A Simplified Strength Development Model for Fly Ash Concrete

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Abstract

This paper presents a simplified strength development model for predicting compressive strength development of concrete incorporating fly ash. To predict compressive strength at any age, the 28-day compressive strength model for fly ash concrete proposed by the authors [1] was used as the basis. In this study, SiO_2 and CaO contents in binders were regarded as the main chemical compositions influencing the strength development of fly ash concrete. In addition, the effects of water-to binder ratio, water-reducing admixture, and particle filling of fly ash were also considered in the model. The verification tests showed that the proposed model could be used to predict compressive strength development of concrete containing fly ash from various sources with various degree of fineness.

1. Introduction

The development of compressive strength of concrete with fly ash has been known to be different from that without fly ash. Furthermore, fly ashes having different chemical composition and physical properties has been known to give different effect on strength development of concrete because the compressive strength of concrete containing fly ash depends on the pozzolanic reaction, which is affected by types of fly ash used, the hydration reaction, and the mix proportion of concrete constituents. The relationship among concrete constituents, their properties and strength development of concrete with fly ash has long been a topic of interest for researchers in order to predict this concrete property.

Smith [2], and Hedegaard and Hansen [3] suggested that a water-to-cement ratio in Abrams' Law might be replaced with a water-to-binder ratio. Cementing coefficient factor, which was given to be 0.25 at the age of 28 days, was introduced to multiply the weight of fly ash so that the water-to-cement ratio in Abrams' Law became the effective water-to-cement ratio for producing concrete with the same strength as plain concrete. However, no chemical or physical properties were shown to influence such cementing coefficient factor.

Ghosh [4], Gopalan and Haque [5] concluded that Abrams' Law was found to be applicable for fly ash concrete when water-to-cement ratio was replaced by water-to-powder ratio. Tahir [6] presented a model to predict the strength development of fly ash concrete by modifying the Feret's model and the Larrard's model and including the effects of fineness and chemical composition of cement and fly ash into the model. However, the parameters used in the Tahir's model seem to be difficult for applying in the real practice work. Therefore, this paper proposes the simplified strength development model for ease of application.

2. Model Formulation

In the strength development model, strength ratio is defined as the ratio between compressive strength at any concrete age and its 28-day compressive strength as expressed in Eq. (1).

$$\phi(t) = \frac{f_c'(t)}{f_c'(28\text{days})} \qquad (1)$$

where $\phi(t)$ is the strength ratio at concrete age t (days), $f_c'(t)$, is the compressive strengths at concrete age t days. $f_c'(28\text{ days})$ is the 28-day

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compressive strength obtained from the model proposed by the authors [1].

So, compressive strength at any age t days can be computed from

$$f_c'(t) = \phi(t) \cdot f_c'(28\text{days}) \tag{2}$$

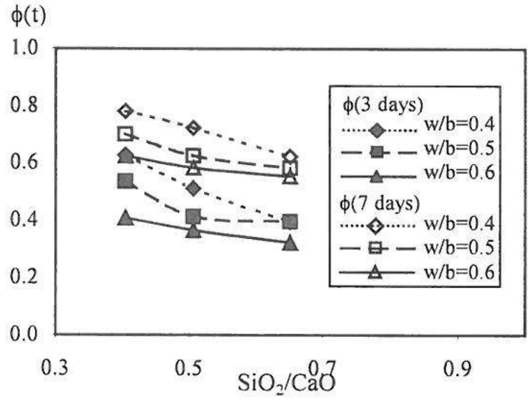
In this study, SiO_2 and CaO contents in the total binders, water-to-binder ratio, and concrete age were considered as the parameters affecting the strength development of fly ash concrete.

2.1 Effect of Chemical Compositions of Cement and Fly Ash

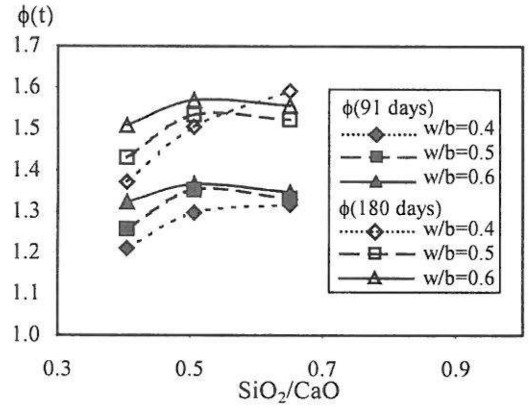
Strength at any age and rate of strength development of fly ash concrete are affected by the characteristics of the fly ash. SiO_2 and CaO are regarded as the main chemical compositions influencing hydration reaction and pozzolanic reaction which are the major contributions to the strength development of fly ash concrete. CaO mainly affects the hydration reaction and the product from the hydration reaction. $Ca(OH)_2$ reacts with SiO_2 in fly ash during the pozzolanic reaction. Although SiO_2 in cement involves hydration reaction and there are still other components such as Al_2O_3 in fly ash that may react in the pozzolanic reaction, the concept of the model was made simple for ease of application. The progress of chemical reactions involving fly ash may vary considerably with the type of fly ash. Therefore, the term SiO_2/CaO was proposed as the ratio between SiO_2 content and CaO content in the total binders as shown in Eq. (23) which implies how fast the progress of hydration and pozzolanic reactions are.

$$\frac{SiO_2}{CaO} = \frac{SiO_{2,c} \cdot W_c + SiO_{2,f} \cdot W_f}{CaO_c \cdot W_c + CaO_f \cdot W_f} \tag{3}$$

where SiO_2/CaO is the ratio of SiO_2 to CaO contents of the total binders, $SiO_{2,c}$, $SiO_{2,f}$, CaO_c, CaO_f, are the SiO_2 content in cement SiO_2 content in fly ash, CaO content in cement, and CaO content in fly ash (percent by weight), respectively. W_c and W_f are the cement and fly



(a) Strength ratios at 3 and 7 days



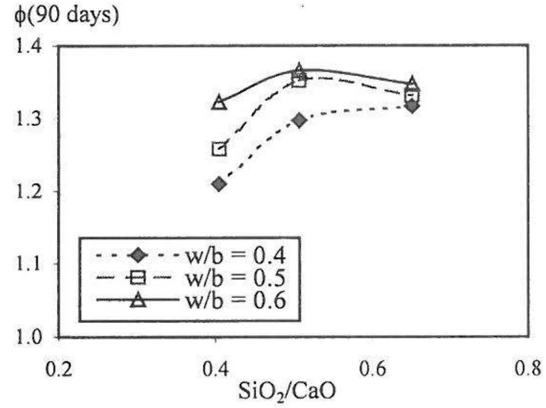
(b) Strength ratios at 91 and 180 days

Fig. 1 Relationships between strength ratios ($\phi(t)$) and SiO_2/CaO in concrete

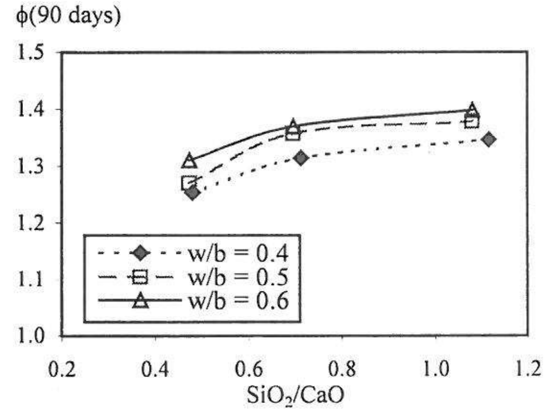
ash contents in concrete (kg/m^3 of concrete).

The relationships between $\phi(t)$ and SiO_2/CaO are illustrated in Fig. 1(a) and Fig. 1(b). These relationships were separated into 2 parts; before 28 days and after 28 days.

From Fig. 1(a), it can be seen that increasing SiO_2/CaO causes lower $\phi(t)$. In other words, when considering concrete with the same amount of binders but different fly ash replacement, it implies that at an early age, concrete with higher fly ash content results in lower $\phi(t)$ than that with lower fly ash content. In addition, this can also imply that when using the same amount of fly ash and same replacement ratio, fly ash with higher CaO content gives better strength development at an early age than that with lower CaO content,



(a) Concrete containing fly ash with CaO content of 23.4 percent by weight



(b) Concrete containing fly ash with CaO content of 8.1 percent by weight

Fig. 2 Relationships between $\phi(90)$ and SiO_2/CaO of binders in concrete containing fly ash with different CaO contents

since high-calcium fly ash usually contains some hydraulic cementitious materials.

On the other hand, it can be seen from Fig. 1(b), which illustrate the relationships between $\phi(t)$ and SiO_2/CaO after 28 days, that increasing SiO_2/CaO results in increasing $\phi(t)$ until it reaches the optimum point, then it decreases with the increase of SiO_2/CaO. This is because SiO_2 in fly ash reacts with $Ca(OH)_2$ obtained from the hydration reaction. The reaction gives calcium silicate hydrate which also contributes to strength in addition to calcium silicate hydrate from the hydration reaction. But if the amount of SiO_2 is more than the $Ca(OH)_2$ supplied by hydration reaction, strength development will be lower.

As mentioned previously, concrete with high-calcium fly ash yields high compressive strength for the strength ratio in the part before 28 days. For the relationship between $\phi(t)$ and SiO_2/CaO after 28 days, concrete with higher calcium fly ash will reach the optimum point of $\phi(t)$ at a smaller SiO_2/CaO ratio as shown in Fig. 2(a) and Fig. 2(b).

2.2 Effect of Water-to-Binder Ratio

From the results shown in Fig. 1(a) and Fig. 1(b), it can be seen that the effect of water-to-binder ratio can be separated into 2 parts, before 28 days and after 28 days. In the period before 28 days during which the pozzolanic reaction is still not very reactive, concrete with lower w/b gives better strength ratio than that with higher w/b which can be explained by the mechanism of reactions within the paste and pore structure. Lower w/b yields denser structure of the paste, which leads to higher strength ratio and vice versa.

In the period after 28 days when pozzolanic reaction becomes more active, concrete with lower w/b gives lower strength ratio than that with higher w/b because with higher w/b, there is more free water for reactions and better dispersion of the cementitious powders. Thus, higher w/b gives better strength ratio at a later age than that of lower w/b.

Considering the effect of SiO_2/CaO ratio and water-to-binder ratio, the strength ratio was derived as:

$$\phi(t) = 1 + \ln\left(\frac{t}{28}\right) \cdot \Gamma \qquad (4)$$

For $t < 28$ days ;

$$\Gamma = \left[0.12(w/b)^{-0.10}\right] \cdot \left(\frac{SiO_2}{CaO}\right)_n + \left[0.28(w/b)^{00.63} + 0.02\right] \qquad (5)$$

For $t \geq 28$ days ;

$$\Gamma = \left[0.44(w/b)^{0.45}\right]\sqrt{1-\frac{\left[\left(\frac{SiO_2}{CaO}\right)_n - 1\right]^2}{1.48(w/b)^{0.20}}} \quad (6)$$

where $\phi(t)$ is the strength ratio at concrete age t days, $\left(\frac{SiO_2}{CaO}\right)_n$ is the normalized ratio of SiO_2 content to CaO content in the total binders, and w/b is the water-to-binder ratio .

$$\left(\frac{SiO_2}{CaO}\right)_n = \frac{\left(\frac{SiO_2}{CaO}\right) - \left(\frac{SiO_{2,c}}{CaO_c}\right)}{\left(\frac{SiO_2}{CaO}\right)_{opt} - \left(\frac{SiO_{2,c}}{CaO_c}\right)} \quad (7)$$

and

$$\left(\frac{SiO_2}{CaO}\right)_{opt} = \exp\left[-3.89\left(\frac{CaO_f}{SiO_{2,f}}\right) + 0.41\right] + 0.56 \quad (8)$$

where $\left(\frac{SiO_2}{CaO}\right)_n$ and $\left(\frac{SiO_2}{CaO}\right)_{opt}$ are the normalized and optimum values of SiO_2/CaO ratio. $\left(\frac{SiO_2}{CaO}\right)$ is the SiO_2/CaO ratio in the total binders (from Eq. (3)). $SiO_{2,c}$, $SiO_{2,f}$, CaO_c, CaO_f, are the contents of SiO_2 in cement, SiO_2 in fly ash, CaO in cement, and CaO in fly ash (% by weight), respectively.

2.3 Filling Effect of Fly Ash

Additionally, the effect of particle filling of fly ash on strength development model was included since its effect contributes to the improvement of the compressive strength differently at different ages. This improvement is significant at early ages and especially in concrete incorporating air-classified fly ash as shown in Fig. 3.

The equation expressing the effect of particle filling of fly ash on strength ratio was obtained as:

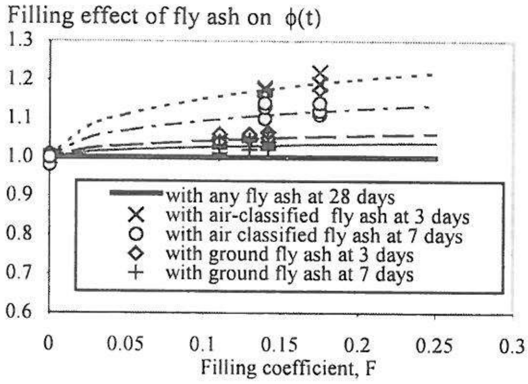


Fig. 3. Relationship between filling coefficients of air-classified and ground fly ashes with shape factors of 1.05 and 1.20, respectively and its effect on strength ratio

$$\omega_F(t) = 1 + (0.545\Psi^{-13.1})\cdot\tan^{-1}(1.2\times10^5 t^{-6.28}) \cdot\sqrt{1-\left(\frac{F-0.5}{0.5}\right)^2} \quad (9)$$

2.4 Effect of Water-Reducing Admixture

As discussed earlier, water reducer affects the compressive strength especially at early age. From Fig. 4 and Fig. 5, it is evident that the compressive strength of concretes at the early age were improved by water reducer more significantly than at the later age.

The equation expressing the effect of water-reducing admixture of fly ash on strength ratio was derived from Fig. 4, and Fig. 5 as:

$$\omega_{wr}(t) = \exp\left[-0.057\log\left(\frac{t}{28}\right)\Omega^{1.3}\nu^{0.4}\right] \quad (10)$$

Finally, the strength ratio at any concrete age can be obtained by Eq. (11).

$$\phi(t) = \left[1 + \ln\left(\frac{t}{28}\right)\cdot\Gamma\right]\cdot\omega_F(t)\cdot\omega_{wr}(t) \quad (11)$$

where $\omega_F(t)$, and $\omega_{wr}(t)$ are the effects of particle filling of fly ash and water reducer on strength ratio at concrete age t (days), from Eq.(9) and Eq.(10), respectively.

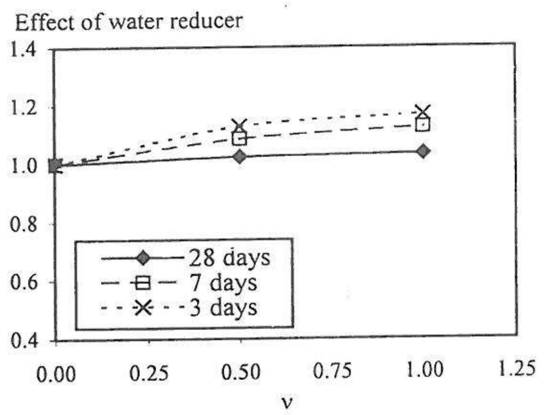


Fig. 4 Relationship between ν and its effect on compressive strength of concrete at 3, 7, 28 days with w/b of 0.30 and incorporating a naphthalene-based water reducer having water reducing efficiency of 0.34

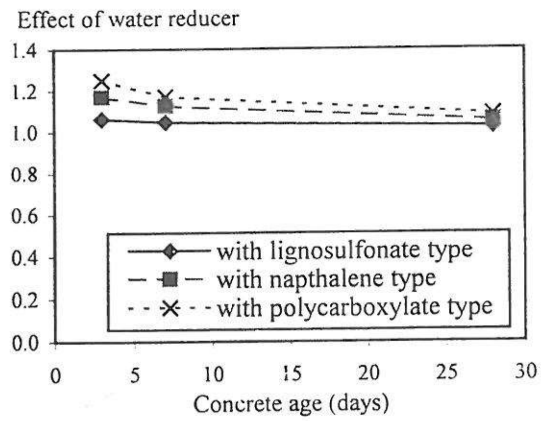


Fig. 5 Relationship between the effects of various water reducing admixtures with 0.5%-dosage on compressive strength of concrete at various ages with w/b of 0.30

3. Verification of the Model

The verification of the simplified strength development model is presented for concretes with various fly ashes having different fineness and using various types of chemical admixtures. The verification was expressed in the form of comparisons between experimental data and predicted results from the model as shown in Fig. 6 and Fig. 7. The data for verification were obtained from the authors' and other researchers' tests [6, 7, 8, 9, 10, 11]

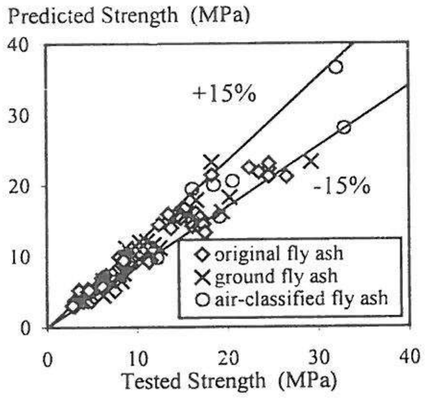


Fig.6 (a) 3 days

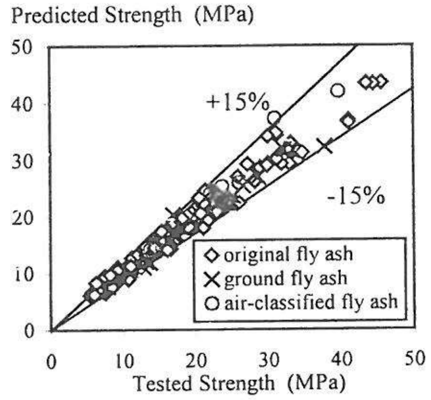


Fig.6 (b) 7 days

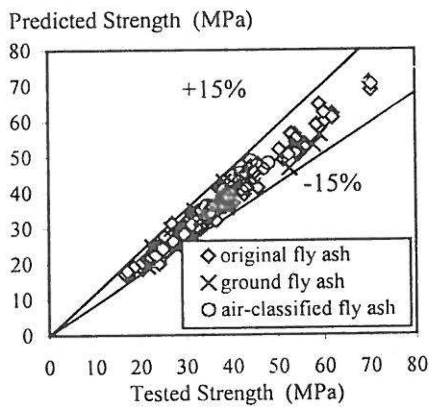


Fig.6 (c) 91 days

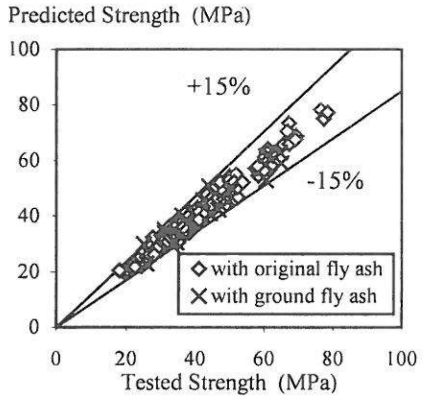


Fig.6 (d) 180 days

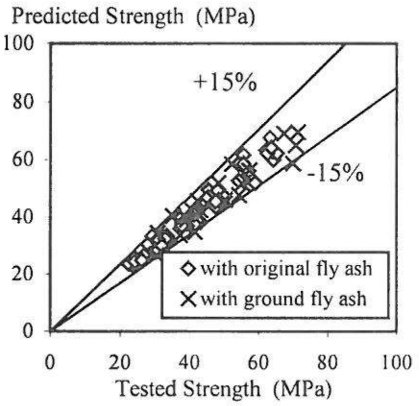


Fig.6 (e) 365 days

Fig. 6 Verification of the model for concretes with various types of fly ash at various concrete ages

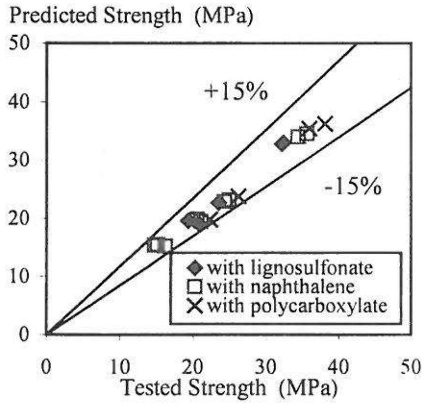


Fig.7 (a) 3 days

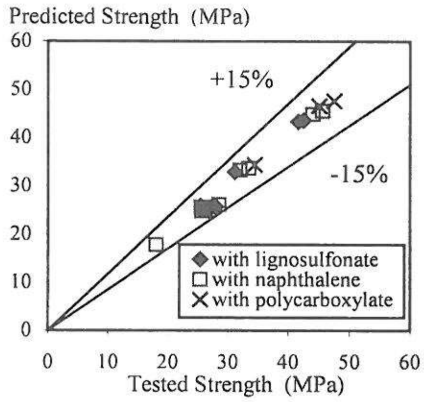


Fig.7 (b) 7 day

Fig.7 Verification of the strength development model for concretes with various types of water-reducing admixtures at various concrete ages

4. Conclusions

Based on the proposed compressive strength models and the verification, the following conclusions can be drawn.

1. The strength development model of fly ash concrete was formulated as functions of concrete age, ratio of silicon dioxide content to calcium oxide content in binders and water-to-binder ratio. In addition, the effects of water-reducing admixture, and particle filling of fly ash on strength development of concrete were also taken into account in the model.
2. The verification showed that the proposed compressive strength models could be used for predicting compressive strength of conventional concrete with various types of fly ash with a satisfactory accuracy.

5. Acknowledgements

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