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Long-term development of compressive strength and elastic modulus of concrete

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Abstract. Compressive strength and elastic modulus of concrete are constantly changing with age. In order to determine long-term development of compressive strength and elastic modulus of concrete, an investigation of C30 concrete cured in air conditions was carried out. Changes of compressive strength and elastic modulus up to 975 days were given. The results indicated that compressive strength and elastic modulus of concrete rapidly increased with age during the initial 150 days and then increased slowly. The gain in elastic modulus was slower than that of compressive strength. Then relationships of time-compressive strength, time-elastic modulus and compressive strength-elastic modulus were proposed by regression analysis and compared with other investigations. The trends of time-compressive strength and time-elastic modulus with age agreed best with ACI 209R-92. Finally, factors contributed to long-term development of compressive strength and elastic modulus of concrete were proposed and briefly analyzed.

Keywords: long-term properties; compressive strength; elastic modulus; influence factors

1. Introduction

During service life of concrete structures, long-term properties of concrete are of vital importance to security assessment and maintenance. Compressive strength of concrete is a fundamental parameter to describe properties of concrete. Rådman (1998) collected a great deal of strength data to evaluate whether it is feasible to take advantage of the possible increase in compressive strength to resist increasing loads. In the Danish Road Report 291 (2004), a guideline for reliability-based classification of existing bridges, a conservative increase in compressive strength of concrete was proposed when evaluating bearing capacity of existing bridges. Knowledge of time-compressive strength relationship is of significance when a structure is subjected to a certain type of loading at later age (AI-Khaiat 2001). Elastic modulus can control concrete behavior particularly in structural elements subjected to flexure (Baalbaki 1992). It is also useful in many analyses and design calculations, such as evaluating stiffness of structural members and estimating creep and shrinkage in concrete structures (Ahmadi-Nedushan 2012). Compressive strength and elastic modulus of concrete are traditionally characterized by the 28-day value. However, they gain growth over a long period of time after pouring the concrete (Chore and Shelke 2013). Most investigations pay more attention to the changes of concrete properties less than 28 days rather than long-term characteristics.

In this investigation, an experiment was carried out according to China's experimental standard - Standard for Test Method of Mechanical Properties on Ordinary Concrete (GB/T50081-2002) (2002) to explore long-term properties of concrete nearly 1000 days. The test methods of compressive strength and elastic modulus in GB/T50081-(2002) are the same with ISO 1920-10 (2010). Then relationships of time-compressive strength, time-elastic modulus and compressive strength-elastic modulus were proposed by regression analysis and compared with other investigations. The proposed regression models would possibly obtain the balance and equality between the quality (quality control process) and economics (saving time and expenses).

2. Literature review

2.1 Compressive strength

As to compressive strength, Komlos (1971) studied the increase of cube strength between 90 and 360 days. He found that when the water-cement ratio was 0.40, compressive strength at 90, 180 and 360 days increased 22%, 38%, and 63% compared to the value at 28 days respectively. Špak and Bašková (2015) fabricated several 150×150×150 mm cube specimens with 9 different fly ash cement ratios or water-cement ratios. The specimens were cured in water for up to 350 days and the compressive strength was tested at 2, 7, 28, 56, 120, and 350 days. The gain in compressive strength after 350 days ranged between 17% and 65% compared to that of 28 days. Dobrowolski

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(1993) discovered that in contrast to the value of 28 days, the compressive strength of concrete showed an increase of 35% and 61% after 3 months and 1 year. Washa *et al.* (1989) tested the compressive strength of a series of specimens with different cement types, mix proportions and methods of placement from 1 month to 50 years, which were cured outdoors after a 28-day moist-curing period. The specimens obtained an increase in compressive strength proportional to the logarithm of the age during the first 10 years and some variable changes thereafter. The average percent change in compressive strength was +65 percent from 1 month to 10 years, -5 percent from 10 to 25 years, -2 percent from 10 to 50 years, and +3 percent from 25 to 50 years.

Besides tests on specimens, long-term strength laws of in-service bridges were also explored. Rådman (1998) investigated the compressive strength increase by collecting data of 47 bridges built during the 20th century. The results indicated that the mean value of the increase was 41% with a standard deviation of 22% but with a single bridge obtaining no increase whatsoever and also two bridges showing a decrease in compressive strength. Aitcin and Laplante (1990) presented results on several cores drilled from the sidewalk concrete ranging from 4 to 6 years. The non-silica-fume concrete showed a 23%-40% gain in strength at the age of 2 years and 50% at 6 years. Thun et al. (2006) tested the compressive strength of drilled cores from 20 bridges during the years 1990-1994. Among them, 19 bridges were built during 1931 to 1946 and 1 bridge was built in 1962. Excluding a bridge with an unreasonable increase, the average increase of the remaining 19 bridges was approximately 20.7 MPa, which roughly corresponded to an increase of 70% compared to the strength at 28 days.

Beyond experimental tests, some methods have been developed to estimate the long-term strength of concrete. For example, Carino (2016) discussed two methods to estimate long-term strength of concrete, the maturity method and the accelerated curing method. Shelke and Gadve (2016) used the result of accelerated compressive strength of the concrete to develop the regression models to predict the short term and long term compressive strength of concrete. However, these methods are complicated and time-consuming, which limits their application.

In addition to discrete experimental data, relationships between compressive strength and age given by some codes are as follows.

1) CEB-FIP model code 1990 (1993):

For a mean temperature of 20°C and curing in accordance with ISO 2736/2,

$$f_{\mathrm{cm}}(t)=\beta_{\mathrm{cc}}(t)\,f_{\mathrm{cm}} \tag{1}$$

With

$$\beta_{\mathrm{cc}}(t)=\exp\left\{s\cdot\left[1-\left(\frac{28}{t/t_1}\right)^{1/2}\right]\right\} \tag{2}$$

Where $f_{\mathrm{cm}}(t)$ is the mean concrete compressive strength at an age of t days,

$\beta_{\mathrm{cc}}(t)$ is a coefficient which depends on the age of concrete t,

f_{cm} is the mean compressive strength after 28 days,

s is a coefficient which depends on the type of cement: s=0.20 for rapid hardening high strength cement, 0.25 for normal and rapid hardening cement, and 0.38 for slowly hardening cement,

t_1=1 day.

2) Explanatory Handbook on Indian Standard Code of Practice for Plain and Reinforced Concrete (1998)

$$f_{\mathrm{t}}=\frac{t}{a+bt}f_{28} \tag{3}$$

Where f_{t} is the strength at t days,

a and b are empirical constants, a=4.7 and b=0.833,

f_{28} is the strength at 28 days.

3) ACI 209R-92 (1992)

$$(f'_{\mathrm{c}})_{\mathrm{t}}=\frac{t}{\alpha+\beta t}(f'_{\mathrm{c}})_{28} \tag{4}$$

Where $(f'_{\mathrm{c}})_{\mathrm{t}}$ is compressive strength at t days,

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 reference to Standard Specification for Portland Cement (2012), $(f'_{\mathrm{c}})_{28}$ is 28-day strength.

2.2 Elastic modulus

Compared to compressive strength, fewer reports care about long-term elastic modulus of concrete. Washat and Fluck (1950) presented the elastic modulus change of concrete specimens which were made of three different cement and three different water-cement ratios over 10.5 years. It was found that elastic modulus increased 2%-33.2%, except specimens made with one kind of cement exhibited a decrease in elastic modulus. Mazotti and Savoia (2012) fabricated some conventional vibration C50 concrete specimens and found that elastic modulus grew with time. Elastic modulus at 120 and 180 days increased 11% and 2% respectively compared to that at 28 days.

Similarly, some relationships between elastic modulus and age are given as follows.

1) CEB-FIP model code 1990 (1993)

$$E_{\mathrm{ci}}(t)=\beta_{\mathrm{E}}(t)\,E_{\mathrm{ci}} \tag{5}$$

With

$$\beta_{\mathrm{E}}(t)=[\beta_{\mathrm{cc}}(t)]^{0.5}=\sqrt{\exp\left\{s\cdot\left[1-\left(\frac{28}{t/t_1}\right)^{1/2}\right]\right\}} \tag{6}$$

Where $E_{\mathrm{ci}}(t)$ is the modulus of elasticity at an age of t days,

$\beta_{\mathrm{E}}(t)$ is a coefficient which depends on the age of concrete,

E_{ci} is the modulus of elasticity at an age of 28 days,

The meaning of other letters is the same with Eqs. (1) and (2).

2) ACI-209R-92 (1992)

$$E(t) = (\frac{t}{\alpha + \beta t})^{1/2} E_{28} \tag{7}$$

Where $E(t)$ is the modulus of elasticity at an age of t days,

E_{28} is the modulus of elasticity at an age of 28 days,

The meaning of the other letters is the same as equation (4).

2.3 Relationship between compressive strength and elastic modulus

Concrete compressive strength can be easily and rapidly determined without sophisticated equipments, while measuring modulus of elasticity is a time-consuming work. Therefore, it has always been very attractive to try to find a simple relationship between compressive strength and elastic modulus of concrete. There are mainly three kinds of equations on compressive strength-elastic modulus relationship: linear, radical, and fraction which are as follows.

1) Hongstead (1951)

$$E_c = 1800000 + 460(f_0) \text{ (in psi)} \tag{8}$$

Where E_c is the elastic modulus,

f_0 is the compressive strength.

2) ACI 363R-10 (2010)

$$E_c = 3320(f_c')^{0.5} + 6900 \text{ (MPa)} \quad \text{for } 21\text{MPa} < f_c' < 83\text{MPa} \tag{9}$$

Where E_c is the elastic modulus,

f'_c is the compressive strength.

3) ACI 318-14 (2014)

$$E_c = 57000\sqrt{f_c'} \quad \text{(in psi)} \tag{10}$$

Where E_c is the elastic modulus,

f'_c is the compressive strength.

4) TS 500 (2000)

$$E_c = 3250(f_c)^{0.5} + 14000 \text{ (MPa)} \tag{11}$$

Where E_c is the elastic modulus,

f_c is the compressive strength.

5) GB 50010-2010 (2010)

$$E(t) = (\frac{t}{\alpha + \beta t})^{1/2} E_{28} \tag{12}$$

Where E_c is the elastic modulus,

$f_{cu,k}$ is cube compressive strength standard value.

As mentioned above, there are some investigations on long-term development of compressive strength and elastic modulus of concrete, but most existing research concentrates on age from 28 days to 1 year. Few investigations concern the properties of concrete whose age exceed 1 year, except Aitcin (1990) (6 years) and Washa *et al*. (1989) (50 years). However, Aitcin's (1990) specimens were drilled from sidewalk concrete, which was affected by other factors such as external loads. Though Washa *et al*. carried out compressive strength test of different kinds of concrete up to 50 years, compressive strength at only 1 month, 1 year, 5 years, 10 years and 25 years were obtained. The experimental data was sparse and test interval was too long. Secondly, some data was obtained by field tests of in service bridges, which cannot consider other factors such as environmental factors, external loads, and damage. Finally, very few attempts were made to explain why compressive strength and elastic modulus change with age.

There are two points that need to be noted. One is that during 1930s and 1940s, Portland cement had a different ratio of dicalcium silicate (C_2S) and tricalcium silicate (C_3S) and was more coarsely ground, which results in higher early strength and a lower increase. However, both "old" and "modern" concrete exhibit similar long-term trends in strength development (Gonnerman and Lerch 1952). The other is that though concrete specimens studied by different researchers were made of different water-cement ratios, cement contents, aggregate contents, admixture types, and dosages, or cured under different conditions, within normal range which is often used, the influence is not obvious (AI-Khaiat and Fattuhi 2001, Waddell 1953, Wood 1991).

Table 1 Mix proportion of concrete

Strength grade	C30	Water-binder ratio	0.46	Water-cement ratio	0.46	Sand ratio	44.0%
Component	Cement	Water	Sand	Stone	Fly ash	Admixture	Mineral Powder
Content per cubic meter (kg/m^3)	245	170	786	1004	73	7.7	65
Alkali content (kg/m^3)	1.52	Mix proportion			1:0.46:2.05:2.62		

3. Experimental program

3.1 Specimens preparation

Portland cement (P.O 42.5), medium sand, gravel of 25 mm maximum size, polycarboxylic acid, I grade fly ash, and mineral powder S95 were chosen as the concrete admixture. The mix proportion of concrete used is given in Table 1 which was according to the Specification for Proportion Design of Ordinary Concrete (2011).

48 prism specimens whose size is 100×100×300 mm were casted and cured in air condition. After 24 hours, they were demolded. The specimens were divided into 8 groups to test compressive strength and elastic modulus at the age of 28, 35, 50, 110, 150, 480, 700, and 975 days.

3.2 Test methods and instrumentation

The tests were carried out on the compression-testing machine according to Standard for Test Method of Mechanical Properties on Ordinary Concrete (GB/T50081-2002) (2002) as shown in Fig. 1(a).

Compressive strength and elastic modulus were tested with 6 prism specimens. Among them, 3 specimens were tested to determine compressive strength. Firstly, specimens' surface as well as upper and lower bearing boards were cleaned. Then the specimen was placed on the lower bearing block and the axis of the specimen was

(a) Compression-testing machine

(b) Failure mode of a specimen

Fig. 1 Compressive strength test

aligned with the center of thrust of the spherical head. The process is illustrated in Fig. 1(b). The loading rate was 0.5-0.8 MPa per second. The failure load should be recorded when the specimen was crushed.
The prism compressive strength is calculated as follows

$$f_{cp} = \frac{F}{A} \tag{13}$$

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 another 3 prism specimens. The deformation measuring instruments (dial gauges) were installed on both sides of the specimen. First of all, steadily increase load to F_0 (the benchmark stress was 0.5 MPa) at a rate of 0.5-0.8 MPa per second. Maintain the load for 60 seconds and record the value of dial gauges ε_0 during the succeeding 30 seconds. Secondly, increase load to F_a which was one third of f_{cp} and maintain for 60 seconds. Read dial gauges' value ε_a at the same time. If the strains differ by more than 20% from their mean value, former operation should be repeated. Otherwise, decrease the load to F_0 with the same loading rate and last for 60 seconds. After completion of the last preloading cycle and a waiting period of 60 seconds under the load F_0, record the strain readings ε_0 during the succeeding 30 seconds. Reload the specimen to load F_a and record the strain reading ε_a during the succeeding 30 seconds. The loading process is

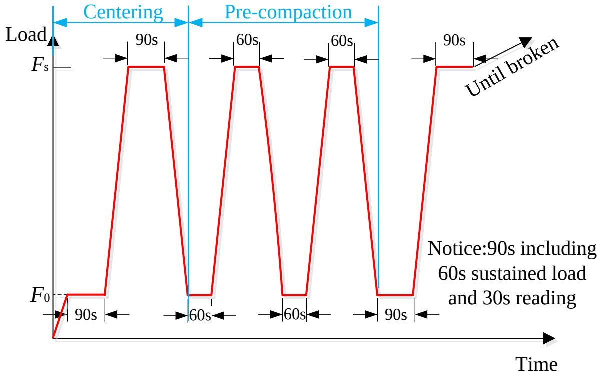
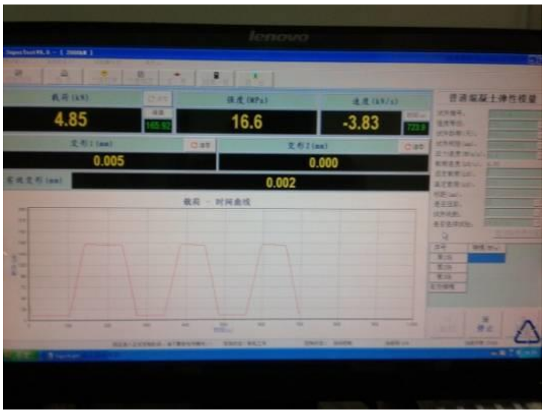


Fig. 2 Loading method of elastic modulus test



(a) Operating system interface

(b) Concrete elastic modulus test

Fig. 3 Elastic modulus test

shown in Fig. 2. Finally, when all elasticity measurements have been completed, increase the load on the test specimen until failure of the specimen occurred. The test process is shown in Fig. 3.

Elastic modulus is calculated as follows

$$E_c = \frac{F_a - F_0}{A} \times \frac{L}{\Delta n} \qquad \Delta n = \varepsilon_a - \varepsilon_0 \tag{14}$$

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 pressure surface (mm^2),

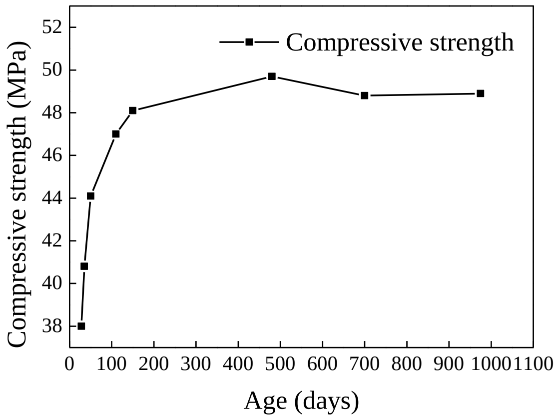


Fig. 4 Compressive strength with age

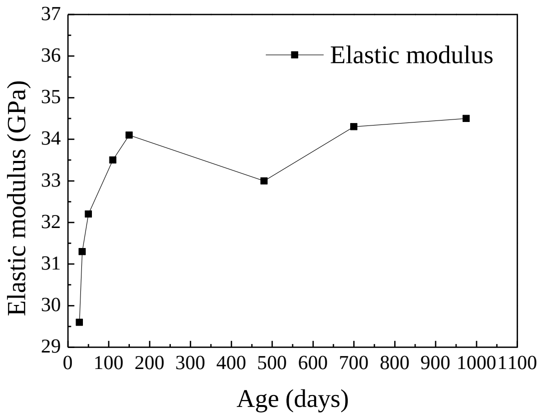


Fig. 5 Elastic modulus with age

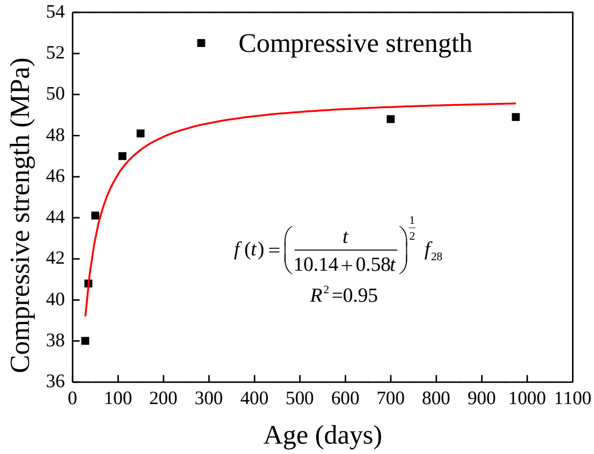


Fig. 6 Evaluation of compressive strength with age

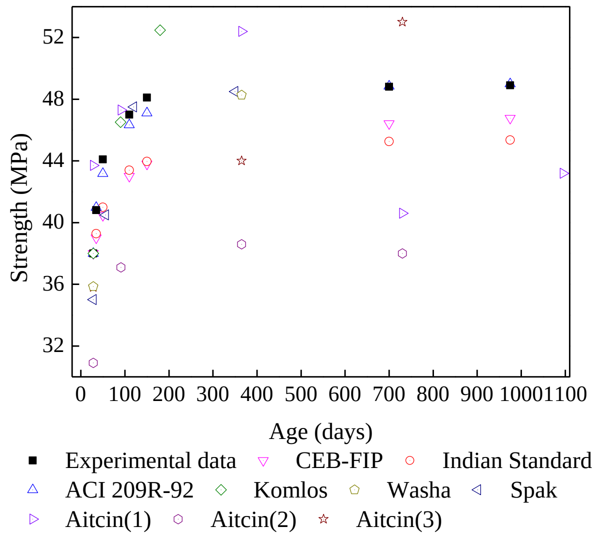


Fig. 7 Compressive strength comparison of different investigations with experimental data

L is the gauge length (mm),

ε_a is the average deformation value of both sides of the specimen when the load is F_a (mm),

ε_0 is the average deformation value of both sides of the specimen when the load is F_0 (mm).

4. Results and discussion

4.1 Test results

The compressive strength and elastic modulus at different age are shown in Figs. 4 and 5.

Generally, the compressive strength increased with age, which was consistent with many other investigations. At 35, 50, 110, 150, 480, 700, and 975 days, the strength increased 7.4%, 16.1%, 23.7%, 26.6%, 30.8%, 28.4%, and 28.7% respectively compared to the value of 28 days. What's more, a significant gain of strength before 150 days was observed. After that, the increase slowed down. The compressive strength at 150 days was 93% of that at 975 days.

The change of elastic modulus was similar to that of compressive strength. At 35, 50, 110, 150, 480, 700, and 975 days, it increased 5.7%, 8.8%, 13.2%, 15.2%, 16.7%, 15.9%, and 16.6% respectively compared to the value at 28 days. Also, during the initial 150 days, the elastic modulus increased distinctly, which accounted for 92% of the 975 days' elastic modulus. Moreover, compared to compressive strength, the growth of elastic modulus was slower.

It is noted that data obtained at 480 days was not in harmony with other data, especially the elastic modulus. It is obviously impossible that the compressive strength increased while the elastic modulus decreased, since the evaluation of elastic modulus is consistent with that of compressive strength. What's more, according to other investigations mentioned above, elastic modulus increases with age. Therefore, test data at 480 days should be abandoned in the following analysis.

4.2 Regression analysis and discussion

4.2.1 Evaluation of compressive strength with age

Based on compressive strength at 28 days, evaluation of compressive strength with age is fitted in Fig. 6 as follows.

The regression equation is

$$f(t)=\left(\frac{t}{10.14+0.58t}\right)^{\frac{1}{2}} f_{28} \quad R^2=0.95 \qquad (15)$$

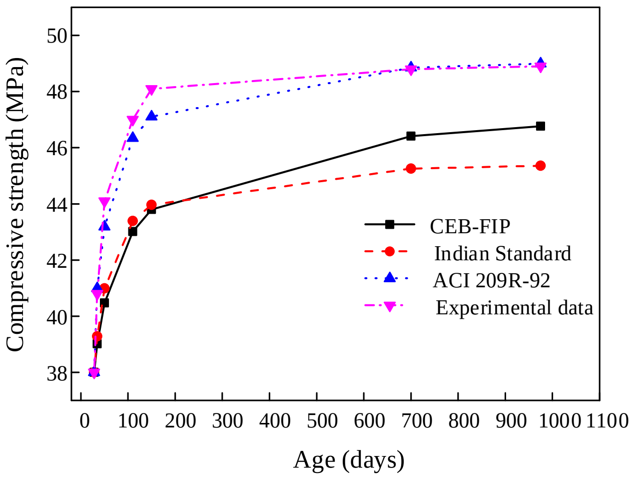


Fig. 8 Compressive strength comparison of empirical formulas with experimental data

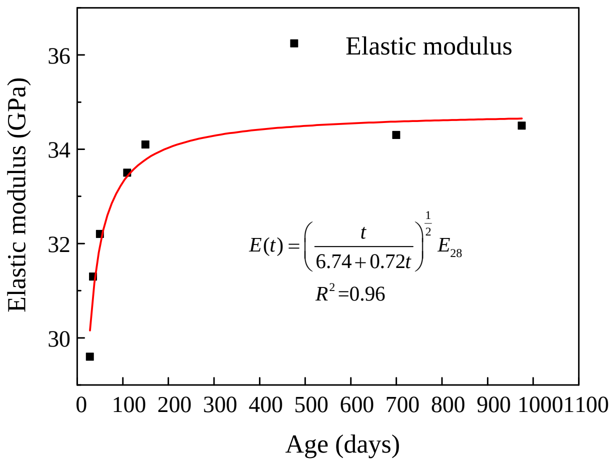


Fig. 9 Evaluation of elastic modulus with age

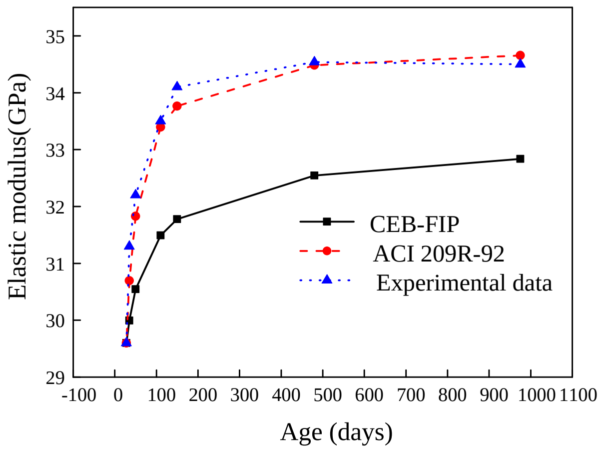


Fig. 10 Elastic modulus comparison of different equations with experimental data

Where $f(t)$ is the concrete compressive strength at an age of t days,

f_{28} is the compressive strength at 28 days.

The regression formula is the same with Explanatory Handbook on Indian Standard Code of Practice for Plain and Reinforced Concrete (1998) and ACI 209R-92 (1992). The residual mean square is 0.95, which indicates that the regression equation is consistent with the experimental results well.

Experimental data is compared with investigation results of Komlos (1971), Špak and Bašková (2015), Aitcin and Laplante (1990), Washa *et al.* (1989), CEB-FIP (1993), Indian Standard (1998) and ACI 209R-92 (1992) as illustrated in Fig. 7. It is worth noting that the experiment lasts less than 1100 days, so strength data more than 1100 days is ignored.

The trend in compressive strength gain is observed in Fig. 7. Since the specimens mentioned above were made by different mix proportions and materials at different time, there is no strongly comparison of the strength value among them. However, strength development proposed by empirical formula of CEB-FIP (1993), Indian Standard (1998), and ACI 209R-92 (1992) are applicable for most specimens, as a result of which experimental time-compressive strength relationship compared with empirical formulas are extracted and plotted in Fig. 8. For CEB-FIP (1993), Indian Standard (1998), and ACI 209R-92 (1992), the compressive strength at 28 days is determined by experimental data.

During the initial 150 days, compressive strength increased significantly. For CEB-FIP (1993), Indian Standard (1998), ACI 209R-92 (1992), and experimental data, the 150 days' compressive strength accounted for 66%, 81%, 83%, and 93% of 975 days respectively. The variation of experimental data was consistent with ACI 209R-92 (1992) both in value and development trend. The variation trend was also consistent well with Indian Standard (1998), but there was a biggest difference in amplification. The variation of Indian Standard was slower than experimental data. The maximum difference between the two equations was less than 8%. Compressive strength of CEB-FIP (1993) agreed well with Indian Standard (1998) before 150 days. While after that, it still increased obviously and the difference between CEB-FIP (1993) and experimental data was smaller and smaller. For example, at 2000 days, the compressive strength of CEB-FIP (1993) is 47.37 MPa, while the experimental data will reach to 49.68 MPa (calculated according to Eq. (15)). Different strength value calculated by various equations may be caused by different sizes of specimens, curing conditions and experimental methods.

4.2.2 Evaluation of elastic modulus with age

Evaluation of elastic modulus with age is fitted in Fig. 9. The regression equation is

$$E(t)=\left(\frac{t}{6.74+0.72t}\right)^{\frac{1}{2}}E_{28} \quad R^2=0.96 \tag{16}$$

Where $E(t)$ is the concrete elastic modulus at an age of t days,

E_{28} is the elastic modulus at 28 days.

The regression formula is also the same with ACI 209R-92 (1992). The residual mean square is 0.96, which indicates that the regression equation is consistent with the experimental results well. A comparison of different

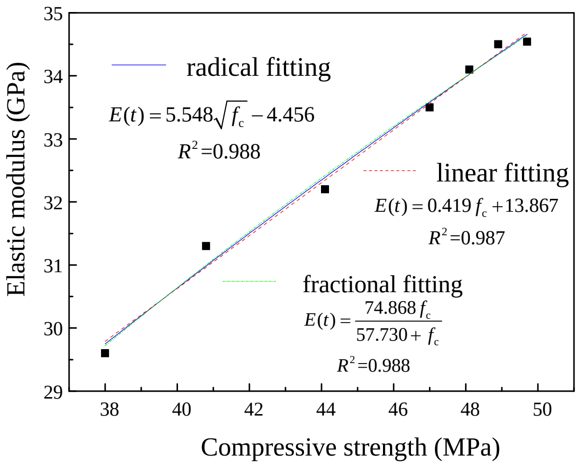


Fig. 11 Prediction of elastic modulus with compressive strength

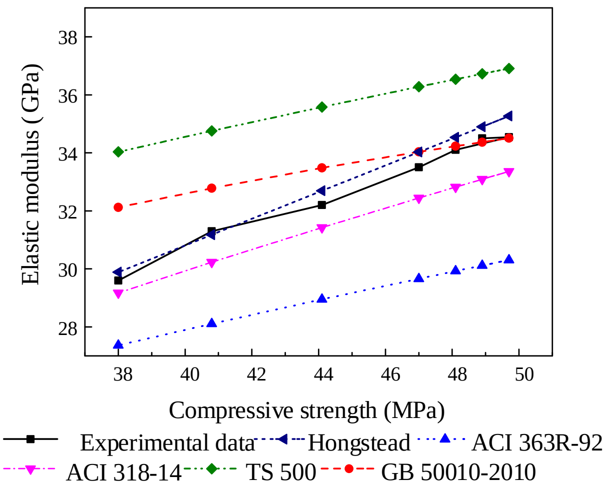


Fig. 12 Comparison of different equations with experimental data

equations and experimental data is shown in Fig. 10.

Contrasted to compressive strength, there are few investigations explore the evaluation of elastic modulus with age. During the initial 150 days, elastic modulus increased with age significantly. For CEB-FIP (1993), ACI 209R-92 (1992), and experimental data, the 150 days' value accounted for 67%, 82%, and 92% of the 975 days. The variation of experimental data agreed better with ACI 209R-92 (1992) both in value and development trend, which is the same with compressive strength. The variation trend was also consistent with CEB-FIP (1993), but there was a biggest difference in amplification. The variation of CEB-FIP (1993) was slower than experimental data. The maximum difference of the two equations was less than 8%.

4.2.3 Relationship between compressive strength and elastic modulus

The relationship between compressive strength and elastic modulus is fitted in Fig. 11.

Since there are mainly three kinds of equations, experimental data was fitted with three forms as follows.

1) Radical fitting

$$E(t)=0.5548\sqrt{f_c}-0.4456 \qquad R^2=0.988 \tag{17}$$

2) Linear fitting

$$E(t)=0.0419f_c+1.3867 \qquad R^2=0.987 \tag{18}$$

3) Fractional fitting

$$E(t)=\frac{7.4868f_c}{57.7304+f_c} \qquad R^2=0.988 \tag{19}$$

Where $E(t)$ is the concrete elastic modulus at an age of t days,

f_c is the compressive strength at t days.

Though the form of these equations is different, the correlation coefficients are almost the same, which means that any equation can predict the relationship between elastic modulus and compressive strength accurately.

A comparison of different equations and experimental data is shown in Fig. 12.

According to Fig. 12, the experimental compressive strength-elastic modulus curve lies among other curves. The slope of ACI 363R-92 (1992), ACI 318-14 (2014), TS 500 (2000), and GB 50010-2010 (2010) are similar though the values have a small difference.

4.2.4 Error analysis

According to Figs. 8, 10, and 12, experimental data's development of compressive strength and elastic modulus vary with age as well as the relationship between them is similar to other investigations, but the numerical values have some differences. There are mainly three reasons. First of all, specimens were made of different water-cement ratios, aggregate contents, admixture types and so on. Secondly, the curing conditions and placement environment are different. Finally, the test methods may have some distinctions. Nonetheless, as the same kind of material-concrete, their hydration mechanism is identical. In the following section, mechanism of the development of compressive strength and elastic modulus is analyzed.

4.3 Mechanism analysis

There are some factors that may contribute to the development of strength and elastic modulus of concrete. First of all, cement hydration happens continuously. Cement hydration is a slow process from surface to interior. With the increase of cement hydration, the porosity decreases and a reduction of porosity in concrete increases its strength (Chen *et al*. 2013). Secondly, micro cracks can heal autogenously with age. Micro cracks occur to relieve stresses. After that, cracks may close due to the continuous hydration and expansion of cement mortar. The decrease of cracks contributes to the increase of compressive strength and elastic modulus of concrete.

As to in-service bridges, various loads are exerted on them. Washat and Fluck (1950) as well as Hughes and Ash's (1970) investigations all showed that long-term load will improve the compressive strength and the elastic modulus of concrete. Some researchers ascribed the increase in strength to a "forced" hydration of the cement due to the water in concrete being under pressure. In addition, creep occurs under the influence of sustained loading. The process of creep can release stress concentrations in concrete. This and the subsequent aging of the concrete can result in a solid body compaction. As a consequence, the compressive strength and elastic modulus increase with age.

Compared to compressive strength, the growth of elastic modulus was slower. This is due to that compressive strength and elastic modulus are influenced by different factors. In general, the strength of aggregate is larger than that of cement mortar. However, the compressive strength of concrete is determined by the strength of cement mortar. Also, the elastic modulus of aggregate is larger than of cement mortar. Elastic modulus of concrete increases with the increase of aggregate's elastic modulus and volume, while the effect of cement mortar's elastic modulus is not as distinct as aggregate. As time goes by, the strength of cement mortar increases, while the strength of aggregate is almost unchanged. As a result of these, the growth of compressive strength is more distinctly than that of elastic modulus.

5. Conclusions

Results of investigations on long-term compressive strength and elastic modulus of concrete were reported in this paper. 48 specimens were tested at the age between 28 days and 975 days. Relationships of time-compressive strength, time-elastic modulus and compressive strength-elastic modulus were proposed and compared with other investigations. The number of specimens is limited and the proposed equations on evaluation of compressive strength and elastic modulus with age do not apply to all situations, but they can still reflect the development of compressive strength and elastic modulus as well as provide a reference for others. Some conclusions can be drawn as follows:

- In air conditions, compressive strength and elastic modulus of concrete rapidly increased with age during the initial 150 days and then increased slowly.
- The gain in elastic modulus was slower than that of compressive strength. At 975 days, the compressive strength showed an increase of 28.7% compared to that of 28 days while the elastic modulus increased only 16.6%.
- Relationships of time-compressive strength, time-elastic modulus and compressive strength-elastic modulus were proposed and proved reasonable which can be a reference to other investigations.
- The development of time-compressive strength and time-elastic modulus are in agreement with ACI 209R-92 (1992).
- The increase of compressive strength and elastic modulus of concrete may be attributed to the continuation of cement hydration, autogenous healing of micro cracking, external loads, and creep.

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