All classes	0.20

s is a coefficient which depends on the strength class of cement as shown in Table 1.

What's more, the effect of elevated or reduced temperatures at the time of testing on the elastic modulus of normal strength and high strength concrete at an age of 28 days was estimated from:

$$E(T) = E(20°C)\,(1.06\text{-}0.003T) \quad (7)$$

CEB-FIP model code 2010 (2013) also considered the effect of elevated or reduced temperatures on the maturity of concrete by adjusting the concrete age when the compressive strength reached before 50% of the 28-day value as shown in the following Eq. (8):

$$t_T = \sum_{i=1}^{n} \Delta t_i \exp[13.65 - \frac{4000}{273 + T(\Delta t_i)}] \quad (8)$$

where t_T is the temperature adjusted concrete age which replaces t in the corresponding equations,

Δt_i is the number of days when a temperature T prevails,

$T(\Delta t_i)$ is the temperature (°C) during the period.

It can be known from Eq. (8) that the effect of temperature on maturity of concrete only exists before the compressive strength reaches about 50% of the 28-day value. That is to say, after 28 days, the hydration of cement is almost completed and temperature has no effects on the concrete maturity. Therefore, Eq. (7) is also applicable to elastic modulus test after 28 days. Eqs. (5), (6) and (7) are combined to develop an expression for the concrete elastic modulus at age t (≥ 28 days) and test temperature T as:

$$E(t,T) = \sqrt{\exp\left\{s \cdot \left[1 - \left(\frac{28}{t}\right)^{1/2}\right]\right\}} E(28, 20℃)(1.06 - 0.003T) \quad (9)$$

where $E(t,T)$ is the elastic modulus at an age of t (≥ 28) days and temperature of T in °C,

the meaning of the other letters are the same as Eqs. (5) and (6).

Shoukry *et al*. (2011) described the development of elastic modulus at varying temperatures and ages. The results indicated that increasing the temperature from -20°C to 50°C resulted in a reduction in the elastic moduli that varied from 62% at day 3 to 23% after 28 days. Based on Eqs. (5) and (6), Shoukry proposed the following equations to express the concrete elastic modulus at an age t and temperature T:

$$\frac{E(t,T)}{E(28,20℃)} = \sqrt{\exp\left\{s \cdot \left[1 - \left(\frac{28}{t}\right)^{1/2}\right]\right\}} \left\{1 + \beta(t)(T - 20)\right\} \quad (10)$$

with

Table 2 Mix proportions and properties of C30 and C50 concrete

Concrete	Water-cement ratio	Sand ratio(%)	Content per cubic meter (kg/m³)					
			Cement	Water	Sand	Gravel	Fly ash	Water reducer
C30	0.46	44	245	170	786	1004	73	–
C50	0.40	34	538	215	577	1120	–	5.38

$$\beta(t) = -0.003 - 0.0074e^{-0.1205t} \quad (11)$$

where $\beta(t)$ is a coefficient which is related to age,

the meaning of s is the same as Eq. (6).

As mentioned above, both environmental temperature and age have significant effects on elastic modulus of concrete. To date, existing research involves either age or environmental temperature. The information available on the change of elastic modulus under changing temperatures and ages is limited. Only two studies including CEB-FIP 2010 (2013) and Shoukry *et al*. (2011) referred to the combined effects of these two factors. However, Shoukry's equations were obtained by the experimental data before 28 days. Therefore, it is necessary to combine the effects of temperature and age together to conduct further study.

The focus of this research aims to examine the effects of temperature and age on the elastic moduli of a series of concrete specimens that have been completely cured via a full set of experiments considering various environmental temperatures, ages and strength of concrete specimens. The research also aims at developing analytical models suitable for determination of the elastic modulus at a given temperature and age.

3. Experimental design

Two different kinds of concrete: grade C30 and C50 concrete specimens were made in this investigation. Each kind of concrete specimen was tested at three different temperatures (room temperature and two elevated temperatures) and ages. C30 concrete specimens were tested at the age of 45 days, 115 days and 175 days. While C50 concrete specimens were tested at the age of 28 days, 125 days and 195 days.

3.1 Preparation of concrete specimens

Portland cement (P.O42.5), medium sand, gravel of 25 mm maximum size, polycarboxylic acid, I grade fly ash and mineral powder S95 were selected as the concrete admixture and chemical admixture. Mix proportions of the concrete were designed according to (JGJ 55 2011) as shown in Table 2.

After mixing, 76 prisms were fabricated in 100 mm × 100 mm × 300 mm plastic molds and cured in standard conditions according to (GB/T 50081 2002). Half of them were C30 specimens and the others were C50 specimens. Plastic molds were removed after 24 hours. For each kind of specimens, 2 temperature calibration specimens were used to detect the temperature of the specimen through five

(a) Thermal sensors (b) Thermal detector

Fig. 1 Thermal sensors and thermal detector

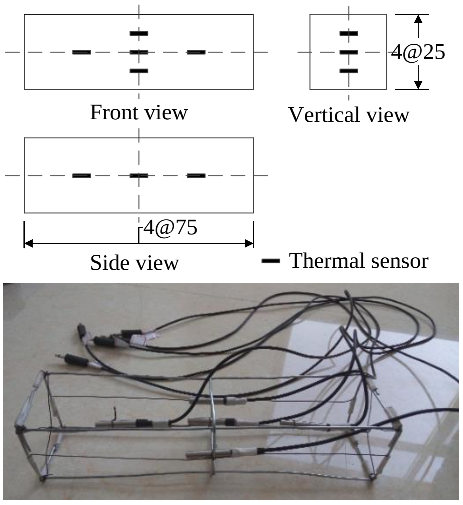


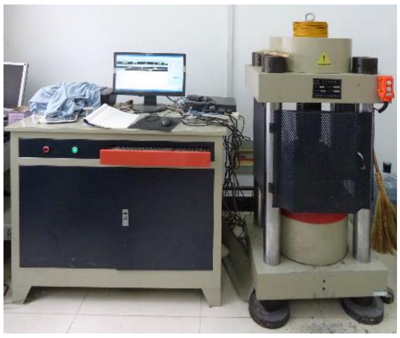
Fig. 2 Layout of the thermal sensors

thermal sensors embedded in it. The thermal sensors have two ends, one is cylinder shape embedded in the concrete and the other is inserted to the thermal detector to obtain the temperature of the concrete as shown in Fig. 1. The sensitivity of the thermal sensor is 0.1°C. Thermal sensors were tied on an intentionally designed iron wire frame with tie wraps. The layout of the sensors is shown in Fig. 2.

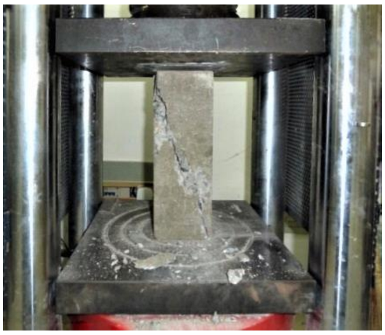
3.2 Heating methods and instrumentations

Specimens were tested at three different ages and temperatures. Three specimens were tested to determine the compressive strength; another three and a forth temperature calibration specimen were heated to two different designed temperatures by two heaters as shown in Fig. 3. To avoid thermal damage, the temperature of the heaters was ensured to be under 80°C and the temperature rising speed was about 5°C per hour. During heating, the position and orientation of the specimen were constantly shifted in accordance with the monitoring values from the thermal sensors to make sure they were uniformly heated. Once the temperature measured from sensors reached to the designed values, elastic modulus tests were carried out. By comparing the values of thermal sensors before and after the test, it was found that they had a small change. What's more, the temperature of the concrete specimens lags behind the air temperature. He *et al.* (2009) analyzed

Fig. 3 Concrete heating



(a) Compression-testing machine



(b) Failure mode of a specimen

Fig. 4 Compressive strength test

the one year monitoring data of Voigt Bridge-four spans reinforced concrete box girder bridge and found that the concrete temperature lagged behind the air temperature by approximately 2~3 hours. Therefore, the variation of specimens' temperature during the test can be ignored.

3.3 Elastic modulus tests and instrumentations

The tests were carried out according to (GB/T 50081 2002) on a compression-testing machine. The test methods regulated in (GB/T 50081 2002) were the same with (ISO 1920-10 2010).

Three specimens were tested to determine the prism compressive strength. Firstly, the surface of the specimen, the upper and lower bearing boards of the hydraulic test machine were cleaned. Then the specimen was placed on the lower bearing block with the axis of the specimen being aligned with the center of the spherical head. The process is

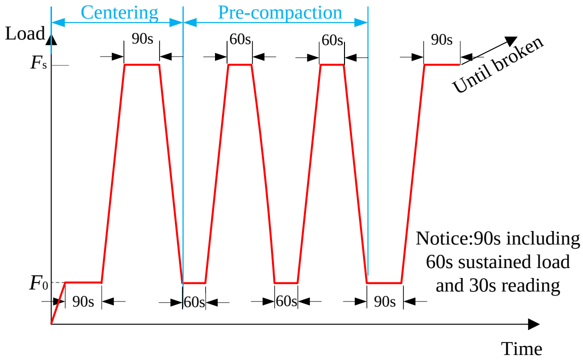


Fig. 5 Loading method of elastic modulus test

illustrated in Fig. 4. The loading rate was 0.5~0.8 MPa per second. The failure load was recorded when the specimen was crushed. The average of the three test results is taken as the cube compressive strength.

The prism compressive strength is calculated as follows:

$$f_{cp}=F/A \tag{12}$$

where f_{cp} is concrete prism compressive strength (MPa),
F is failure load of specimens (N),
A is the bearing area of specimens (mm^2).

Elastic modulus was tested with three prism specimens. Two deformation measuring instruments (dial gauges) were installed on both sides of the specimen. First of all, the load was steadily increased to F_0 (the benchmark stress was 0.5 MPa) at a rate of 0.5~0.8 MPa per second and maintained for 60 seconds. The values of dial gauges l_0 were recorded during the succeeding 30 seconds. Secondly, the load was increased to F_a which was one third of $A*f_{cp}$ and maintained for 60 seconds. The values of dial gauges l_a were recorded. For each dial gauge, if the ratio of l_0 or l_a and their average value exceed 20%, former operation should be repeated. Otherwise, the load was decreased to F_0 and then increased to F_a with the same loading rate and maintained for 60 seconds. After at least two repetitions, the load was decreased to F_0 and maintained for 60 seconds, the deformation values l_0 were recorded during the succeeding 30 seconds. Then the load was increased to F_a and maintained for 60 seconds. The deformation values l_a were recorded during the succeeding 30 seconds. Finally, the specimen was loaded to failure after all the elasticity measurements being completed. The loading is shown in Fig. 5 and the test process is shown in Fig. 6.

Elastic modulus is calculated as follows:

$$E_c=\frac{F_a-F_0}{A}\times\frac{L}{\Delta n} \quad \Delta n=l_a-l_0 \tag{13}$$

where E_c is the elastic modulus of concrete (MPa),
F_a is the load of one third of prism compressive strength (N),
F_0 is the initial load when the stress is 0.5 MPa (N),
A is the area of the pressure surface (mm^2),
L is the gauge length (mm),
l_a is the average displacement value of both sides of the specimen when the load is F_a (mm),
l_0 is the average displacement value of both sides of the specimen when the load is F_0 (mm).

(a) Operating system interface

(b) Concrete elastic modulus test

Fig. 6 Elastic modulus test

4. Results and discussion

Analysis is conducted in this section aiming at figuring out the effects of temperature and age on the change of elastic modulus of concrete. First of all, a temperature coefficient K is proposed to describe the influence of temperature on elastic modulus of concrete at a certain age. Then, age effect is considered based on the elastic modulus at 20°C. Finally, formulas combined with the temperature and age effects are proposed to estimate the elastic modulus of concrete at a given temperature and age.

4.1 Test results

For C30 concrete, specimens were tested at the age of 45 days, 115 days and 175 days. At different ages, three groups of prisms (A, B and C) were tested to obtain their elastic moduli at room temperature and another two designed temperatures. Moreover, for C50 concrete, groups named X, Y and Z were tested at the age of 28 days, 125 days and 195 days. The test results are tabulated in Table 3 and Table 4.

As mentioned in section 2.1, changes of elastic modulus caused by changeable temperatures were studied in the literature. Then the experimental data is compared with existing experiments. Since concrete specimens studied by different researchers are made of different water-cement ratios, cement contents, aggregate contents, admixture types and dosages, or cured under different conditions, it is more reasonable to contrast the gradients of elastic moduli. For each experiment, the elastic modulus obtained at 20°C is regarded as a baseline value. Divide elastic modulus obtained at a certain temperature by the baseline value, the percentage change of the elastic modulus with temperature is obtained as shown in Fig. 7.

Table 3 Elastic moduli of C30 concrete under different temperatures at different ages

Specimens Age(days)		A			B			C		
45	T (°C)	13.0	23.2	33.5	13.7	23.2	32.8	13.3	22.3	31.2
	E (GPa)	31.02	29.01	27.00	30.96	29.08	27.20	29.05	27.43	25.80
115	T (°C)	1.5	25.4	37.6	2.8	23.5	36.2	4.2	22.4	33.6
	E (GPa)	33.00	28.45	25.78	33.00	28.45	25.78	33.00	29.46	27.50
175	T (°C)	9.3	27.5	41.1	10.3	26.4	37.6	9.8	27.0	39.4
	E (GPa)	33.00	28.45	25.00	30.56	27.50	25.00	31.73	27.97	25.00

Table 4 Elastic moduli of C50 concrete under different temperatures at different ages

Specimens Age(days)		X			Y			Z		
28	T (°C)	18.3	25.6	41.0	18.5	25.6	41.4	18.7	25.7	42.0
	E (GPa)	46.00	44.39	41.04	45.00	43.50	40.28	44.10	42.65	39.55
125	T(°C)	3.5	16.7	30.1	4.5	16.7	28.7	5.1	16.3	27.2
	E (GPa)	48.35	45.91	43.27	48.44	45.59	43.56	48.44	46.50	43.87
195	T(°C)	7.3	24.6	34.3	7.9	23.9	33.1	7.6	24.2	33.7
	E (GPa)	48.75	45.70	43.66	48.75	45.00	43.01	48.75	45.35	43.33

Notes: T is the average temperature of five thermal sensors of the temperature calibration specimen. E is the elastic modulus of the test specimen at temperature T.

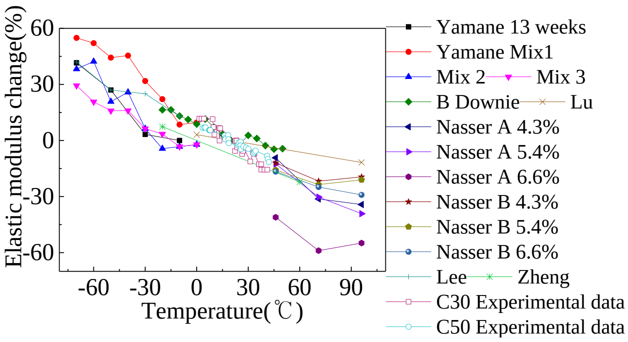


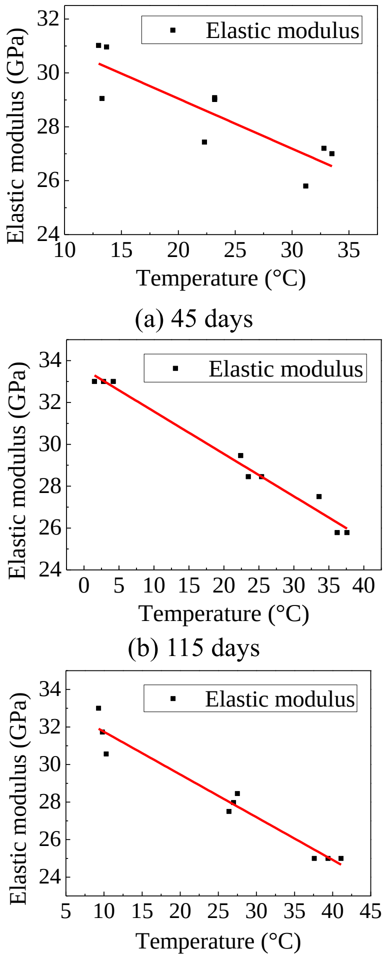
Fig. 7 Comparison of the elastic modulus change with temperature

As can be seen in Fig. 7, although existing studies cover different temperature ranges, the drop rates of elastic moduli with temperature are quite close to each other. This also indicates that the experimental data is reliable.

4.2 Regression analysis and discussion

4.2.1 Temperature effects

In order to eliminate the impact caused by age, elastic moduli obtained at different ages are analyzed respectively. Firstly, elastic moduli at the age of t days $E(t,T)$ are fitted with temperature. Next, elastic modulus at the age of t days and 20°C can be obtained as $E_{20°C}$ according to the regression equations. The temperature coefficient K is defined as the ratio of elastic modulus at temperature T to that at 20°C, $K=E(t,T)/E_{20°C}$. Finally, K is fitted with temperature.



(a) 45 days

(b) 115 days

(c) 175 days

Fig. 8 Variations of elastic moduli of C30 concrete with temperature at different ages

Elastic moduli of C30 concrete at the age of 45 days, 115 days and 175 days are fitted with temperature as shown in Fig. 8.

The regression models are:

$$\begin{aligned} &E(45,T) = 32.763 - 0.186T && R^2 = 0.71 \\ &E(115,T) = 33.596 - 0.203T && R^2 = 0.98 \\ &E(175,T) = 34.020 - 0.228T && R^2 = 0.94 \end{aligned} \tag{14}$$

where $E(t,T)$ is elastic modulus at the age of t days and temperature T.

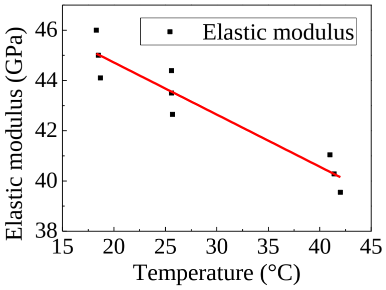
Elastic moduli of C50 concrete at the age of 28 days, 125 days and 195 days are fitted with temperature as shown in Fig. 9.

The regression models are:

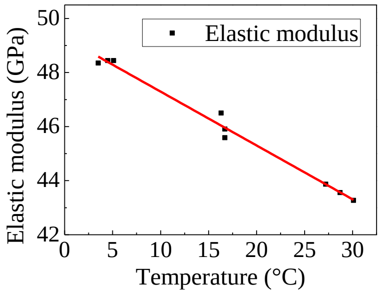
$$\begin{aligned} &E(28,T) = 48.862 - 0.207T && R^2 = 0.88 \\ &E(125,T) = 49.285 - 0.199T && R^2 = 0.99 \\ &E(195,T) = 50.319 - 0.206T && R^2 = 0.98 \end{aligned} \tag{15}$$

where $E(t,T)$ is elastic modulus at the age of t days and temperature T.

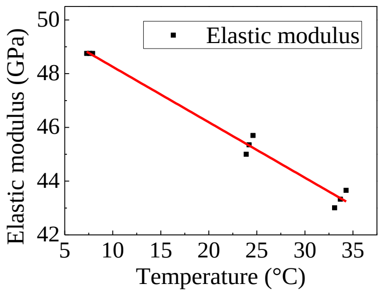
According to Eqs. (14) and (15), elastic modulus at the age of t days and temperature 20°C can be obtained as $E(t,20°C)$. Then the temperature coefficient K is calculated and fitted with temperature in Fig. 10. At a certain age t, K



(a) 28 days



(b) 125 days



(c) 195 days

Fig. 9 Variations of elastic moduli of C50 concrete with temperature at different ages

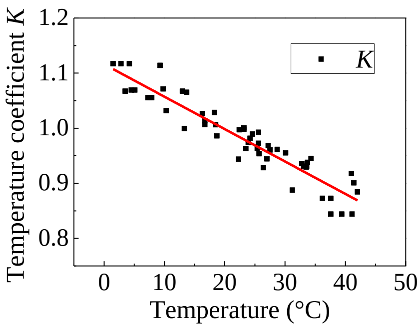


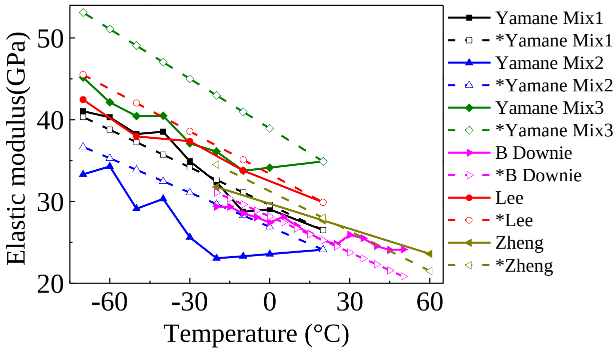
Fig. 10 Changes of temperature coefficient K with temperature

offers a method to calculate the elastic modulus of concrete at an arbitrary temperature on the basis of the elastic modulus obtained at a certain temperature.

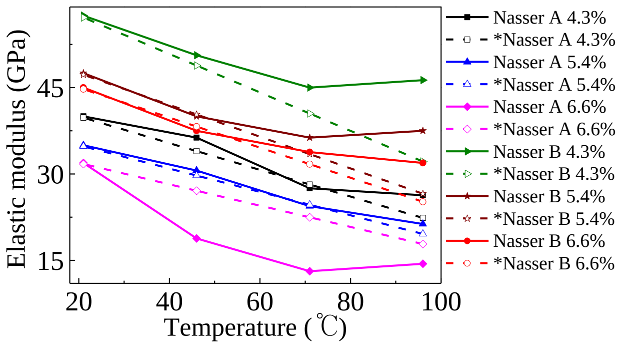
The regression model is:

$$K=1.116-0.006T \qquad R^2=0.89 \tag{16}$$

Experiments elastic moduli mentioned in section 2.1 are used to validate the temperature coefficient K. In terms of elastic modulus acquired at 20°C, elastic modulus at a



(a)



(b)

Fig. 11 Comparison of elastic moduli with its predictions

certain temperature is predicted by temperature coefficient K and compared with the original data as shown in Fig. 11. For the mentioned investigations in section 2.1, elastic moduli at different temperatures are obtained at the same day. Therefore, no age effects exists. Nasser's results (1973) are separately illustrated in Fig. 11(b) for clarify. The solid symbols are original experimental data and the hollow symbols are prediction data.

According to Fig. 11, experimental data shows an overall decrease of elastic moduli with the rise of temperature. In Fig. 11(a), the predictions agree well with the original data except Yamane's Mix 2 and 3. Yamane's Mix 2 and 3 display distinctive elastic moduli changes between -20°C and 20°C. The elastic modulus decreases with the decrease of temperature, which is opposite to the general trend. The reasons that attribute to these abnormal changes are unknown, but these abnormal changes may lead to the large differences between experimental data and prediction data. Shown in Fig. 11(b) are Nasser's results. When the temperature is below 70°C, the predictions agree well with original data, except for group A with 6.6% air contents. However, when the temperature is higher than 70°C, the inconformity becomes larger.

The deviations between the original data and the prediction data with temperature are plotted in Fig. 12.

As can be seen in Fig. 12, deviations of Yamane Mix 2, Yamane Mix 3 and Nasser A 6.6% exceed 20% and up to more than 70% in certain conditions. Except these three groups, other deviations are generally below 10%. When the temperature is higher than 70°C, the temperature coefficient K is inapplicable. Therefore, the effective range

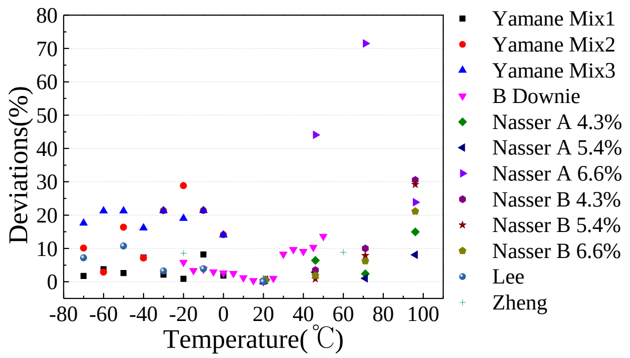
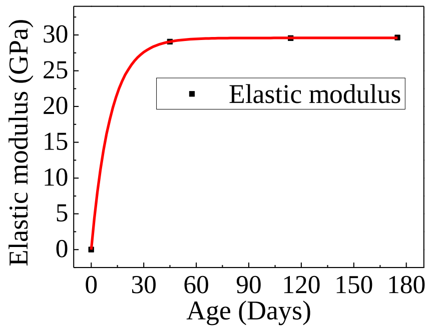
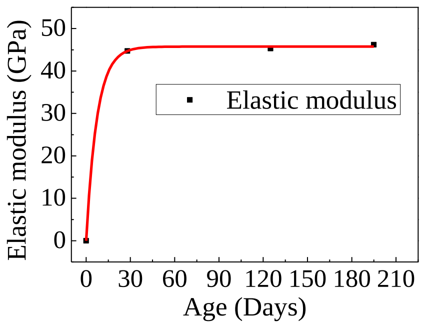


Fig. 12 Deviations between the original data and the prediction data with temperature



(a) C30 concrete



(b) C50 concrete

Fig. 13 Variations of the elastic modulus at 20°C with age

of temperature coefficient K is set to -80°C to 70°C, with the deviation less than 10%.

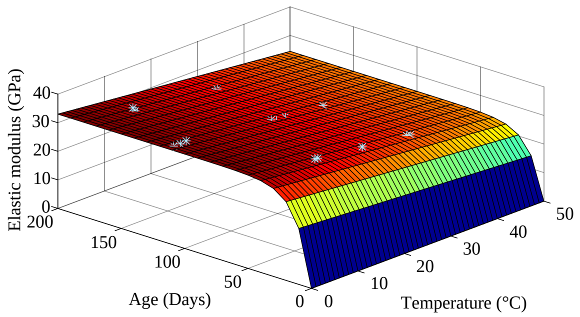
4.2.2 Age effects

As the elastic modulus of concrete also changes with respect to time, the effect of concrete aging should also be assessed. In order to eliminate the impact caused by environmental temperature, elastic moduli are normalized to 20°C according to Eqs. (14) and (15). By fitting elastic moduli with age, their evaluation with age is illustrated in Fig. 13.

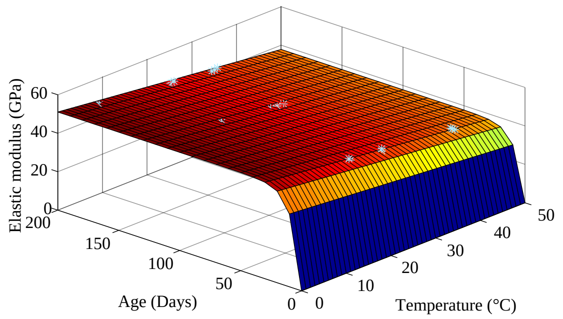
The regression equations of C30 and C50 concrete are:

$$\begin{aligned} &E_{C30}(t,20℃)=29.581-29.581e^{-t/11.125} \quad R^2=0.99 \\ &E_{C50}(t,20℃)=45.750-45.750e^{-t/7.377} \quad R^2=0.99 \end{aligned} \tag{17}$$

where $E_{C30}(t,20°C)$ is elastic modulus of C30 concrete at the age of t days and temperature 20°C, $E_{C50}(t,20°C)$ is elastic modulus of C50 concrete at the age of t days and temperature 20°C.



(a) C30 concrete



(b) C50 concrete

Fig. 14 Changes of the elastic modulus with temperature and age

As shown in Fig. 13, the elastic modulus increases sharply during the beginning 28 days and then increases slowly. Though experimental data regarding the advance of elastic modulus with age is limited, the authors' former work (Yang *et al*. 2018) can be referred to. It explored the development of elastic modulus of C30 concrete up to 975 days. In air conditions, concrete elastic modulus increased rapidly with age during the initial 150 days and then exhibited a smooth increase. Thus, the trend acquired in Fig. 13 is reliable.

4.2.3 Combined temperature and age effects

Based on Eq. (17) and taking the effect of temperature into consideration, changes of elastic modulus with temperature and age are expressed by the following equations:

$$\begin{aligned} &E_{C30}(t,T)=K(29.581-29.581e^{-t/11.125}) \\ &E_{C50}(t,T)=K(45.750-45.750e^{-t/7.377}) \end{aligned} \quad R^2=0.99 \tag{18}$$

where $E_{C30}(t,T)$ is elastic modulus of C30 concrete at the age of t days and temperature T,

$E_{C50}(t,T)$ is elastic modulus of C50 concrete at the age of t days and temperature T,

T ranges from -80°C to 70°C.

A comparison of the regression Eq. (18) and the experimental data is shown in Fig. 14.

When only temperature effects are taken into consideration in section 3.2.1, the residual mean square of temperature coefficient K is 0.89. Moreover, if both temperature and age effects are considered, the residual

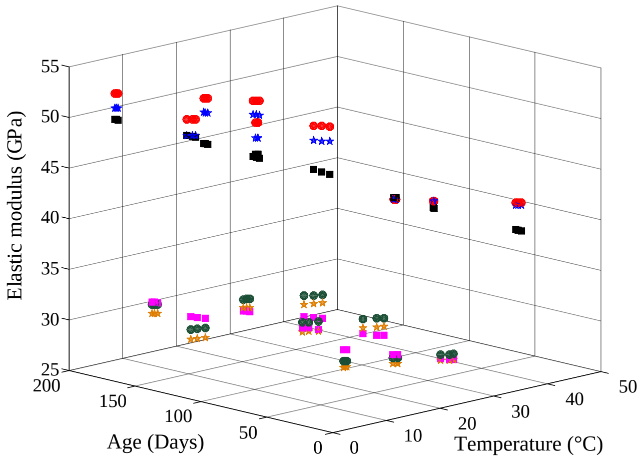


Fig. 15 Comparison of proposed equations, CEB-FIP and Shoukry's equations

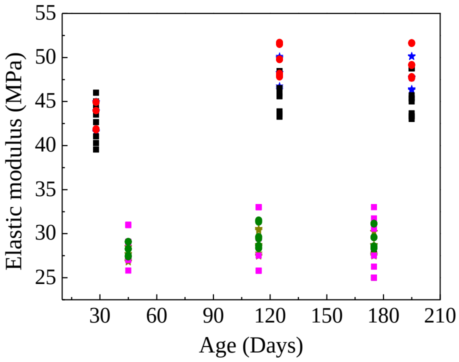


Fig. 16 Development of elastic moduli with age

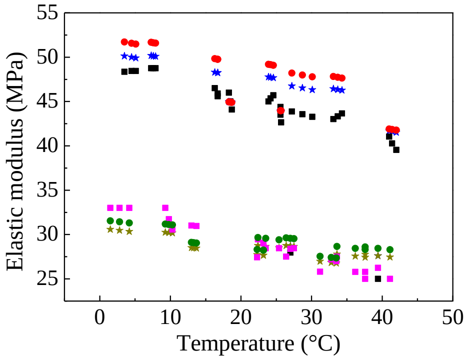


Fig. 17 Development of elastic moduli with temperature

mean square of the proposed Eq. (18) is 0.99. This indicates that the elastic modulus of concrete is mainly affected by temperature. It is also notable that age is a significant factor which contributes to more accuracy results.

The proposed Eq. (18) is compared with Shoukry's Eqs. (10) and (11) and CEB-FIP (9) in Fig. 15. Then the scatter is projected to 2D space as shown in Fig. 16 and Fig. 17.

It is found that the predicted elastic moduli obtained by Shoukry's method, CEB-FIP and the proposed method in this research coincide well with each other. The maximum deviation between them is less than 10%. Since Shoukry's method is proposed based on CEB-FIP, they have similar variation tendencies. In Fig. 16, when the ages of concrete are identical, the proposed data is more scattered, which reveals that the effect of temperature is more significantly in the proposed equations. This can also be reflected in Fig. 17.

5. Conclusions

To explore the effects of temperature and age on the elastic modulus of concrete, 76 prisms have been tested at three different ages and temperatures. The effects of temperature and age on the elastic modulus are analyzed respectively and then combined together. Some conclusions are made as follows:

- Elastic modulus of concrete decreases with the rise of temperature but increases with the increase of age. Furthermore, the effect of temperature is more significant than age.
- The proposed temperature coefficient K is reliable to describe the impact of temperature (varying from -80°C to 70°C) on elastic modulus of concrete, regardless of cement types, mix proportions, water to cement ratios, etc.
- The combined analytical models indicate a practical feasibility method for accurate determining the elastic moduli of concrete at the given ages and temperatures varying from -80°C to 70°C accurately.

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