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# Evaluation of early age mechanical properties of concrete in real structure

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**Abstract.** The curing temperature is known to influence the rate of mechanical properties development of early age concrete. In realistic sites the temperature of concrete is not isothermal 20˚C, so the paper measured adiabatic temperature increases of four different concretes to understand heat emission during hydration at early age. The temperature-matching curing schedule in accordance with adiabatic temperature increase is adopted to simulate the situation in real massive concrete. The specimens under temperature-matching curing are subjected to realistic temperature for first few days as well as adiabatic condition. The mechanical properties including compressive strength, splitting strength and modulus of elasticity of concretes cured under both temperature-matching curing and isothermal 20˚C curing are investigated. The results denote that comparing temperature-matching curing with isothermal 20˚C curing, the early age concretes mechanical properties are obviously improved, but the later mechanical properties of concretes with pure Portland and containing silica fume are decreased a little and still increased for concretes containing fly ash and slag. On this basement using an equivalent age approach evaluates mechanical properties of early age concrete in real structures, the model parameters are defined by the compressive strength test, and can predict the compressive strength, splitting strength and elasticity modulus through measuring or calculating by finite element method the concreted temperature at early age, and the method is valid, which is applied in a concrete wall for evaluation of crack risking.

**Keywords:** concrete; temperature-matching curing; equivalent age; mechanical properties; early age

## 1. Introduction

Fundamentally concrete structures showed various behaviors after being placed at construction sites due to the stress inducing mechanisms of hydration heat, autogenous shrinkage, and drying shrinkage (Schutter 2002, Maria 2002). Prediction of the early age mechanical properties was essential for modernized concrete construction as well as for the manufacturing of structural parts (Gutsch 2002, Wirquin *et al*. 2002, Lu *et al*. 2010, Kim *et al*. 2008). Safe and economic scheduling of such crucial operations as form removal and reshoring, application of post-tensioning or other mechanical treatment, and in-process transportation and rapid delivery of products should be based upon a good grasp of the strength development of the concrete in use. It is found that the

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performance of concrete in real structures is quite different from concrete prepared in laboratory and cured under standard conditions because the hydration heat of Portland cement makes the temperature in the core of concrete structure increase gradually (Breugel 1998, Broda *et al*. 2002, Farry *et al*. 1989). The most of hydration heat resealed at early age, and the hydration heat should enhance greatly the hydration of composite binders containing mineral admixtures in concrete. Therefore the mechanical properties of concrete containing mineral admixture are greatly affected by concrete self-heating (Kahouadji *et al*. 1997). More recent research (Sukumar *et al*. 2008, Hans *et al*. 2012, Ballim *et al*. 2004) states that the degree of hydration concept is a fundamental method and the equivalent age based hydration degree is currently used for the estimation of concrete mechanical properties at early age. For the verification and prediction of concrete behavior, numerical schemes such as the finite element method are considered powerful tools (Schutter 2002, Zhenhuan *et al*. 2011, Kim *et al*. 2012, Gang *et al*. 2012). The numerous efforts have been undertaken to develop constitutive material models for the description of the mechanical behavior

Table 1 Physical properties and chemical compositions of raw materials

| Physical properties | | | | | | | Cement | Fly ash | Silica fume | Slag |
|---|---|---|---|---|---|---|---|---|---|---|
| Density, g/cm$^3$ | | | | | | | 3.15 | 2.20 | 2.2 | 2.9 |
| Median particle size, $\mu$m | | | | | | | 17.0 | 35.4 | - | - |
| Water requirement, % | | | | | | | - | 95 | - | - |
| Chemical composition, % | | | | | | | | | | |
| | $SiO_2$ | $A1_2O_3$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | $Na_2O_{eq}$ | $SO_3$ | LOI |
| Cement | 22.80 | 4.55 | 2.82 | 65.34 | 2.74 | - | - | 0.55 | 2.92 | 3.9 |
| Fly ash | 57.6 | 21.9 | 7.7 | 3.87 | 1.68 | 2.51 | 1.54 | - | - | 2.9 |
| Silica fume | >85.0 | - | - | - | - | - | - | <1.5 | - | 2.2 |
| Slag | 34.63 | 13.92 | 029 | 38.28 | 10.52 | - | - | - | 0.25 | 0.25 |

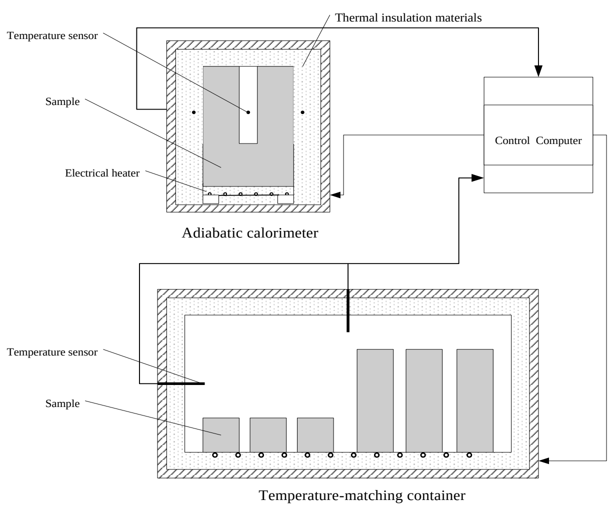


Fig. 1 Schematic diagram of the test

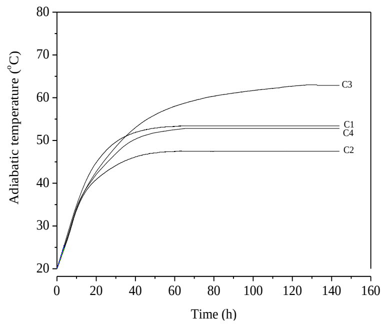


Fig. 2 Concrete adiabatic temperature increase curves

of early age concrete. But the mechanical properties of early age concrete need more effectively calculated formulas in a real construct, which are often used to predict the cracking or failure of concrete structures as requisite data. The object of this research is based on the equivalent age which makes it possible to predict the concrete's mechanical properties evolution in a structure on the basis of 20˚C characterization. Assessment of hydration heat and mechanical properties such as compressive strength, splitting strength and elastic modulus are considered in this paper. For this purpose a temperature-matching curing (TMC) schedule in accordance with the adiabatic temperature increase of concrete is adopted to simulate the situation in real massive concrete. The mechanical performance of concrete under TMC and standard conditions isothermal 20˚C curing are investigated.

## 2. Experiment

### *2.1 Materials*

PO42.5 ordinary Portland cement complying with the Chinese National Standard GB 175-1999 and a kind of fly ash qualified as first class according to the Chinese National Standard GB 1596-91 is used. The specific surfaces of cement and slag with Blaine measured are 350 $m^2$/kg and 430 $m^2$/kg. Silica Fume, with a surface area on about 20000 $m^2$/kg when measured by nitrogen absorption technique is used in study. Their chemical composition and physical properties are given in Table 1.

A polycarboxylic superplasticizer is used to prepare concrete. Crushed limestone with a size range of 5~20 mm and natural river sand with a fineness modulus of 3.0 are used as coarse and fine aggregate.

### *2.2 Proportions and properties measuring of concrete*

The proportions of the concrete mixes are summarized in Table 2. All mixes are prepared in a 60 liter of capacity rotary pan mixer. The dry materials are premixed for 1 min. Then water is added and the mixing is continued for an additional 3 min. Superplasticizer is used to enhance the workability of mix C4. According to Chinese standard strength grade of these concretes is from C30 to C40 and these kinds of concretes are mainly used in real structure of china now.

Table 2 Proportions of the concrete mixtures (Kg/m3)

| Mix No. | W/B | Water | Cement | Fly ash | slag | Silica fume | Fine aggregate | Coarse aggregate | SP | Slump (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| C1 | 0.50 | 184 | 368 | - | - | - | 694 | 1132 | - | 82 |
| C2 | 0.50 | 184 | 294 | 74 | - | - | 683 | 1116 | - | 75 |
| C3 | 0.50 | 184 | 294 | - | 74 | - | 692 | 1128 | - | 60 |
| C4 | 0.50 | 184 | 332 | - | - | 36 | 690 | 1124 | 0.55 | 70 |

The adiabatic temperature increase of fresh concrete is determined using a computer controlled measuring system in Fig. 1. The peripheral temperature of a fresh concrete sample is controlled at 0.1˚C lower than the central temperature. Data are recorded once every 5min until the temperature ceases to change. The temperature-matching container is controlled curing temperature according to the control computer indication. The test apparatus is shown in Fig. 1.

Tests are carried out at different ages under isothermal and realistic temperature histories. The specimens are covered with plastic film and water-saturated burlap at 20 ± 2˚C for 12 h and then placed in the temperature-matching curing tank with mould. The specimens are demoulded after 24h and are still kept over water in the temperature-matching curing tank. The temperature in the container rises from ambient temperature according to the adiabatic temperature profile of each concrete mixture. The temperature in the container is controlled according to Fig. 2. After temperature fell to ambient temperature, the specimens are cured in isothermal 20 curing. At predetermined intervals of 1, 2, 3, 4, 5, 7 and 28 days specimens are remove from their container and cooled to ambient temperature.

### *2.3 Description of the test methods*

The specimens of test are carried out: compressive strength tests: 100×100×100 mm cubes; splitting strength: 100×100×100 mm cubes; elastic modulus in compression: 100×100×300 mm prisms. The modulus of elasticity is determined according to the Chinese Standard GB/T50081-2002 (Standard for test method of mechanical properties on ordinary concrete). Indirect tensile test methods like the tensile splitting test have been widely used because of the difficulties experienced with direct tensile methods. In splitting test, the specimen is loaded along tow opposite faces. According to linear elastic theory, the tensile splitting strength at failure, $f_{ts}$ is found as Eq.(1).

$$f_{ts} = \frac{2p}{\pi A} \tag{1}$$

Where, $P$ is the failure load, $A$ is splitting area. A wooden fiber stip, 15 mm in width and 4 mm in thickness, is used to transmit the load to the concrete. The 100 mm cube is used in compressive strength testing. The tests are performed with a loading rate 0.3-0.5 MPa/s .

## 3. Results and discussion

### *3.1 Temperature-matching curing*

The concretes adiabatic temperature increase curves as Fig. 2 are obtained by adiabatic tests, and the concrete hydration release heat make itself temperature increase at adiabatic system at early age. The different concrete hydration ability is different, therefore the curves is different. Concrete C1 with pure Portland cement reach temperature peak after about 48hours, concrete C3 with 10% dosage silica fume is similar to C1, The temperature peak of concrete C2 with 20% dosage of fly ash is obviously decrease comparison with that of C1 because the hydration ability of fly ash is lower than that of Portland cement at early age. The hydration ability of 20% dosage slag in Portland cement environment is enhanced and released hydration heat more than C1 concrete at early age. Therefore the concrete temperature is influenced by the kinds of mineral materials.

The TMC of concretes are given according to adiabatic temperature increases when the concrete temperature reaches the highest temperature of adiabatic conditions at 144 hours, then decrease to room temperature with a constant decreasing temperature rate. The concrete samples are respectively placed in TMC and isothermal 20˚C curing conditions, and their mechanical properties are measured at required time.

### *3.2 Mechanical properties*

Table 3, Table 4 and Table 5 present the 72 hours and 672 hours results for the different concretes qualities for TMC and isothermal 20˚C curing. Table 3 shows that at 72 hours age the compressive strengths of concretes obviously increase for the elevated temperature. The maximum ratio of compressive strength under TMC and isothermal 20˚C curing in four concretes is 1.83 of C4 concrete with 10% dosage silica fume, this denotes that concrete containing silica fume are more sensitive than other concretes at early age. At 672 hours age the compressive strength of C2 with 20% fly ash and C3 with 20% slag are still increased, but that of C1 and C4 with 10% silica fume are slightly decreased. The elevated temperature enhances the hydration of the binders (Kjellsen 1991) and coarse hydration products are likely to form and a non-compact paste structure is yielded when hydration goes too fast. As a result, the strength development rate of concrete C1 at later age declines. The pozzolanic reaction of fly ash and slag is accelerated by elevated temperatures. It consumes the coarse $Ca(OH)_2$ crystals formed during the hydration of Portland cement and forms a fine dense gelatinous hydration product, which strengthens the paste structure greatly. Therefore, concrete containing fly ash and slag shows much better mechanical performance in a real structure than when cured under standard conditions. The pozzolanic reaction of silica fume is very fast at TMC, so at early age the silica fume can obviously enhance the compressive strength of C4, but later age the pozzolanic reaction is disappeared, therefore later age compressive strength of C4 is also decreased. The development of splitting strength and

Table 3 Compressive strength under isothermal 20˚C and TMC (MPa)

| Concrete | 72hours | | | 672hours | | |
|---|---|---|---|---|---|---|
| | TMC | Isothermal 20˚C | Ratio: TMC/Isothermal 20˚C | TMC | Isothermal 20˚C | Ratio: TMC/ Isothermal 20˚C |
| C1 | 31.20 | 17.48 | 1.78 | 36.50 | 38.00 | 0.96 |
| C2 | 32.71 | 23.42 | 1.39 | 47.54 | 43.00 | 1.10 |
| C3 | 31.89 | 25.99 | 1.22 | 50.35 | 44.55 | 1.13 |
| C4 | 44.55 | 24.21 | 1.83 | 48.00 | 50.00 | 0.95 |

Table 4 Splitting strength under isothermal 20˚C and TMC (MPa)

| Concrete | 72 hours | | | 672 hours | | |
|---|---|---|---|---|---|---|
| | TMC | Isotherml 20˚C | Ratio: TMC/Isothermal 20˚C | TMC | Isotherml 20˚C | Ratio: TMC/ Isothermal 20˚C |
| C1 | 3.24 | 2.67 | 1.21 | 3.76 | 3.80 | 0.99 |
| C2 | 3.10 | 2.38 | 1.29 | 3.93 | 3.75 | 1.05 |
| C3 | 3.16 | 2.42 | 1.30 | 4.20 | 4.00 | 1.05 |
| C4 | 4.58 | 3.11 | 1.47 | 5.00 | 5.10 | 0.98 |

Table 5 Compression elastic modulus under isothermal 20˚C and TMC (GPa)

| Concrete | 72 hours | | | 672 hours | | |
|---|---|---|---|---|---|---|
| | TMC | Isothermal 20˚C | Ratio: TMC/Isothermal 20˚C | TMC | Isothermal 20˚C | Ratio: TMC/Isothermal 20˚C |
| C1 | 30.0 | 23.0 | 1.33 | 31.0 | 32.0 | 0.95 |
| C2 | 30.4 | 20.9 | 1.45 | 36.9 | 35.0 | 1.05 |
| C3 | 33.6 | 23.7 | 1.41 | 37.9 | 36.5 | 1.04 |
| C4 | 36.1 | 28.6 | 1.26 | 36.9 | 37.2 | 0.99 |

elastic modulus of concrete cured under TMC and isothermal 20˚C curing conditions is similar to their compressive strength in Table 4 and Table 5.

The results to a certain extent show the conclusion that mechanical properties of concrete under TMC benefit from pozzolanic effects of fly ash, slag of at early age and long age, and the strength loss of concrete with pure Portland or containing silica fume such as C1 and C4 due to elevated temperature appears at 672 hours.

### *3.3 Equivalent age*

In the real construes the concrete temperature is varied in environment, then is also easy to be measured at early age. Therefore the relation between the mechanical properties of concrete and concrete temperature at early age is very useful. The concept of equivalent age is an alternative to the temperature-time factor to account for the combined effects of temperature and time on strength development. Equivalent age represents the age at a reference curing temperature that would result in the same fraction of the limiting strength that would occur from curing at other temperatures. Hansen and Pedersen (1977) developed the equivalent age function as shown in Eq. (2).

$$t_e(T_r)=\sum_0^t \exp\left(\frac{E_a}{R}\left(\frac{1}{T_r}-\frac{1}{T}\right)\right)\Delta t \tag{2}$$

Where, $t_e(T_r)$ is equivalent age at reference curing temperature $T_r$, $h$; $\Delta t$ is chronological time interval, $h$; $T$ is average concrete temperature during time interval $\Delta t$, $K$; $T_r$ is reference

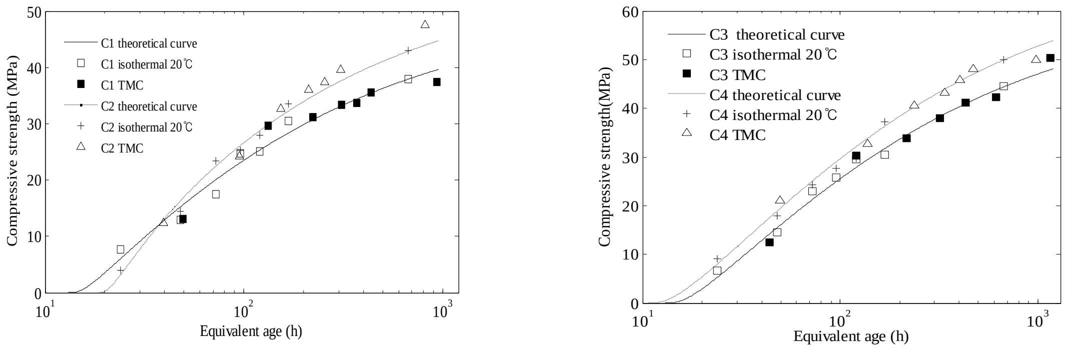


Fig. 3 The relation of compressive strength of concrete and equivalent age

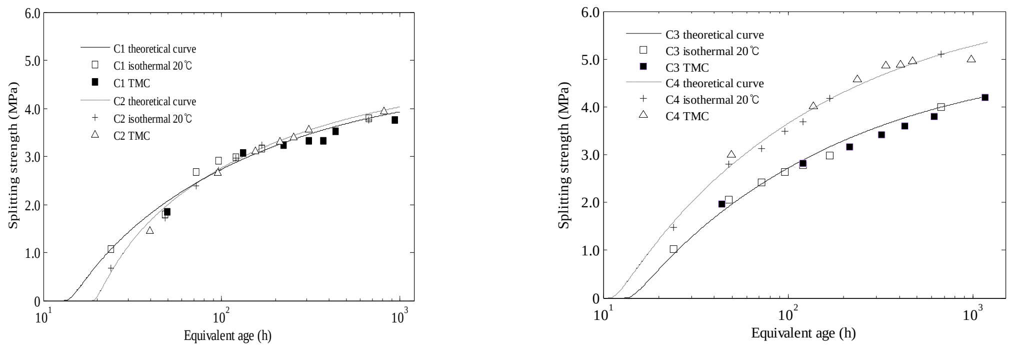


Fig. 4 The relation of splitting strength of concrete and equivalent age

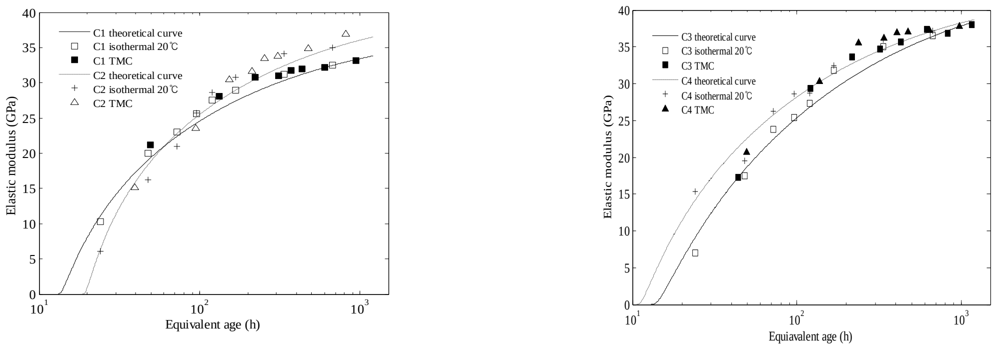


Fig. 5 The relation of elasticity modulus of concrete and equivalent age

Temperature 293 K; $E_a$ is activation energy, J/mol; $R$ is universal gas constant, 8.314 J/mol/K.

In general the type of equation chosen to describe the property development versus equivalent age is useful for estimation the concrete mechanical properties actual structure at early age. Mean apparent active energies of C1, C2, C3 and C4 are given respectively 31.75 kJ/mol, 25.73 kJ/mol, 29.40 kJ/mol, 35.19 kJ/mol (Jiachun 2007).

The expressions of compressive strength, tension strength and modulus of elasticity in the CEB-FIP1990 Model Code describe their development versus equivalent age. At the early age the mechanical models are given in Eq. (3), Eq. (4) and Eq. (5).

$$f_c(t_e) = f_{c672} \times \exp[s \times (1 - \sqrt{\frac{672}{t_e - t_0}})] \tag{3}$$

$$f_t(t_e) = f_{t672} \times \exp[s \times (1 - \sqrt{\frac{672}{t_e - t_0}})]^{nt} \tag{4}$$

$$E_C(t_e) = E_{C672} \times \exp[s \times (1 - \sqrt{\frac{672}{t_e - t_0}})]^{nE} \tag{5}$$

Where, $f_{c672}$ is compressive strength at age of 672 hours, MPa; $f_{t672}$ is tensile strength of at age of 672 hours, MPa; $E_{c672}$ is compression elastic modulus at age of 672 hours, MPa; $t_e$ is equivalent age, *h*; $t_0$ is age at which the concrete strength and stiffness is defined to be zero, *h*; *nt* and *nE* are constant.

The parameters *s* and $t_0$ are common for all three equations, and therefore may be determined from compressive tests. This approach leaves then only two parameters to be determined from the tensile strength and modulus of elasticity tests. This makes the test programme more efficient.

Splitting tensile tests are carried out on 100 mm cubes. Applying linear regression analysis (Hammer *et al.* 2003), the following relations between tensile strength and splitting strength of concrete is found by 100 mm cubes as shown Eq. (6)

$$f_t = 0.77 \times f_{ts} + 0.21 \tag{6}$$

Where $f_t$ is tensile strength of concrete and $f_{ts}$ is splitting strength of concrete.

Fig. 3, Fig. 4 and Fig. 5 show that the development of the compressive strength the tensile strength, the elasticity modulus of four concretes is relate to the equivalent age. It is clearly seen that the scatter is smaller for the test results at early ages than that at later ages in these figures. Therefore the early age concretes mechanical properties can be given through equivalent age, which be calculated by the concrete temperature easily obtained in real structures.

The model parameters $t_0$ and *s* are determined from the compressive tests by least square method. Similarly *nt* and *nE* are also determined form splitting strength and elasticity modulus test. These parameters and average values are presented in Table 6.

## 4. Example

The concrete damages of many engineering in the world have clearly shown that crack formation is at the origin of the majority of durability problems, where many of such cracks are proved being formed at an early age. Although the load bearing capacity of concrete structures

Fig. 6 Concrete wall

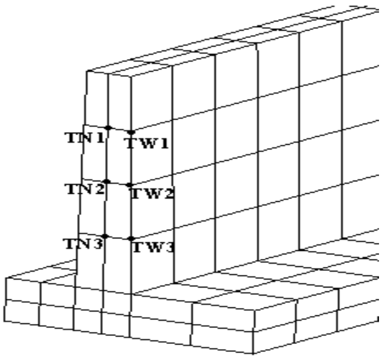


Fig. 7 Gridding of FEM

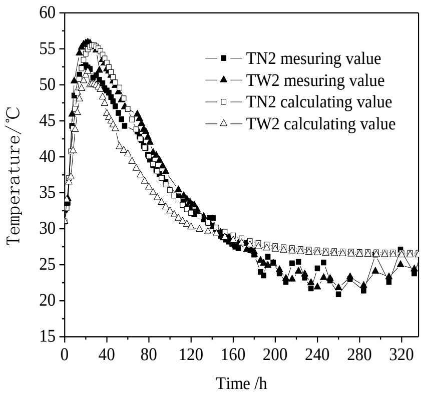


Fig. 8 Temperature of TN2 and TW2

may not be compromised by such early age damage, the service life may be reduced, and the early age concrete crack should be avoided. The target structure for the analysis is a newly cast concrete wall on the previously constructed and hardened concrete foundation as show in Fig. 6. The wall has 0.6 m width on the top and 0.815 m width on the bottom, 4.0 m height and 10 m length. The foundation has 4.0 m width, 1.0 m height and 10 m length. The environment temperature is 25˚C. The mesh of concrete wall is shown in Fig. 7. Table 7 shows the mixtures proportions of concrete. The thermal field of concrete wall analysis with solid 70 element, and temperature values of TN2 and TW2 are showed in Fig. 8. The calculating value is closed to measuring value especially early age. The temperature field results are loaded on the finite element nodes during the analysis of thermal stress field, and thermal stress with solid 45 element are defined by Ansys 9.0. The early age concrete shows plasticity and viscosity, the influence of stress relaxation must be thought, the Bazant’s two power creep model for young concrete is used for the creep of concrete (Bazant 1984, Atrushi 2000) as shown in Eq. (7)

$$\phi(t_e,t_0)=\varphi_0 t_0^{-d}(t_e-t_0)^p \tag{7}$$

Where, $\varphi(t_{e,}t_0)$ is creep coefficient of concrete at equivalent age, $\varphi_0$ = 0.90, $d$ = $p$ = 0.32.

The temperature stress and tensile strength curves of TN2 and TW2 on the concrete wall are

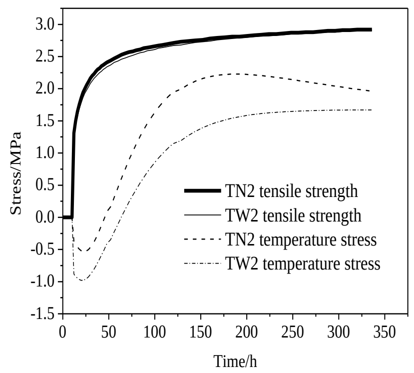


Fig. 9 Development of temperature stress and tensile strength of concrete

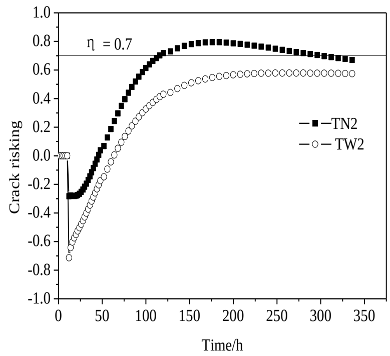


Fig. 10 Crack risking of concrete

shown in Fig. 9，which wall center temperature is higher than that of wall surface. In concrete structure, due to coefficient of conduction for concrete is small, when the Portland cement hydration heat is conducted slowly than that of surface concrete, so the internal temperature has distinct hysteresis and higher than surface temperature at early age. The calculating temperature value is close to measuring value before 160 hours, but later temperature is varying obviously owing to the environment temperature. The tensile strength of centre in concrete is greater than that of surface of concrete owing to temperature influence. The cracking risk is defined by Eq. (8)

$$\eta = \frac{\sigma(t)}{f_t(t)} \tag{8}$$

Where $\eta$ is the crack risking; $\sigma(t)$ is the temperature stress at a certain time *t*; $f_t(t)$ is the tensile strength at the same time *t*.

The cracking risk curves of TN2 and TW2 on the concrete wall are shown in Fig. 10. At 100 hours the crack risking reaches 0.7 and this indicates that the concrete wall crack (Springenschmid 1998). In fact the formwork is pulled down at 120 hours and there is a crack cross concrete wall. Therefore the evaluation of mechanical properties of concrete can forecast the concrete crack risking.

## 5. Conclusions

This study has investigated the predicting mechanical properties of early age concrete in real structure. The following conclusions can be drawn:

1) The mechanical properties of concrete at early age under temperature math curing and isothermal 20˚C curing. The effect of realistic curing temperatures on the mechanical properties at 72hours and 672 hours has been investigated. It is found that fly ash and slag can eliminate the negative effects of elevated temperatures on mechanical properties at long age.

2) The model parameters for the modified CEB-FIP 1990 equation to be used in calculation

programs are determined for concretes. The common concretes from C30 to C40 are reported in this paper *s*, $t_0$ , *nt* and *nE* varies typically in some range, and the average values of parameters are given, such as $s = 0.286$, $t_0 = 13.7$ *h*, $nt = 0.685$, $nE = 0.607$.

3) Evaluation of mechanical properties of early age concrete is applied to optimize the concrete mixtures reducing the non-loaded cracks at early age in real structure considering the temperature influence, which benefit concrete durability.

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