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Research Article

Effect of Reinforcement on Early-Age Concrete Temperature Stress: Preliminary Experimental Investigation and Analytical Simulation

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For concrete under short-term loading, effect of reinforcement on concrete crack resistance capability is usually negligible; however, recent research results show that extension of this viewpoint to concrete under long-term loading (temperature variation) may be unsuitable. In order to investigate this phenomenon, this paper presents the experimental and analytical results of early-age reinforced concrete temperature stress development under uniaxial restraint. The experiments were carried out on a temperature stress testing machine (TSTM). Experimental results show that the coupling of reinforcement and concrete creep behavior influenced the concrete temperature stress development, and nearly 16% of concrete stress was reduced in the current research. Moreover, the cracking time of reinforced concrete was also delayed. Finally, based on the principle of superposition, analytical simulations of effect of reinforcement on concrete temperature stress have been performed.

1. Introduction

The tensile strength of concrete is relatively low and mass concrete structures after casting are prone to crack at early-age. Concrete deformation caused by cement hydration, if restrained, can result in tensile stress during the cooling phase. These tensile stresses will cause concrete cracking when exceeding the tensile strength.

Although many researchers studied the early-age cracking behavior of restrained concrete with ring tests [1–3], the defects of this test, such as uncertain restraint degree and uncontrolled temperature history, limit its use in complex issues. To overcome these limits, a temperature stress testing machine (TSTM) which was firstly developed by Springenschmid et al. [4] and then improved by others [5–7] was gradually used. Numerous studies have been performed. Tao and Weizu [8] investigated the early-age tensile creep behavior of high strength concrete with different concrete mixtures. Igarashi et al. [9] evaluated the effects of water/binder ratio and silica fume on the early-age concrete stress development. Darquennes et al. [10] found that the expansion of slag cement concrete at early-age greatly relaxes internal stresses.

To the authors' knowledge, most studies about the early-age concrete temperature and stress development have been performed on unreinforced concrete [11–13]. Lee et al. [11] discussed the thermal stress of reactor containment building under hot/cold weather and corresponding cracking risk indexes were given. Honorio et al. [12] investigated the influence of boundary and initial condition on temperature development of massive concrete structures. Benboudjema and Torrenti [13] developed a numerical model to predict early-age cracking of massive concrete structures and several factors, such as creep, damage, and hydration, have been taken into account. Few researches about the effect of reinforcement on concrete temperature stress and cracking behavior can be found [14, 15]. Observation in practice [16] and research results [14, 17], however, clearly show the benefit of reinforcement on reduction of concrete cracking risk. Sule and Van Breugel [14] investigated the effect of reinforcement on early-age cracking in high strength concrete

Figure 1: Uniaxial tension test [18].

and a strain enhancement factor was introduced to quantify the effect of reinforcement decreasing the risk of early-age concrete cracking. Briffaut et al. [17] studied the early-age concrete behavior of massive structures with a thermal active restrained shrinkage ring and found that the cracking time of concrete was delayed when concrete was reinforced. It is noted that this phenomenon is not consistent with the cracking behavior of reinforced concrete under short-term loading. Usually, the usage of reinforcement on concrete structures is not to prevent concrete from cracking [18] but to limit the deflection and crack width [19, 20]. Obviously, the effect of reinforcement on cracking behavior of concrete under long-term loading (temperature variation) is not negligible. It is necessary to investigate how reinforcement influences the development of concrete temperature stress.

On the other hand, concrete deformation closely relates to the cooling rate and the effect of temperature control on mass concrete casting projects has already been proven [21]. A good understanding of the effect of cooling rate on concrete temperature stress development is also of great importance.

Thus, the following studies have been carried out in this paper:

(1) Temperature stress tests of plain concrete and reinforced concrete specimens were conducted on a TSTM. The effect of reinforcement on concrete temperature stress development has been analyzed. Moreover, concrete temperature stress developments under different cooling rates were preliminarily studied.

(2) Based on the principle of superposition, analytical simulations of effect of reinforcement on concrete temperature stress were performed on Matlab software.

2. Analysis of Temperature Stress Development of TSTM Test

2.1. Effect of Reinforcement on Concrete Stress under Short-Term Loading. Figure 1 shows a traditional uniaxial tension test for the determination of concrete cracking load. The test is performed under a multistage loading and the applied load can be monitored by a load sensor.

The cracking load can be estimated by the following equation:

$$N_{\mathrm{cr}} = f_t A \left[1 + \left(\frac{E_s}{E_c} - 1 \right) \rho \right], \quad (1)$$

where f_t is the tensile strength of concrete, A is the cross section area of specimen, E_s and E_c are the modulus of reinforcement and concrete, respectively, and ρ is the reinforcement ratio.

Equation (1) shows that the cracking load of reinforced concrete member is increased as reinforcement can bear additional load. However, the effect of reinforcement on concrete stress evolution is negligible in this test.

2.2. Effect of Reinforcement on Concrete Stress under Long-Term Loading. As shown in Figure 2, the total deformation of plain concrete specimen increases when an initial stress applied and this stress keeps constant thereafter, known as creep. However, for a reinforced concrete, the concrete stress decreases with time because of the interaction between concrete and reinforcement during the loading period.

For plain concrete, if loaded and totally restrained, stress will decrease in the concrete, also known as relaxation (Figure 3). However, for reinforced concrete, the evolution of concrete stress will still be the same as that of plain concrete because no deformation is generated and the effect of reinforcement will not be activated.

2.3. Temperature Stress Development of TSTM Test. Usually, the deformation of TSTM specimen is not always zero, but within a threshold ε_0 [5]. The specimen will be pushed/pulled to the original position when the absolute deformation exceeds the threshold (Figure 4(a)). The evolution of concrete temperature stress is illustrated in Figure 4(b): if a perfect bond between concrete and reinforcement is assumed, then stress decrement $\Delta\sigma_i$ of concrete is transferred to reinforcement because of concrete creep behavior during each cycle (e.g., the time periods t_{i-1} to t_i, t_i to t_{i+1}); on the other hand, stress increment $\Delta\sigma_i'$ of concrete is loaded to maintain the original length of the specimen at the time of t_{i-1}, t_i, and t_{i+1}, and so forth. Both concrete stress reduction and creep strain increase with the number of cycles. The TSTM test consists of numerous cycles and concrete temperature stress can be reduced in each cycle. These minor changes will add up over time, and the total change may be considerable (Figure 5).

As mentioned in Section 2.2, the reduction of concrete stress is accompanied by the deformation of concrete, indicating that concrete creep behavior is crucial for assessing concrete temperature stress development. For a TSTM test, two identical specimens are tested in the same time. One is free to deform while the other is restrained. The induced load can be recorded from restrained specimen and shrinkage deformation can be measured from free deformed specimen, and the concrete creep can be easily deduced from measured deformation data. The particularly designed TSTM system makes it possible to resolve concrete creep behavior.

Once concrete creep is known, the effect of reinforcement on concrete temperature stress development can be quantitatively assessed.

3. Experimental Program

3.1. Mechanical Property Test. According to the Chinese code GB/T 50081-2002 [22], the mechanical properties of concrete mixtures at the ages of 3 days, 7 days, and 28 days were

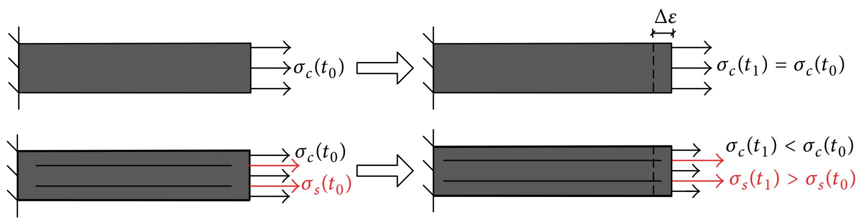

Figure 2: Effect of reinforcement on concrete stress in creep tests (σ_c: concrete stress; σ_s: reinforcement stress).

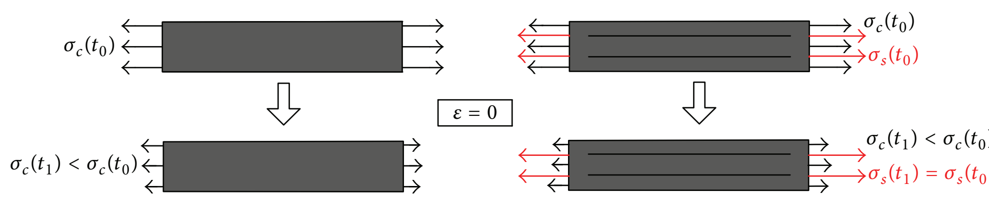

Figure 3: Effect of reinforcement on concrete stress in relaxation tests (σ_c: concrete stress; σ_s: reinforcement stress).

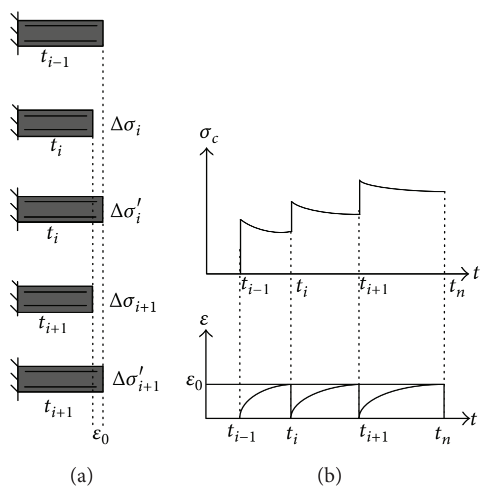

Figure 4: Evolution of (a) deformation and (b) concrete stress of reinforced concrete.

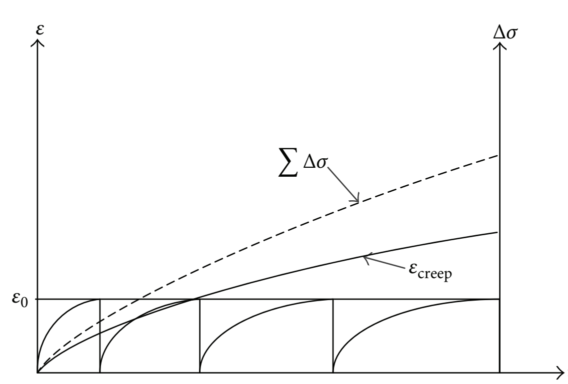

Figure 5: Evolution of creep strain and stress reduction of concrete.

measured on specimens of 100 mm × 100 mm × 300 mm for elastic modulus test and 100 mm × 100 mm × 100 mm for splitting tensile test.

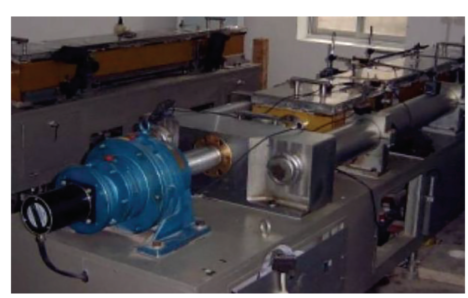

Figure 6: Temperature stress testing machine.

3.2. TSTM Test. The specimens were tested on a TSTM (Figure 6). Concrete was directly cast in the TSTM mould and the top surfaces of all specimens were then covered with a plastic sheet to maintain a constant humidity. Details of temperature stress testing procedure can be found elsewhere [4, 5].

Table 1: Mix proportion of concrete (kg/m^3).

Mix	Cement	Fly ash	Sand	Gravel	Water	Water reducer	Air entraining
Mass	255	85	748	1133	146	4.074	0.068

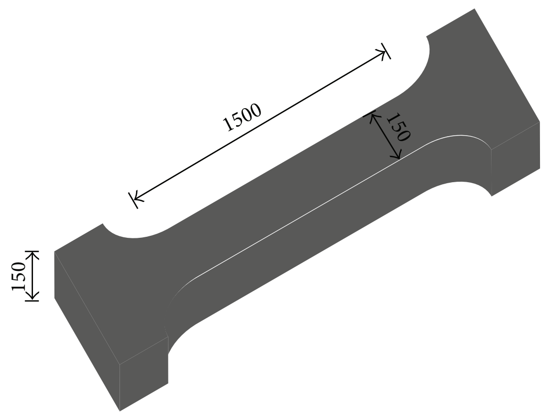

Figure 7: Dimensions of the TSTM specimen (mm).

Table 2: Specimen numbers and parameters.

Specimen	Reinforcement configuration	Cooling rate
C-0-1	—	0.33°C/h
C-0-2	—	0.21°C/h
C-0-3	—	0.33°C/h
C-1-1	4φ12	0.33°C/h
C-1-2	4φ12	0.33°C/h

Note: C-0-3 and C-1-1 are free deformed; C-0-1, C-0-2, and C-1-2 are fully restrained.

Table 1 shows the mix proportion of concrete. The concrete mixture (w/cm = 0.43) was made with ordinary Portland cement, natural sand, and crushed stone with a maximum particle size of 30 mm. The steel reinforcement used in this research is with an elastic modulus of 200 GPa and a yield strength of 235 MPa.

The dimension of specimens is illustrated in Figure 7.

Numbers of specimen are listed in Table 2. Specimens of TSTM tests were cast from the same batch of concrete and the reinforcement ratio of reinforced specimens is 2.0%. The specimens went through a three-phase temperature variation (Figure 8(a)): an adiabatic temperature phase, an isothermal temperature phase, and a cooling temperature phase. The temperature decrease rate of the massive wall structures is approximately with a linear decrease of 0.35°C/h [17] and the evolution of temperature of concrete structures depends on several factors, such as concrete mix, wind, and casting temperature; therefore, two cooling rates were selected and the cooling phase lasts until the concrete cracks.

4. Experimental Results and Discussions

4.1. Mechanical Properties. Mechanical property test results are listed in Table 3.

Table 3: Mechanical properties of concrete.

Age/days	Splitting tensile strength/MPa	Elastic modulus/GPa
3	1.81	19.39
7	2.87	27.51
28	3.21	31.30

4.2. Deformation Behavior

4.2.1. Free Strain. Figure 8(b) shows a typical strain evolution of free specimen (solid line). It can be seen that the free strain increased rapidly during the adiabatic temperature phase (in the first 24 h); the variation of free strain was not distinct when the temperature was kept constant (isothermal temperature phase). At the last stage, the free strain simultaneously decreased with the dropping temperature.

Figure 9 shows the free strain evolution of plain and reinforced concrete. It was found that the free strains of plain and reinforced concrete were almost the same, indicating that the thermal expansion coefficients of concrete and reinforcement are about the same in the current research. Meanwhile, Figure 9 also indicates that the effect of autogenous shrinkage is minor for concrete mixture with high w/c [14] and the thermal strain caused by temperature variation is the key part of free strain measured in the tests.

4.2.2. Creep Strain. For a restrained specimen, the total strain consists of elastic strain ε_e, thermal strain $\varepsilon_{\text{ther}}$, shrinkage strain ε_{sh}, and tensile creep strain $\varepsilon_{\text{creep}}$. The elastic strain is recorded by the computer during the test (dash line in Figure 8(b)). For a full restraint test, $\varepsilon_{\text{tot}} = 0$, and thus the concrete creep strain can be calculated by subtracting accumulated elastic strain from free strain and this method (Figure 10) is also used by other researchers [5, 6].

4.3. Temperature Stress Development. Figure 11 shows a typical stress evolution of plain concrete specimen. Compressive stress increased due to thermal expansion caused by cement hydration, and this stress decreased after the peak of temperature. Finally, the tensile stress was generated at a critical moment, also known as point of "the second zero stress" [23]. The concrete tensile stress still increased with the dropping temperature and ultimately exceeded tensile strength of concrete. The whole process can be divided into two phases: a compression time zone (phase 1) and a tension time zone (phase 2). Since the tensile stress of concrete is strongly related to the cracking at early-age, attention will be paid to phase 2.

The mechanical properties of concrete are strongly influenced by the temperature variation and an equivalent age

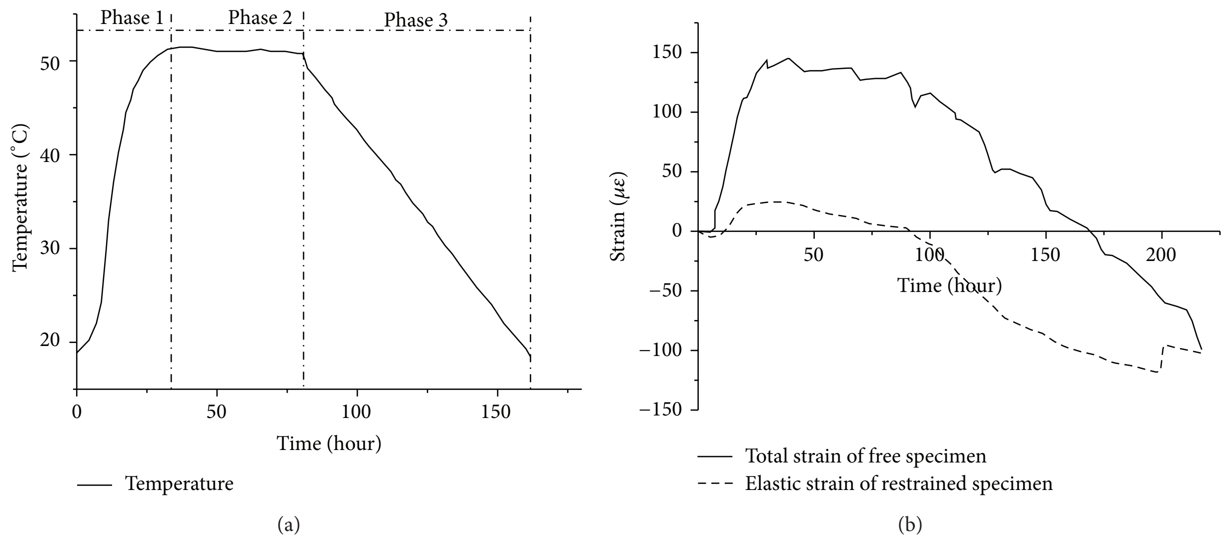

Figure 8: A typical evolution of (a) temperature and (b) strain.

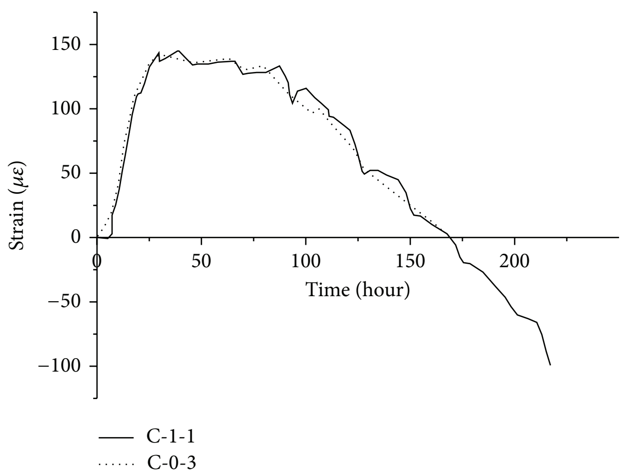

Figure 9: Free strain evolution of C-0-3 and C-1-1.

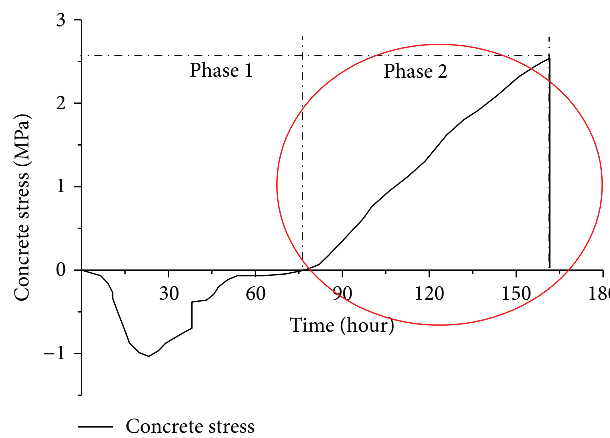

Figure 11: A typical stress evolution.

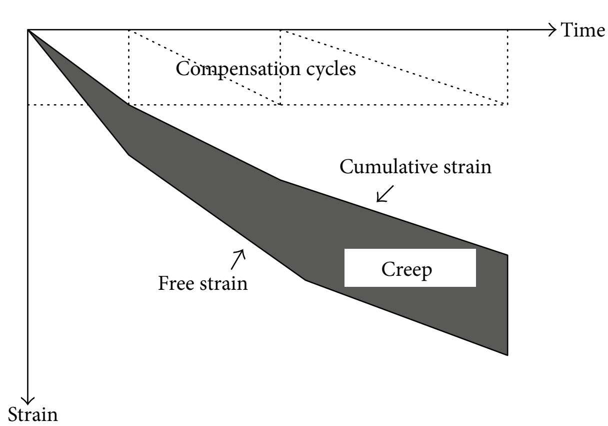

Figure 10: Creep strain calculation method [5].

concept [24] should be adopted to calculate related parameters. For an arbitrary temperature history $T(t)$, concrete age can be converted to equivalent age t_e via Arrhenius law [25]:

$$t_e = \int \exp\left[\frac{E_h}{R}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right] dt, \tag{2}$$

where E_h is the activation energy (J/mol), R is the ideal gas constant (J/mol/K), T_0 is the reference temperature, and T is the actual temperature (K). E_h equals 33500 J/mol for the temperature $T \geq 20^{\circ}$C and $33500 + 1470(20 - T)$ J/mol for the temperature $T < 20^{\circ}$C [25]. T_0 equals 293.15 K.

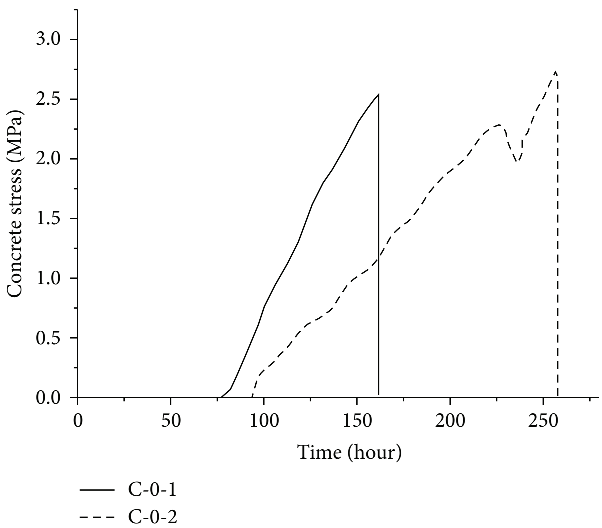

Figure 12: Concrete stress curves of C-0-1 and C-0-2.

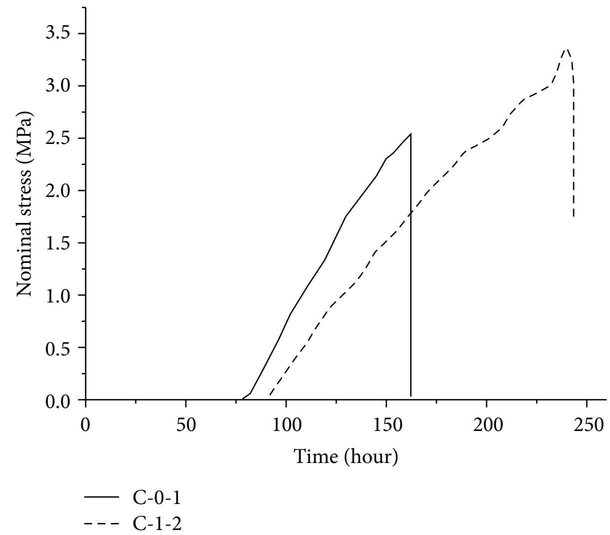

Figure 13: Nominal tensile stress of C-0-1 and C-1-2.

The temperature variation (Figure 8(a)) takes the following expression:

$$\theta(t) = \begin{cases} 273.15 + \theta_0 \left(1 - \exp\left(-a\left(t^b\right)\right)\right), & 0 \le t \le t_1 \\ 273.15 + \theta_{\max}, & t_1 < t \le t_2 \\ 273.15 + \theta_{\max} - kt, & t_2 < t, \end{cases} \quad (3)$$

where θ_0, $\theta_{\max}$, a, and b are parameters fitted by experimental data, t_1 and t_2 are critical points of different temperature phases, respectively, and k is the cooling rate.

Figure 12 presents the stress curves of C-0-1 and C-0-2. The stress curve at a cooling rate of 0.33°C/h is steeper, indicating that larger deformation of concrete caused by temperature variation leads to greater tensile stress. The slower cooling rate, when applied at the cooling phase, leads to longer cracking time. A decrease in stress before the peak value of C-0-2 is visible and the possible explanation is that concrete does not crack thoroughly. The cracking stresses of C-0-1 and C-0-2 are 2.54 MPa and 2.74 MPa, respectively. A small cracking stress decrease is noted as the cooling rate increases. This phenomenon may be explained by the fact that the nonuniform stress distribution in concrete can be improved with a slow stress increase. The calculated ratios of cracking stress to tensile strength of C-0-1 and C-0-2 are 0.81 and 0.86, respectively. Under long-term loading, microcracks propagate and the mechanical properties of concrete may deteriorate until concrete fails.

The nominal stress of specimen is calculated via

$$\sigma^{\text{nom}} = \frac{P}{A}, \quad (4)$$

where A is the cross section area of specimen and P is the ultimate load of specimen.

The nominal tensile stress curves are plotted in Figure 13. One interesting phenomenon shown in Figure 13 is that the cracking time of C-1-2 was delayed, indicating that the reinforcement improved the crack resistance ability of concrete in the current research.

Based on the principle of deformation compatibility, the value of $\Delta\sigma_c$ and the concrete cracking stress σ_{crack} can be calculated by the following expressions:

$$\Delta\sigma_c = \frac{\varepsilon_{\text{creep}} E_s A_s}{A_c}, \qquad \sigma_{\text{crack}} = \frac{\sigma^{\text{nom}} A - \varepsilon_e E_s A_s}{A_c}, \quad (5)$$

where $\varepsilon_{\text{creep}}$ is creep strain and can be calculated in Section 4.2 and ε_e is the elastic strain recorded by the computer.

In the current research, the calculated $\Delta\sigma_c$ and σ_{crack} are 0.51 MPa and 2.65 MPa, respectively, and a stress transfer factor can be defined to describe the effect of reinforcement:

$$\gamma = \frac{\Delta\sigma_c}{\Delta\sigma_c + \sigma_{\text{crack}}} = 16\%. \quad (6)$$

Thanks to the reinforcement and concrete creep behavior, the cracking time of concrete was also delayed to some extent.

5. Analytical Simulation of Effect of Reinforcement on Concrete Temperature Stress Development

5.1. Methodology. Reinforcement restrains concrete time-dependent deformation caused by creep behavior, resulting in stress transfer between concrete and reinforcement. The concrete temperature stress can be calculated based on the principle of superposition [26] and deformation compatibility. The flow chart of calculation is given in Figure 14 and the programming has been performed on Matlab software.

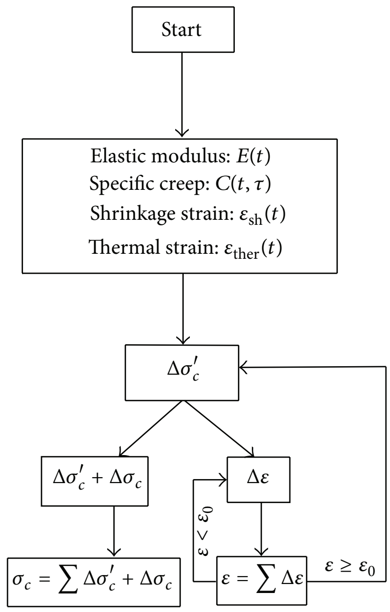

Figure 14: Flow chart of stress calculation.

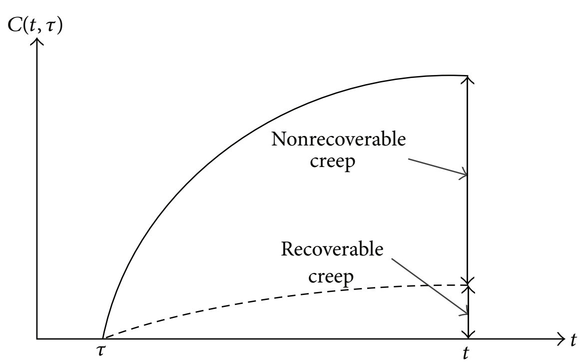

Figure 15: A general description of specific creep.

5.2. Comparison with Experimental Results. Literature [27] reported that the thermal expansion coefficient of concrete became stable ($10^{-5}/^{\circ}$C) after one day and this value is adopted for assessing thermal deformation of concrete in the current research. A specific creep expression in literature [26] is adopted. Equation (7) is an exponential function, which is beneficial for programming, as well as reduction of calculation amount. The first term of (7) represents nonrecoverable creep and the second term of (7) represents recoverable creep. A general description of specific creep is shown in Figure 15. Creep parameters are given in Table 4. Consider

$$C(t,\tau) = \sum_{i=1}^{2} \left(f_i + g_i \tau^{-p_i}\right)\left[1 - e^{-r_i(t-\tau)}\right], \quad (7)$$

where τ is the loading age and t is the concrete age.

Figure 16 shows the comparison between analytical results and experimental results. It can be seen that the benefit of reinforcement has been observed in this preliminary analysis. The differences between measured results and analytical results are due to inaccuracy of creep parameters and measurement errors. More experimental tests are needed for further investigation.

Table 4: Parameters of specific creep [26].

Parameter	f_i (10^{-4})	g_i (10^{-4})	p_i	r_i
$i = 1$	0.1045	0.9614	0.7	0.3
$i = 2$	0.2360	0.4012	0.7	0.005

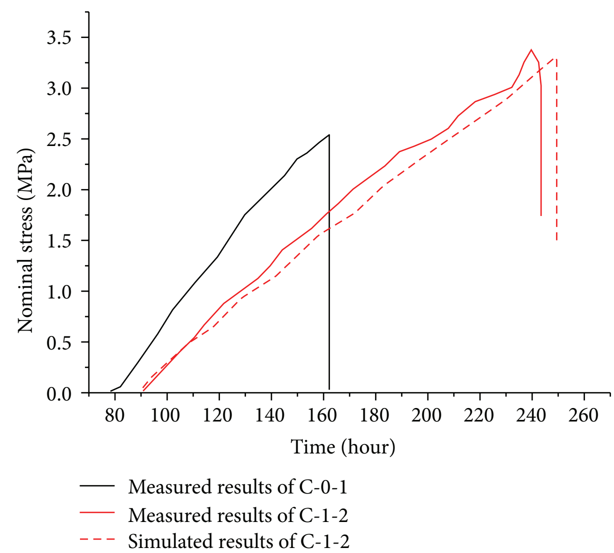

Figure 16: Comparison of experimental results and analytical simulation.

Extended analytical results are drawn for different reinforcement ratios and the results have been normalized based on the experimental reinforcement ratio ($\rho_0 = 2\%$). As illustrated in Figure 17, the stress transfer factor γ increases with reinforcement ratio while the rate becomes slower with the increasing reinforcement ratio.

6. Conclusions

Effect of reinforcement on concrete temperature stress development has been investigated and the following conclusions can be drawn in this paper:

(1) A small concrete cracking stress increase was observed when slower cooling rate was applied at the cooling phase. The nonuniform stress distribution in concrete can be improved with a slow stress increase.

(2) Concrete temperature stress can be reduced in each cycle of TSTM test due to the interaction between concrete and reinforcement. These minor reductions added up over time and almost 16% of concrete temperature stress was reduced in the current research. Moreover, the cracking time of reinforced concrete was also delayed. It should be noted that this paper

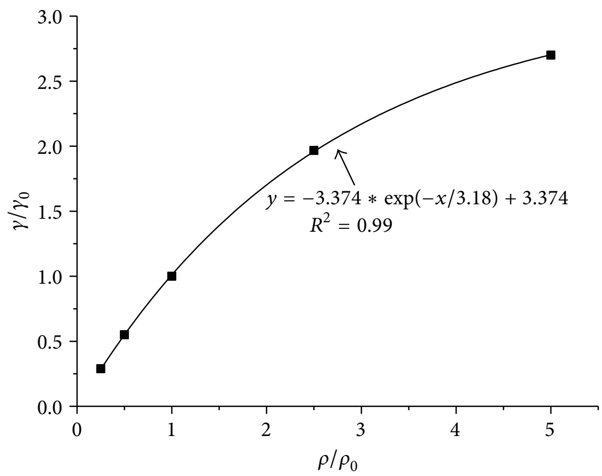

Figure 17: Effect of reinforcement ratio on reduction of concrete stress.

provides only limited experimental evidence and preliminary results. More experiments are needed.

(3) Analytical simulations of effect of reinforcement show an agreement with the experimental results. The influences of reinforcement ratio on reduction of concrete temperature stress were investigated and a correlation was developed between the reinforcement ratio and the reduction of concrete temperature stress.

For practice, the deformation of early-age concrete is not totally restrained by the rock foundation or the adjoining structures, and this feature provides a possibility for the interaction between reinforcement and concrete. The effect of reinforcement on reduction of concrete temperature stress may be activated in realistic reinforced concrete structures under long-term loading (temperature variation) and the cracking probability of reinforced concrete structures is lowered when the effect of reinforcement has been taken into consideration.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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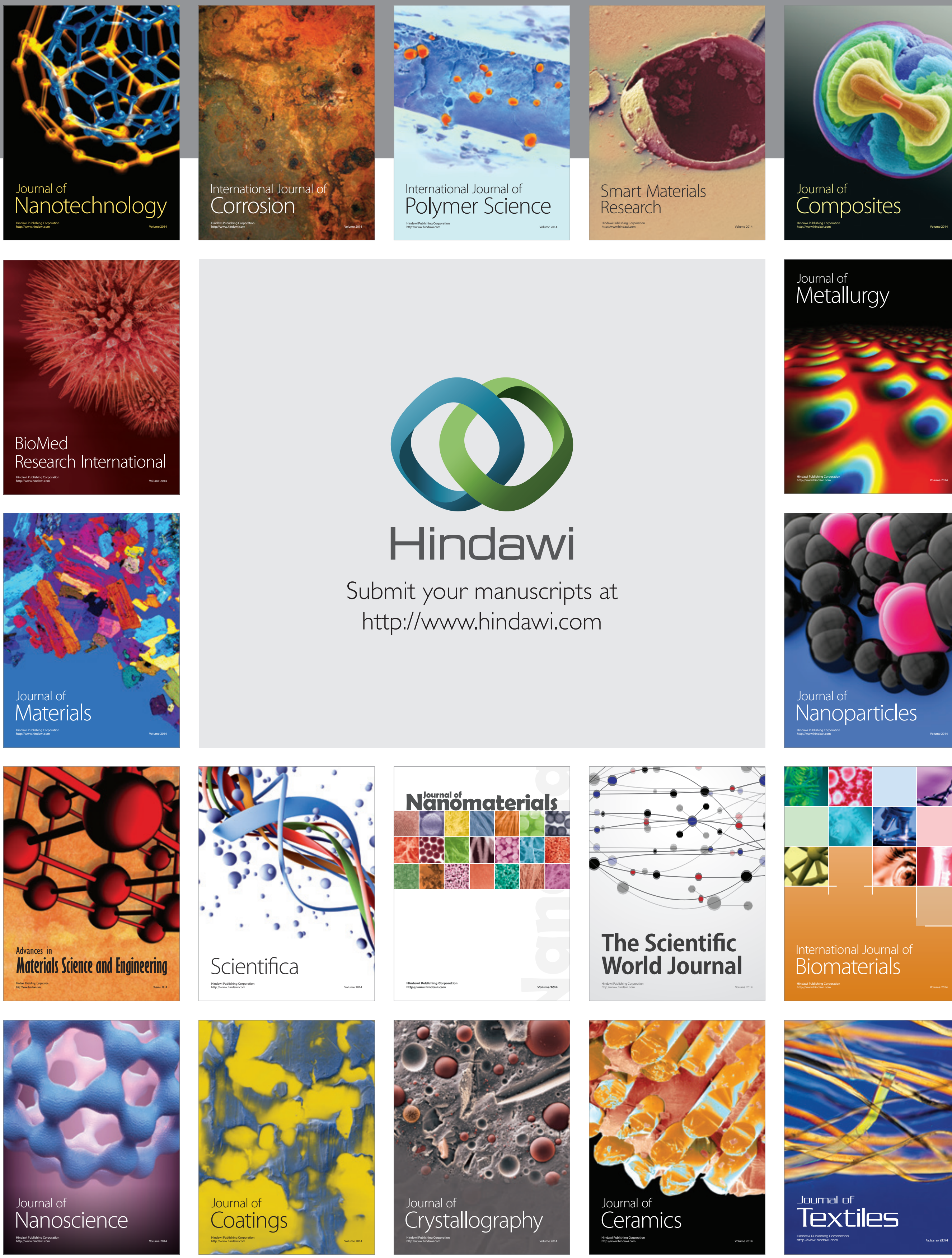
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