Compressive Strength Prediction Model for Fly ASH Concrete

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Abstract

This study is aimed at finding an equation for estimating compressive strength of concrete containing fly ash. The concept of using chemical composition of the constituent materials as one of the main parameters for various types of fly ash is proposed. Initially, 28-day compressive strength is considered to vary with unit CaO content, ratio of water to binder (w/b) and ratio of paste volume to void volume of compacted aggregate phase (γ). The CaO is a dominant chemical composition in hydration reaction of cement and pozzolanic reaction of fly ash. γ represents a relation of the availability of paste to fill void and to provide bonding among aggregates. After that, degree of hydration and pozzolanic reaction in term of strength development ratio of concrete is introduced to predict compressive strength at other ages. It was found that the introduced parameters can be satisfactorily used to develop a model for predicting compressive strength of fly ash concrete from ages 3 days up to 1 year.

1. Introduction

It is estimated that in recent years, Thailand has annually produced approximately 3 million tons of fly ash from electricity generation using coal. While the majority of fly ash is still disposed of as a landfilled solid waste, attempts have been continued to utilize it in the construction industry. One of the prime problems for its application is the lack of standards for material, design and construction for fly ash concrete. Recently, the subcommittee on concrete and materials under the Engineering Institute of Thailand has incorporated the specifications for fly ash into the Standard Specification for Materials and Construction of Reinforced Concrete Structures, 1997 version [1]. However, the design standard including mix proportioning and information for structural design for fly ash concrete have not yet been established. This paper concentrates on an attempt to predict the compressive strength of fly ash concrete by creating a prediction model that will be useful as a tool for mix proportioning of fly ash concrete in Thailand.

In addition, the concept of this paper is also extended to predict compressive strength of other special concrete such as self-compacting concrete and roller-compacted concrete which have different methods of compaction from conventional concrete.

2. Compressive Strength Prediction Model for Conventional Concrete

The 28-day compressive strength prediction, a basis for predicting compressive strength at different ages, was developed by reasonably assuming that the 28-day compressive strength varies with unit calcium oxide content in the concrete (C), water to binder ratio (w/b), and ratio of paste volume to void content of the compacted aggregate phase (γ). In this study, the effect of air void is not considered since entrained air is not necessary because of no freezing and thawing attack in Thailand. It is noted here that the model was created for conventional fly ash concrete in which aggregates are normally stronger and denser than the paste. For fly ash concrete in normal practice, the compressive strength increases in concrete with higher unit CaO content and lower w/b as illustrated in Fig.1. [2]

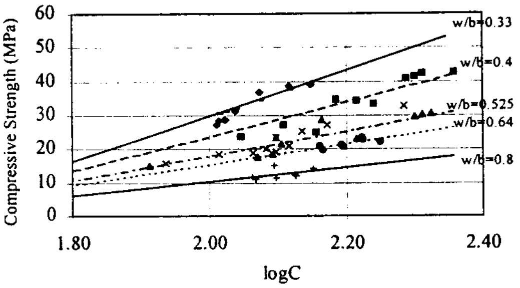

Fig.1 Relationship between 28-day compressive strength and logarithm of unit CaO content of fly ash concrete

The compressive strength will decrease when paste content increases much beyond the void of the compacted aggregate (γ increases) as shown in Fig.2. [2]. To get the optimum compressive strength, the paste not only fills the voids but also

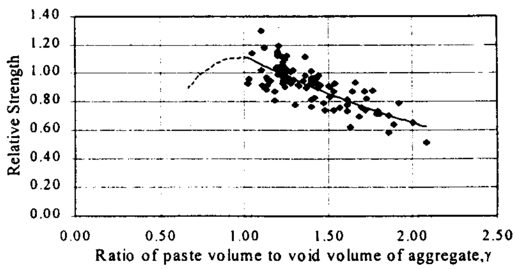

Fig. 2 Relationship between relative strength and γ-factor

creates bonding among aggregate particles. If concrete has too much paste, the mixture will have more water content which results in higher porosity and lower density of the concrete. On the other hand, if concrete has not enough paste, it will affect the bonding among aggregate particles since paste could not completely fill the void of the aggregate phase. Both cases will cause lower compressive strength in concrete.

Based on the information in Fig.1 and Fig.2, the equation for predicting 28-day compressive strength of concrete with fly ash was formulated as

$$f_c(28) = [(16.45\times(w/b)^{-1.26}) \times (\log C-1.8)-10.91\times \ln(w/b)+3.96] \times (1.8931\times e^{-0.53\gamma}) \quad (1)$$

where $f_c(28)$ is the 28-day compressive strength (MPa); C is the unit calcium oxide content in the combined cement-fly ash powder (kg/m^3 of concrete), w/b is water to binder ratio, γ is the ratio of paste volume to void content of the compacted aggregate phase. The unit CaO content, C, can be computed from

$$C=[w_{fa}\times CaO_{fa}+w_{ce}\times CaO_{ce}]/100 \quad (2)$$

where w_{fa} and w_{ce} are fly ash and cement content, respectively (kg/m^3 of concrete), CaO_{fa} and CaO_{ce}, are calcium oxide content in fly ash and cement, respectively (% by weight).

The ratio of paste volume to void content of the compacted aggregate phase can be computed from

$$\gamma = \frac{Vp}{Vv}\text{ , and} \quad (3)$$

$$Vp = Vc + Vf + Vw + Va \quad (4)$$

where Vp is the volume of paste in one cubic meter of concrete (liter), Vv is the volume of void of compacted aggregate in one cubic meter container (liter), Vc is the volume of cement in one cubic meter of concrete (liter), Vf is the volume of fly ash in one cubic meter of concrete (liter), Vw is the volume of water in one cubic meter of concrete (liter) and Va is the volume of air in one cubic meter of concrete (liter).

However, not only the 28-day compressive strength but also the strength at other ages is necessary in designing. To predict the compressive strength at other ages, the concept of strength development ratio is introduced. Strength development ratio (ϕ) is the ratio of compressive strength of concrete at the time considered, $f_c(t)$, to the compressive strength at one year, $f_c(365)$, by assuming that there might be only a negligible increase of compressive strength after 1 year. In this study, the strength development ratio is considered as the function of glass/lime ratio (SiO_2/CaO), water to binder ratio (w/b) and time (t) which can be explained by the concept of pozzolanic reaction and hydration reaction. Finally, the compressive strength of concrete at any time 't' can be predicted by

$$f_c(t) = \frac{\phi(t)\times f_c(28)}{\phi(28)} \quad (5)$$

where $f_c(t)$ is compressive strength at time t (MPa). $\phi(t)$ and $\phi(28)$ are strength development ratio at time t and 28 days, respectively. The function of strength development ratio can be expressed as

$$\phi(t) = p \times \log(t+1) + q \quad (6)$$

where p, which is the slope of the equation, denotes the rate of strength development function and q, which is the y-intercept, denotes the strength development ratio at 0 day. It is realized that the strength development curve should pass through the origin where time is equal to zero since compressive strength of the concrete just after mixing (0 day) shall be zero as shown in Fig.3.

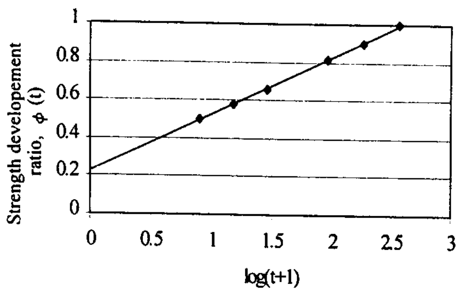

Fig. 3 Relationship between strength development ratio and logarithm of time, t+1

Therefore, the compressive strength at very early ages (earlier than 3 days) can not be accurately predicted using this proposed strength development function.

By the concept of pozzolanic reaction and hydration reaction, it is assumed that the coefficients, p and q have relation with the glass per lime ratio (SiO_2/CaO) for each particular w/b as expressed in the following equations.

$$p=(0.2375\times w/b+0.1216)\times(SiO_2/CaO)+(-0.3325\times w/b+0.4165)\text{when } \frac{SiO_2}{CaO} \leq 0.86 \quad (7a)$$

$$q = (-0.2395\times w/b-0.4828)\times(SiO_2/CaO)+(-0.4335\times w/b+0.5808)\text{when } \frac{SiO_2}{CaO} \leq 0.86 \quad (7b)$$

$$p=(-0.0386)\times(SiO_2/CaO)+0.2415\times(w/b)+0.3672 \quad \text{when } \frac{SiO_2}{CaO} \rangle 0.86 \quad (8a)$$

$$q=(0.115)\times(SiO_2/CaO)-0.832\times(w/b)+0.1685 \quad \text{when } \frac{SiO_2}{CaO} \rangle 0.86 \quad (8b)$$

where

$$SiO_2/CaO = \frac{r\times(SiO_2)_f+(1-r)\times(SiO_2)_c}{r\times(CaO)_f+(1-r)\times(CaO)_c} \quad (9)$$

where SiO_2 is total SiO_2 content in both cement and fly ash (kg/m^3 of concrete), CaO is total CaO content in both cement and fly ash (kg/m^3 of concrete), r is replacement ratio of fly ash in total powder content by weight, $(SiO_2)_f$, $(SiO_2)_c$ are SiO_2 content in fly ash and cement, respectively (%) and $(CaO)_f$, $(CaO)_c$ are CaO content in fly ash and cement, respectively (%).

As shown in Fig.4, the rate of strength development, p, increases with increase of glass to lime ratio due to the increase of pozzolanic reaction when glass content increases under the condition of sufficient $Ca(OH)_2$ paste environment. It can be noted by observing Fig.4 and Fig.5 that the rate of strength development increases up to the glass to lime ratio about 0.86 whereas beyond 0.86, the glass content will be too much so that the concentration of $Ca(OH)_2$ in the pore solution is not enough for processing the pozzolanic reaction. So the rate of strength development gradually decreases. The rate of strength development also increases with w/b because paste with higher w/b has more water for the reactions.

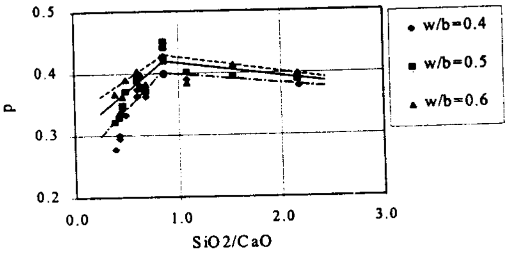

Fig. 4 Relationship between p and SiO_2/CaO

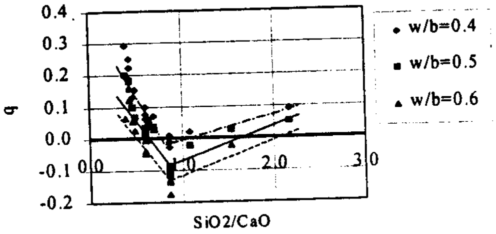

Fig. 5 Relationship between q and SiO_2/CaO

3. Verification of Compressive Strength Prediction Model of Conventional Concrete

The verification of the 28-day compressive strength model was presented in the form of comparison between experimental data from various sources and computed results from the model as shown in Fig.6.

The verification of 3-day, 90-day, 180-day and 365-day strength by using the 28-day compressive strength model together with the strength development ratio are presented in Fig. 7a-7d [8].

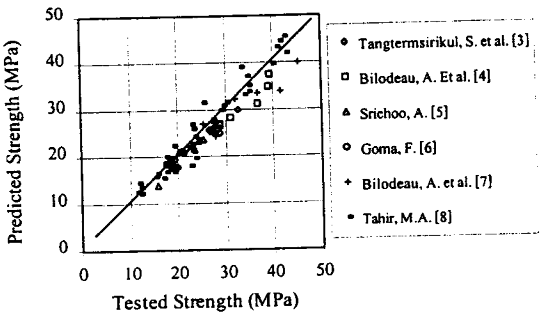

Fig. 6 Comparison between the tested and predicted 28-day compressive strength

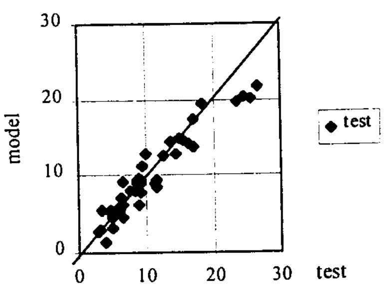

Fig.7a The 3-day compressive strength

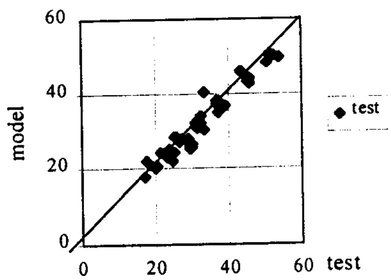

Fig.7b The 90-day compressive strength

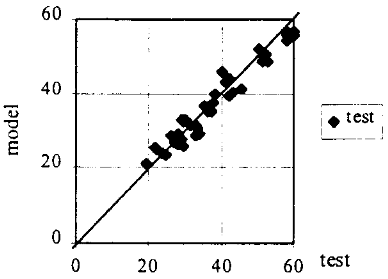

Fig7c The 180-day compressive strength

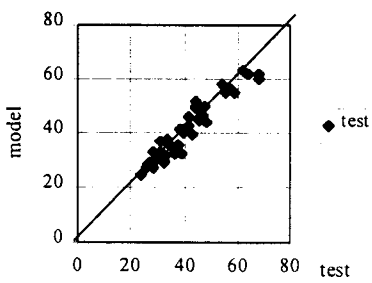

Fig.7d The 365-day compressive strength

4. Compressive Strength Prediction Model for Special Concretes

On some occasions, special concretes might be used due to the limitations of conventional concrete. The decision to select concrete type depends on work condition and construction cost, for example, low-heat concrete (LHC) is suitable for massive construction such as dams and footings, roller-compacted concrete (RCC) is suitable for dams and pavements, and self-compacting concrete is suitable for complicated or heavily reinforced structures.

The same concepts as conventional concrete are introduced in order to predict the compressive strength of the mentioned special concretes. Low-heat concrete has already been taken into consideration in the conventional concrete model in the case of low lime (CaO content). Therefore, only the prediction of compressive strength of roller-compacted concrete and self-compacting concrete will be discussed.

4.1 Roller-Compacted Concrete (RCC)

RCC differs from conventional concrete principally in aggregate grading, paste content and consistency. It is generally compacted by applying large compaction effort due to its extremely low consistency. The model for RCC is constructed based on 91-day compressive strength. The equation for estimating 91-day compressive strength of RCC [$f_{c(RCC)}(91)$] is proposed as shown below.

$$f_{c(RCC)}(91)=(46.568\times(w/b)^{-0.54})(\log C-1.7) -37.153\times(w/b)+37.022 \qquad (10)$$

To predict the compressive strength of RCC at other ages, the compressive strength of concrete at any time 't' [$f_{c(RCC)}(t)$] can be predicted by

$$f_{c(RCC)}(t) = \frac{\phi_{RCC}(t)\times f'_{c(RCC)}(91)}{\phi_{RCC}(91)} \qquad (11)$$

where the equation of strength development ratio is introduced and expressed as shown below

$$\phi_{RCC}(t)=[(0.1473\times\exp(0.5443\times(w/b)))\times\ln(SiO_2/CaO)+0.1482\times\ln(w/b)+0.5879]\times\log(t+1) +(0.2118\times(w/b)-0.4233)\times\ln(SiO_2/CaO)-0.4529\times\ln(w/b)-0.3438 \qquad (12)$$

4.2 Verification of Compressive Strength Prediction Model for Roller-Compacted Concrete

The verification of 3-day, 7-day, 28-day and 91-day compressive strength by using the 91-day compressive strength model together with the strength development ratio are illustrated in Fig.8a-8d.

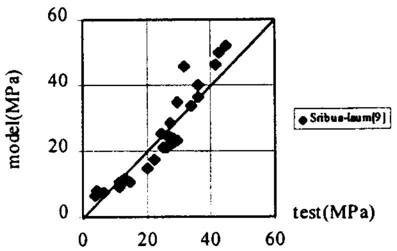

Fig.8a The 3-day compressive strength of RCC

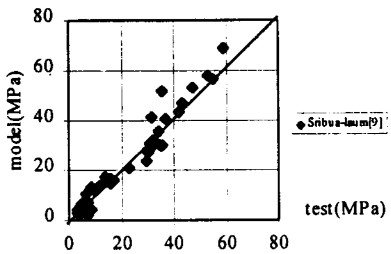

Fig.8b The 7-day compressive strength of RCC

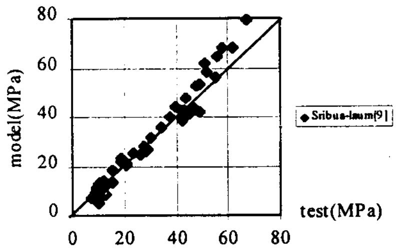

Fig.8c The 28-day compressive strength of RCC

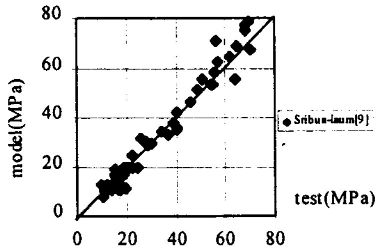

Fig.8d The 91-day compressive strength of RCC

4.3 Self-compacting Concrete (SCC)

Since conventional concrete may not be capable of perfectly filling in some complicated formwork, SCC had been introduced with its performance based on very high filling ability without segregation. Consequently, the vibration process is unnecessary. The model for SCC is constructed based on 28-day compressive strength. The equation for predicting 28-day compressive strength of SCC [$f_{c(SCC)}(28)$] is proposed as shown below.

$$f_{c(SCC)}(28) = [56.041+\exp(16.66-44.322\times(w/b))] \times(\log C-2.15)+95.68\times\exp(-3.24\times(w/b)) \quad (13)$$

4.4 Verification of 28-Day Compressive Strength Prediction Model of Self-Compacting Concrete

The verification of the 28-day compressive strength model for SCC is presented in the form of comparison between test data from various sources and computed results from the model as shown in Fig. 9.

Due to insufficient test data, both models do not take into account the effect of γ. For more accuracy, this effect should be considered.

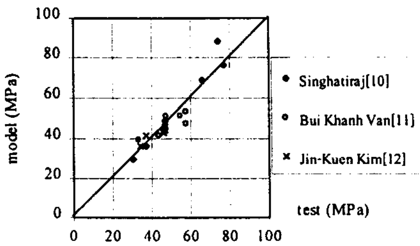

Fig.9 The 28-day compressive strength of SCC

5. Concluding Remarks

A compressive strength prediction model which takes into account the effect of unit CaO content in the mixture, water to binder ratio and paste content to void content of the compacted aggregate phase was developed to predict the 28-day compressive strength of concrete using fly ash with various chemical compositions. The function of strength development ratio, which is the function of the glass to lime ratio (SiO_2/CaO), is also proposed to compute the compressive strength at different ages based on 28-day compressive strength. The proposed 28-day compressive strength model and the strength development function were verified to be efficient for predicting the compressive strength of conventional and low-heat concrete having ages from 3 to 365 days. Moreover, the other models for special concretes also illustrated satisfactory prediction.

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