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Creep and effective stiffness of early age concrete slabs

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ABSTRACT: Experimental study was performed to investigate the effective stiffness and long-term deflection of concrete slabs subjected to loading at early age. From the tests of one-way slabs, long-term deflections were measured. The test variables were the magnitude of loading, load pattern, reinforcement ratio, compression re-bars, and concrete age. The material properties of early age concrete resulting from cylinder tests were compared with the predictions by current design code, ACI 209. The long-term deflections of the slab specimens were also compared with the predictions. The result showed that ACI 209 & 318 overestimated the compressive strength and elastic modulus of the early age concrete cured at low temperature, and underestimated the long-term deflections of slabs.

1 INTRODUCTION

As construction period for multi-story building is getting shorter, frequently, construction load causes concrete cracking in early age slabs. The initial damage of the early age concrete accelerates the long-term deflection and aggravates serviceability problem due to excessive deflection.

Lee et al. (2008) measured long-term deflections of slabs loaded at ages of 3, 7, 28 days. The results showed that the long-term deflection as well as the initial deflection was significantly increased when loading was applied to the concrete at early age. This is because the mechanical properties of the early-age slabs were worsened when early loading was applied. However, more experimental tests on various parameters are required to quantify the material and mechanical properties of early age slabs.

2 TEST SET-UP AND PARAMETERS

Six one-way slabs were tested. Figure 1 shows the dimensions and details of the specimens. The net span was 4.5 meters. Two concentrated loads were applied at the mid-span. The reinforcement ratio ranged from 0.50% to 1.04%. Concrete mix was designed for the concrete strength 30MPa at 28 days.

Table 1 presents the test parameters for the specimens. T3B, the control specimen, had the reinforcement ratio of 0.52% (D13-@200mm). At age of 3 days after concrete casting, loading of 12kN was applied, and was maintained for 110 days (Fig. 2(a)). T3S was the same as T3B except for the magnitude of load (8kN). In T7B, 12kN was applied at age of 7 days. In T3C, multiple step loading was applied as shown in Figure 2(b). In the step loading, 4kN was loaded at 3 day intervals, and only slab weight was maintained after 12 days. TT3B had doubled reinforcement ratio, 1.04% (D13@100mm). TC3B was reinforced with compression re-bars (D13@200mm).

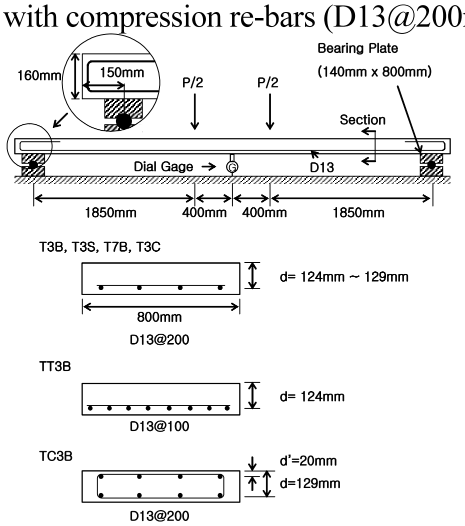
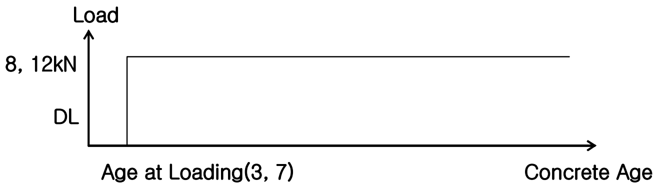


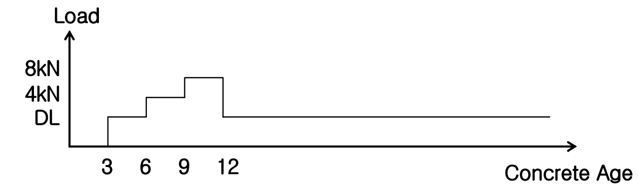
Figure 1. Specimens and Test setup.

Table 1. Test specimens.

Speci -mens	Reinforce -ment	age at loading	Load condition	Load	Effective depth	Steel ratio(%)
T3B	D13@200	3day	LC1	12kN	124	0.52
T3S	D13@200	3day	LC1	8kN	124	0.52
T7B	D13@200	7day	LC1	12kN	129	0.50
T3C	D13@200	3day	LC2	---	129	0.50
TT3B	D13@100	3day	LC1	12kN	124	1.04
TC3B	D13@200	3day	LC1	12kN	129/20	1.00



(a) One step loading (LC1)



(b) Multiple step loading (LC2)

Figure 2. Loading history.

The slab specimens are categorized into two groups, according to the date of concrete casting and effective slab depth.

For Group1, T7B, T3C, TC3B, the effective depth was 129 mm, while for Group2, T3B, T3S, TT3B, the effective depth was 124 mm. Group2 was cast 9 days after Group 1 was cast.

The magnitude of load was 12kN or 8kN, which was 2~2.45 times the slab‘s self-weight, the typical maximum construction load for actual slabs. The magnitude of load were between the cracking load and the yield load of the slabs. For T3B at age of 3 days, the cracking load and the yield load were 1.6 kN and 17.8 kN, respectively.

Deflections were measured at the slab's center for 110 days(Fig. 1). Temperatures were also measured. After curing of the concrete, the specimens were tested at the ambient temperature as low as 5℃.

3 TEST RESULTS

3.1 *Cylinder test*

100 mm×200 mm concrete cylinders were cured for 3 days. After 3 days, they were cured in a water tank. Figure 3(a) shows the variations of the compressive strength of the early age concrete. The results showed that the strengths of the concrete at ages less than 10 days were as low as 30% of the predictions by current design code ACI 209.

$$f_c(t) = \frac{t}{\alpha + \beta \cdot t} f_{c,28} \tag{1}$$

where α =4.0, β =0.85 for moist cured normal cement, t is the concrete's age, and $f_{c,28}$ is the 28 day strength of the concrete.

This result indicates that current design code significantly overestimates the strength of the early age concrete cured at low temperature.

In a recent study, Kim et al. (1998) used modified Arrhenius model to predict the time-dependent compressive strength affected by curing temperature. In the present study, the modified Arrhenius model was used to calculate the time-dependent compressive strength of the concrete cylinders.

$$t_e = \sum \gamma \Delta t = \sum exp\left[\frac{E}{R}\left(\frac{1}{T_r + 273} - \frac{1}{T + 273}\right)\right]\Delta t \tag{2}$$

$$t_{em} = \sum \gamma \frac{1 + t_e^2}{a + t_e^2} \Delta t \tag{3}$$

$$S_u = S_{ur}\left(1 - \sum \frac{1 + t_e^2}{b + t_e^2} \Delta t\right) \tag{4}$$

$$S = \frac{S_u \cdot k_r \cdot t_{em}}{1 + k_r \cdot t_{em}} \tag{5}$$

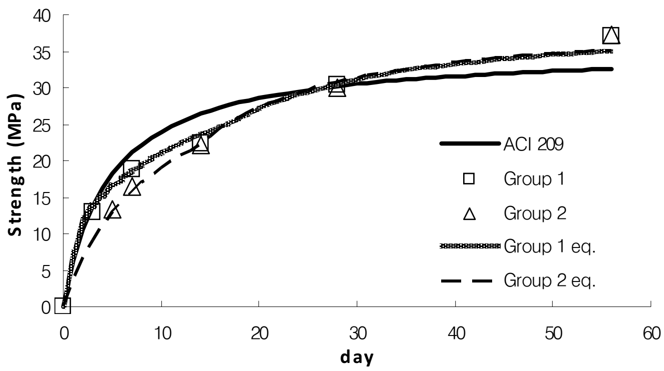
where T =curing temperature, T_r =reference curing temperature(20℃), E =apparent activation energy(= 33.5 kJ/mol at 20℃, 62.9 kJ/mol at 0℃), R =universal gas constant(=8.314 J/mol-K), γ =an age conversion factor, t_e = equivalent age at the reference temperature, t_{em} = modified equivalent age at the reference temperature, and S_{ur} =limiting strength. a =0.6855 and b =1.0655 at low curing temperature. k_r =rate constant at standard temperature 20℃. S =compressive strength at age t.

As shown in Figure 3(a), the modified Arrhenius model predicted well the test results of the concrete cylinders for both Group 1 and Group 2.

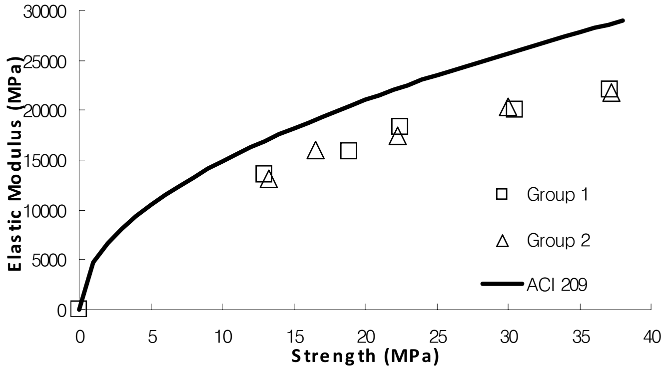
Figure 3(b) compares the elastic modulus of the concrete cylinders with the prediction by ACI 209 (2008). In the prediction, the test results for the compressive strengths was used to evaluate the elastic modulus of the early age concrete. Nevertheless, current design code overestimated the test results. This result indicates that in the concrete cured at low temperature, the decrease of elastic modulus was more pronounced than the decrease of compressive strength.

3.2 *Slab test*

Figure 4 shows the long-term deflections of the slab specimens. In (Figs. 4(a)-(e)), the effects of design parameters (the magnitude of load, concrete age at initial loading, loading type, reinforcement ratio, and compression re-bars) are shown by comparing the test results of the control specimen T3B or T3S with other specimens.



(a) Time-dependent compressive strength



(b) Relationship between strength and elastic modulus

Figure 3. Test results for compressive strength and elastic modulus of concrete cylinders.

As shown in (Figs. 4(a)-(e)), the long-term deflection's pattern was similar regardless of the design parameters. However, all the test parameters were able to reduce long-term deflections. The TC3C showed the least result in the long-term deflection as well as in the short-term deflection.

Figure 4(c) shows the effect of loading type. In this figure, T3C was compared with T3S that had the same maximum load 8kN. Though the superimposed load was completely removed, deflection recovery was not significant due to concrete crack damage developed by the initial loading. For this reason, T3C showed considerable long-term deflection.

4 EVALUATION OF SLAB DEFLECTION

The long-term deflections of the slab specimens were predicted by using current design code. As shown in Figure 3, since the compressive strength and elastic modulus of early age concrete are not accurately predicted by current design code, the results of cylinder tests were used in the predictions.

In the present study, Bischoff's equation (Bischoff & Scanlon 2007) was used to calculate the effective moment of inertia(I_e) of the slabs. In the Bischoff's equation, the effective moment of inertia(I_e) is defined as

$$I_e = \frac{I_{cr}}{1-\left(\frac{M_{cr}}{M_a}\right)^2\left(1-\frac{I_{cr}}{I_g}\right)} \le I_g \qquad (6)$$

where I_g is the moment of inertia of the gross section, and I_{cr} is the moment of inertia of the cracked section. M_{cr} is the cracking moment of the slab defined with $f_c(t)$ (concrete strength at age t).

Using the effective moment of inertia, the curvature distribution along the slab length was calculated from the moment distribution. Then, by integrating the curvature distribution, the inelastic short-term deflection of the slab specimens calculated.

In this test, only the deflections for superimposed loading were measured. Therefore, the deflection caused by the self weight of the slab was calculated, and was added to the measured short-term deflection to estimate the total short-term deflection of the slabs.

The long-term deflections of the specimens were calculated by multiplying the short-term deflection with the creep coefficients specified by ACI-318 (2008). In ACI-318, the creep coefficient is defined as

$$\lambda = \frac{\xi}{1+50\rho'} \qquad (6)$$

The long-term deflection is calculated as

$$\Delta_T = \lambda(t,t_0)\Delta_D \qquad (7)$$

where Δ_D is the short-term deflection.

Figure 4 compares the predicted long-term deflections and the corresponding test results.

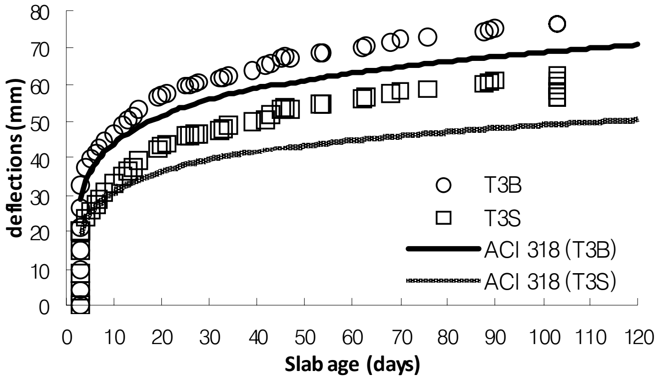
As shown in the figures, ACI-318 underestimated the test results though the material test results, compressive strength and elastic modulus were used for this estimation.

5 CONCLUSIONS

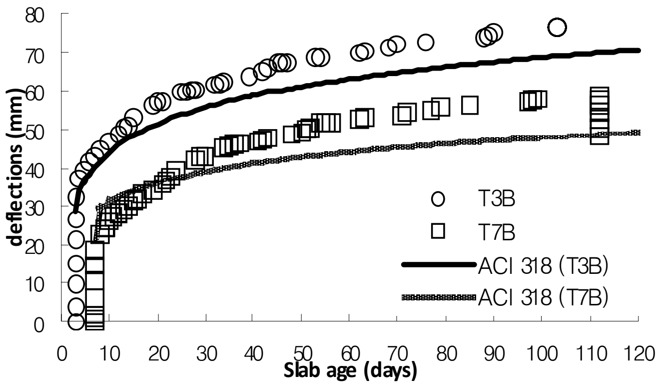
The primary finding of the present study can be summarized as follows.

1) The compressive strength of early age concrete at ambient temperature 5℃ was as low as 30% of the predictions by current design code. The modified Arrhenius model considering the effect of curing temperature well predicted the compressive strength.
2) Current design codes overestimated the elastic modulus of the early age concrete by 20% even though the concrete strengths resulting from the test were used in the estimation.
3) Although the compressive strength and elastic modulus resulting from the cylinder tests were

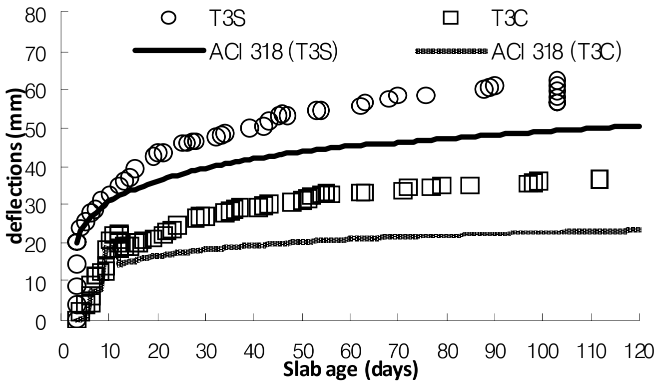
used, the ACI 318 creep model still underestimated the long-term deflections of the slabs which were subjected to loading at early age.



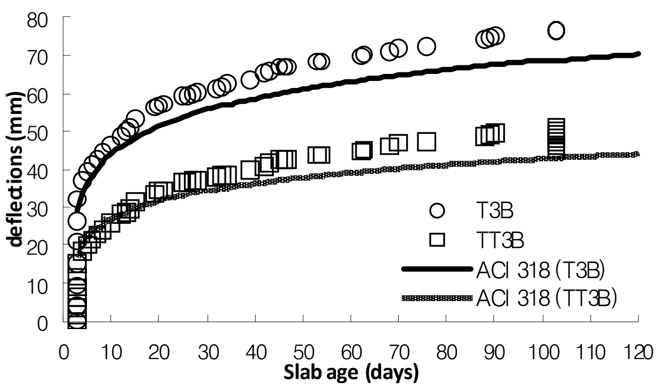
(a) Effect of magnitude of load



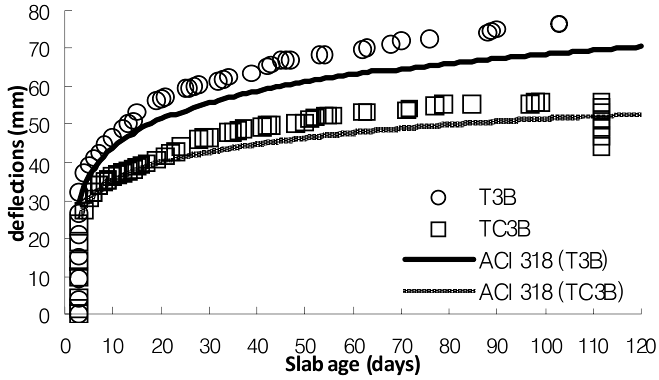
(b) Effect of concrete age at initial loading



(c) Effect of loading type



(d) Effect of reinforcement ratio



(e) Effect of compression re-bars

Figure 4. Long-term deflections of slab specimens; effects of design parameters.

ACKNOWLEDGEMENT

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