Effect of Curing Temperature on Early-Age Compressive Strength of Fly Ash Concrete

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Abstract

This study is aimed to investigate the effect of curing temperatures on early-age compressive strength of fly ash concrete. The compressive strength results were collected at 6 hours, 12 hours, 1 day, 3 days and 7 days. From the experimental results, it was shown that when curing temperature is increased at early ages, the compressive strength of concretes cured at higher temperature are higher than concretes cured at lower temperature due to accelerated reaction. However at later ages the compressive strength of concretes cured at higher temperature are lower than that of the concrete cured at lower temperature due to poorer pore structures. In addition the early-age compressive strength model was derived to predict compressive strength at early ages by using the strength development ratio concept. The proposed model exhibited satisfactory accuracy.

1. Introduction

Fly ash is one of the pozzolanic materials that is a by-product of burning ground coal in electrical power plants. The tendency of this ash annually increases due to increasing of power demand. Instead of discarding, it is more beneficial and economical to utilize fly ash in construction industries. Use of fly ash as a cement replacing material in concrete not only benefits in effective using of natural resources and reducing cost of construction but also enhances various properties of concrete, for instance, workability, long term strength and some durability properties.

Various massive concrete structures such as dams, mat foundations are frequently constructed. Temperature gradient occurring inside the concrete mass due to heat of hydration induces thermal stress that may lead to cracking especially at early ages of concrete as stated by Saengsoy [1]. If compressive strength of concrete at early ages is high enough, cracks may not occur. Therefore the early-age compressive strength model is important to predict early-age compressive strength whether it is high enough to resist cracks.

There have been several concepts and models proposed by many researchers for example, Abrams [2] proposed the compressive strength which is based on water to cement ratio ,as shown below

$$f'_c = \frac{A}{B^{w/c}} \quad (1)$$

where f'_c is the compressive strength of concrete, A and B are constants for a given set of material and test condition. This model can be used to predict compressive strength of plain concrete at 7 days and 28 days only. However, there are still some researchers proposed the compressive strength model which can be used to predict compressive strength at early ages. Olokun et. al [3] presented early-age strength prediction model by applying the maturity concept and can be written as:

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$$f_{cx} = f'_c(1 - e^{-\alpha m}) \quad (2)$$

where f_{cx} is compressive strength of concrete at ages other than 28 days (psi). At given maturity M (F°-hr), m is maturity M divided by 10,000 (m=M/10,000), M is maturity in F°-hr, f'_c is 28-day compressive strength (psi) and α is a constant. The maturity M can be calculated from:

$$M = (T - 11)t \quad (3)$$

where T is the curing temperature (F°), t is the age of concrete in hour.

Unfortunately, these two models and many of the compressive strength models failed to incorporate the effect of chemical composition of cementitious materials and also can not be used in Thailand according to different materials and climate conditions. Hence, the aim of this study is to propose a mathematical model for predicting early-age compressive strength of fly ash concrete by considering effect of curing temperature and chemical composition of cementitious materials in term of reactions (hydration and pozzolanic reactions).

2. Concept of Early-Age Compressive Strength Model

As discussed previously, there are several approaches to predict compressive strength of concrete at early ages, for example, maturity laws. In this study the strength development ratio (ϕ) is introduced and is defined as:

$$\phi(t,T) = \frac{f'_c(t,T)}{f'_c(28days, 30°C)} \quad (4)$$

where $f'_c(t,T)$ is compressive strength of concrete at considered age of t days (MPa). f'_c(28days, 30°C) is the 28-day compressive strength of concrete cured at normal temperature (MPa). $\phi(t,T)$ is strength development ratio at any considered age t and cured at any elevated temperature. T is curing temperature (°C) and t is age of concrete (days).

The model to predict compressive strength of early-age concrete can be formulated by multiplying the 28-day compressive strength with the strength development ratio at the considered age and curing temperature. So the compressive strength at any ages and at any curing temperatures can be obtained as follows:

$$f'_c(t,T) = f'_C(28days, 30°C) \cdot \phi(t,T) \quad (5)$$

3. Experimental Program

3.1 Mix proportion and materials

In this study there were 9 mixes that were prepared and tested for compressive strength so as to investigate various parameters affecting the early-age compressive strength. Two types of cementitious materials, i.e. ordinary portland cement type I (OPC type I) and fly ash obtained from Mae Moh were used. The mix proportions, physical properties and chemical composition of ordinary portland cement type I and fly ash used in the test are shown below:

Table 1 Mix proportions for testing early-age compressive strength of fly ash concrete cured at 30°C, 45°C and 70°C

γ	w/b	%R	Cement (kg/m^3)	Fly Ash (kg/m^3)	Water (kg/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)
1.2	0.55	0	327	0	180	1134	777
1.2	0.55	30	217	93	171	1134	777
1.2	0.55	50	150	150	165	1134	777
1.4	0.4	0	464	0	186	1056	723
1.4	0.4	30	305	131	174	1056	723
1.4	0.4	50	209	209	167	1056	723
1.4	0.55	0	384	0	211	1056	723
1.4	0.55	30	255	109	200	1056	723
1.4	0.55	50	176	176	193	1056	723

γ is ratio of paste to void volume of the densely compacted aggregate phase . w/b is water to binder ratio. %R is replacement percentage of fly ash.

Table 2 Chemical composition of OPC Type I and fly ash

Chemical Composition (%)	OPC type I	Fly Ash
SiO_2	20.61	43.12
Al_2O_3	5.03	22.04
Fe_2O_3	3.03	9.78
CaO	64.89	12.55

MgO	1.43	3.09
Na_2O	0.22	1.30
K_2O	0.46	5.22
SO_3	2.70	2.76
Loss on ignition	1.23	*
Free lime	0.79	-
Gypsum content	5.6	-
(C_3S)	57	-
(C_2S)	17	-
(C_3A)	83	-
(C_4AF)	10	-

* means non detectable due to very low LOI

Table 3 Physical properties of OPC Type I and fly ash

Physical properties	OPC Type I	Fly ash
Blaine fineness (cm^2/g)	3150	2809
Specific gravity	3.15	2.1

3.2 Curing conditions

All of concrete specimens were sealed and cured under different three isothermal curing temperatures, i.e. 30°C, 45°C and 70°C to investigate the effect of curing temperature on early-age compressive strength.

3.3 Experimental procedures

All specimens were mixed according to the designed mix proportions and cast in ϕ100×200mm steel moulds. Then all specimens were immediately covered by plastic sheets and aluminum foils in order to prevent evaporation of water as shown in Figure.1. Thereafter those specimens were put in the curing temperature control cabinet as shown in Figure.2. After 24 hours all specimens were demoulded and covered by plastic sheets and aluminum foils as shown in Figure.3. Then those specimens were kept in different temperatures of 30°, 45° and 70°C. Compressive strength was tested at 6hrs, 12hrs, 24hrs, 3 days, 7 days.

3.4 Compressive strength results of concrete at normal curing temperature and elevated temperatures

The compressive strength results of concrete, tested at ages from 6hrs to 1 day, cured at normal temperature and elevated temperature are shown in Figure.4 (a) to (i).

In addition the compressive strength results of concrete at later ages are shown in Figure.5 (a) to (i).

Figure.1 Covered plastic sheet specimen

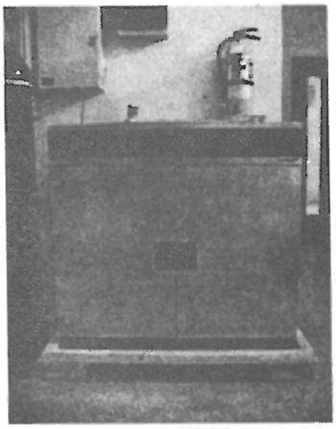

Figure.2 Curing temperature control cabinet

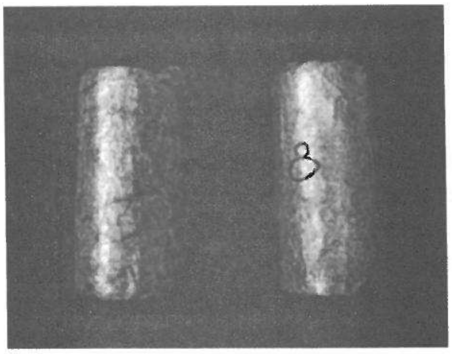

Figure.3 Sealed specimens

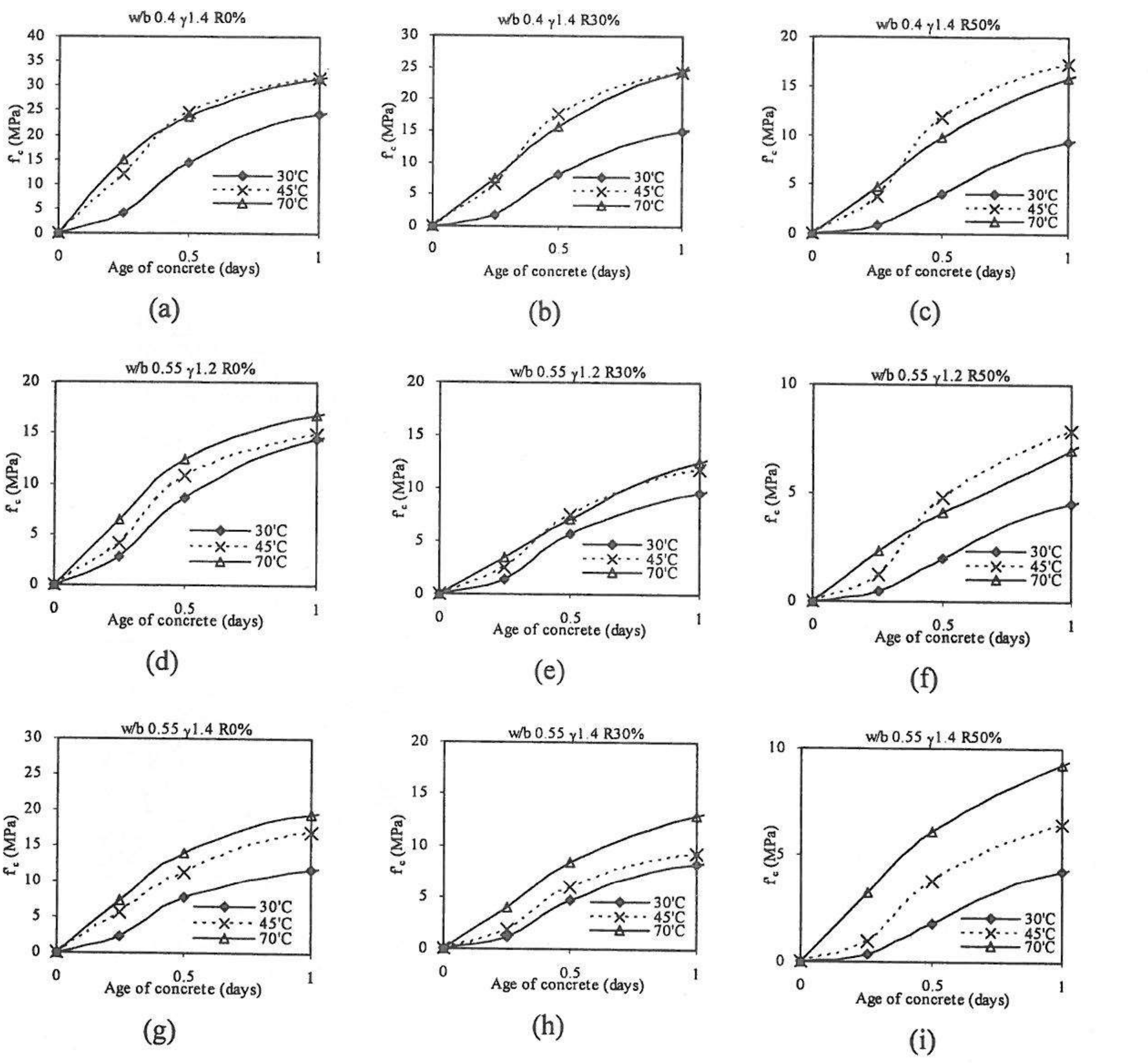

Figure.4 Compressive strength results of concrete at early ages cured at normal temperature and elevated temperatures when w/b 0.4, 0.55, γ=1.2, 1.4 and %R = 0%, 30%, 50%

From Figures.4 (a) (d) (g) and Figures.5 (a) (d) (g), it was found that curing temperature significantly influenced the compressive strength of the cement-only concrete. The higher curing temperature, the higher compressive strength was obtained at early-age state. However, the compressive strength of concrete cured at higher temperature became lower than the compressive strength of concrete cured at normal temperature in long term.

At early-age state the compressive strength of concrete cured at higher temperature was higher than compressive strength of concrete cured at normal temperature due to the fact that reaction in the paste matrix was accelerated. In addition, the compressive strength of concrete at later ages will decrease. Verbeck and Helmuth [4] provided the reason that if hydration is accelerated by increasing curing temperature, the high rate of reaction does not allow time

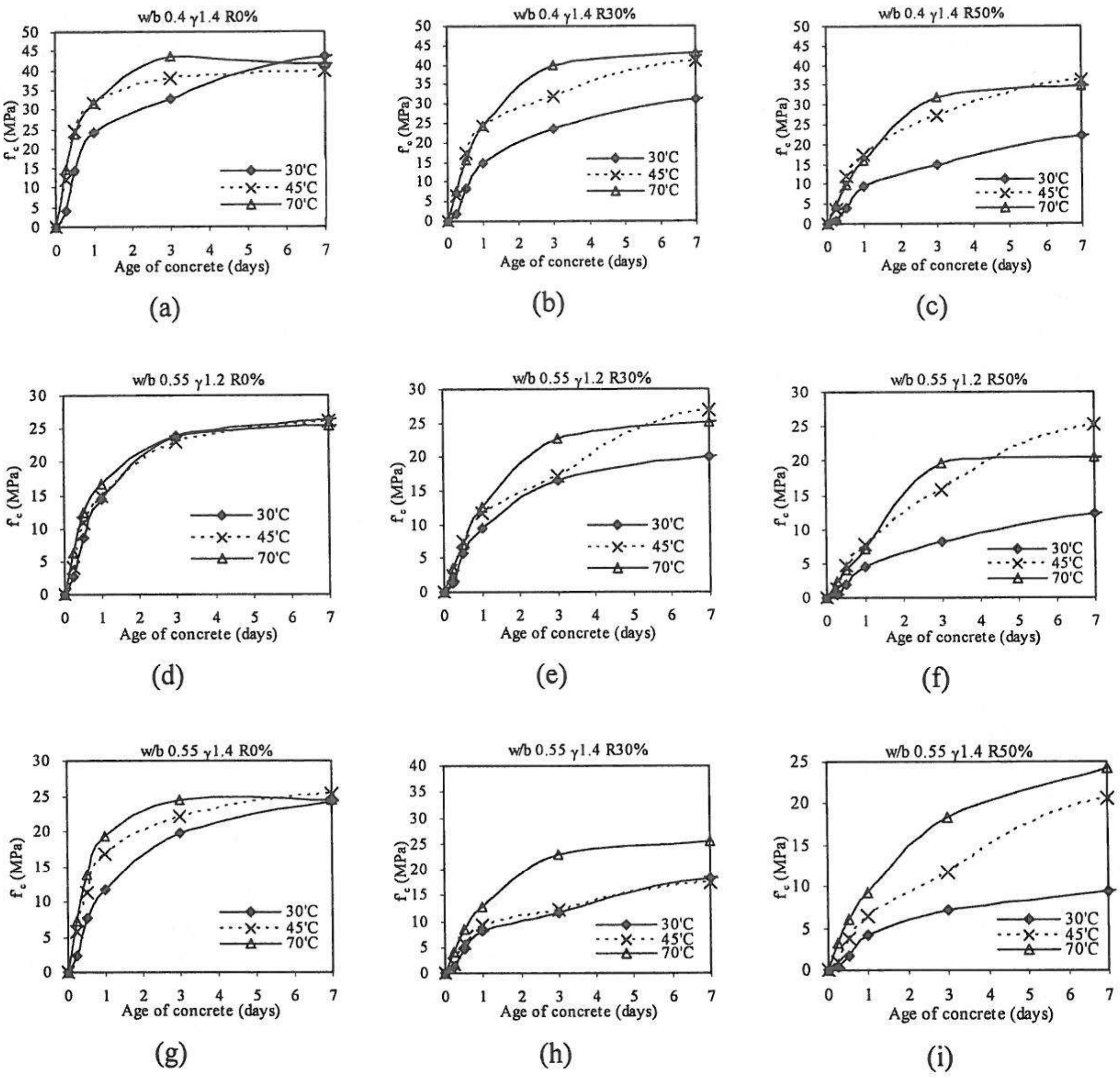

Figure.5 Compressive strength results of concrete at later ages cured at normal temperature and elevated temperatures when w/b 0.4, 0.55, γ=1.2, 1.4 and %R = 0%, 30%, 50

for hydration product to diffuse and precipitate uniformly throughout the interstitial space between the cement grains. Therefore, a high concentration of hydration products are built up in the zone surrounding the hydrating cement grains. The presence of this highly concentrated, dense and encapsulating layer, which forms an impermeable rim around the cement grain, should retard subsequent hydration. Moreover, the hydration product of a weaker physical structure are formed, more porous than usual, so that the larger portion of pores remains unfilled. So the compressive strength of concrete will decrease in later ages.

In the case of compressive strength results of fly ash concrete as shown in Figures.4 (b) (c) (e) (f) (h) and (i), the early-age compressive strength of fly ash concrete cured at higher temperatures were higher than that of the fly ash concrete cured at lower temperature because of accelerated reactions. From Figures.5 (b) (c) (e) (f) (h) and (i), at later ages compressive strength of fly ash concrete cured at higher temperature was higher than that of the concrete cured at lower temperature due to slow rate of pozzolanic reaction. For example, it can be seen from Figures. 5 (a) that the compressive strength results of cement-only concrete at higher temperature was lower than that of the concrete cured at normal temperature. Whereas Figures. 5 (b) and 5 (c) shows that compressive strength at 7 days of concrete incorporating 30% and 50% of fly ash and cured at higher temperature were higher than that of the concrete cured at normal temperature because of slow rate of pozzolanic reaction. It can be recognized that the differences of strength between that cured under normal temperature and that cured at elevated temperatures are larger when fly ash is incorporated into the mixtures. In other words, it can be said that high temperature affects fly ash concrete more severely than cement-only concrete.

4. Model of Early-Age Compressive Strength of Fly Ash Concrete by Taking into Account Effect of Curing temperature

From Eq. (5) it can be seen that the strength development ratio at any times and at any curing temperatures ϕ (t,T) must be derived in order to determined compressive strength at any times and at any curing temperatures from the 28-day compressive strength at normal curing temperature.

In this study strength development ratio ϕ (t,T) is assumed to be the function of average degree of reaction (hydration and pozzolanic reactions) as shown in Eq. (6)

$$\phi(t,T) = f(\text{average degree of reaction}) \tag{6}$$

The term average degree of reaction (α_{ave}) is introduced to formulate the model as shown in Eq. (7)

$$\alpha_{ave} = \{[(1.13 \cdot w/b^{0.38})r^{1.95} + (0.49 \cdot w/b^{3.28} + 0.25)] \cdot (1.11 \cdot T^{0.21})\} \cdot [(1-r) \cdot \alpha_{hy}(t) + 0.4\tan^{-1}(13\alpha_{poz}(t))] \tag{7}$$

where w/b is water to binder ratio, r is replacement ratio of fly ash, T is curing temperature (°C), $\alpha_{hy}(t)$ is average degree of hydration of paste (%), $\alpha_{poz}(t)$ is degree of pozzolanic reaction of paste (%).

The relationship between α_{ave} and strength development ratio, $\phi(t)$, at normal temperature and elevated temperature are shown in Figures. 6, 7 and 8.

From those relationships the strength development ratio model ϕ (t,T) can be derived as shown in Eq. (8) and (9)

α_{ave}<35%

$$\phi(t,T) = \frac{[0.02 \cdot (0.05 \cdot w/b^{-1.53})^{(0.04 \cdot T^{2.02})} \cdot \alpha_{ave}]^{0.01}}{[(-0.03 \cdot T^{0.39}) + (0.21 \cdot \alpha_{ave}^{-0.12})]^{-0.24}} \tag{8}$$

α_{ave}>35%

$$\phi(t,T°C) = [(0.79 \cdot T^{0.007} - 0.79) \cdot w/b^{[-2.61 \cdot (0.04 \cdot T)^{27.86} - 0.29]}] \cdot \alpha_{ave} + (-0.002 \cdot T^2 + 0.14 \cdot T - 3.87) \cdot w/b^{0.44} \tag{9}$$

where α_{ave} is average degree of reaction, w/b is water to binder ratio, r is replacement ratio of fly ash, T is curing temperature (°C), $\phi(t,T)$ is strength development ratio.

Finally, the early-age compressive strength model can be computed from Eq. (5) whereas the 28-day compressive strength equation at normal curing temperature had been proposed by KaewKhluab and Tangterm sirikul [5] as shown in Eq. (10)

$$f'_c\,(28days, 30°C) = [\alpha_1 \log(CaO_{eff}) + \lambda_f \cdot \alpha_2] \cdot \chi_\gamma \cdot \chi_{LOI} \cdot \chi_{air} \cdot \chi_{wr} \tag{10}$$

where f'_c (28days, 30°C) is the 28-day compressive strength in MPa, w/b is the water to binder ratio, CaO_{eff} is the effective calcium oxide content in concrete (kg/m^3 of concrete). α_1 and α_2 are the slope and the y-intercept of the log (CaOeff)-f'_c (28days) curve which depends on water to binder ratio. λ_F represents the filling effect of fly ash, χ_γ is the effects of γ, χ_{LOI} is the effect of LOI in fly ash, χ_{air} is the effect of entrained air, χ_{wr} is the effect of water reducing admixture. The equations of the parameters appeared in the Eq. (10) can be found in the publication by Kaewkhluab and Tangtermsirikul [6].

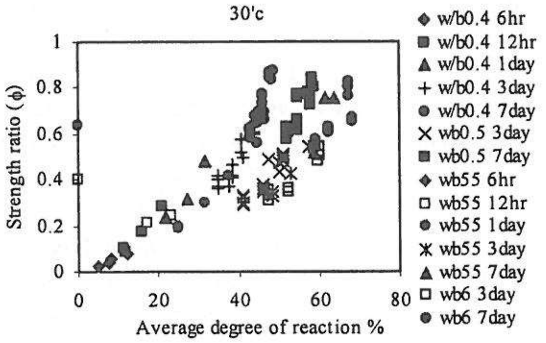

Figure.6 Relationship between strength develop ment ratio and average reaction at 30°C

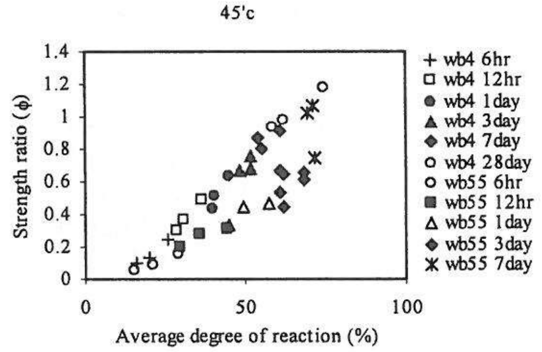

Figure.7 Relationship between strength develop ment ratio and average reaction at 45°C

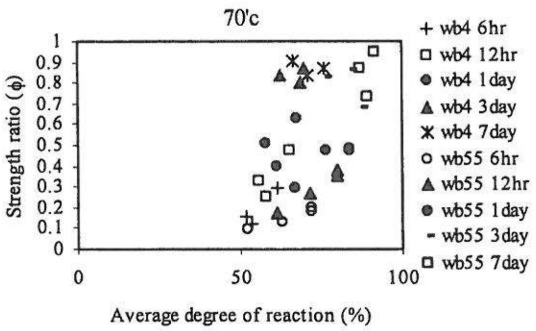

Figure.8 Relationship between strength develop ment ratio and average reaction at 70°C

The verification of early-age compressive strength at normal and elevated temperatures are shown in Figures.9 to 13. It is important to note that this model is applicable for concretes incorporating original fly ash with normal fineness and cured at 30°C, 45°C, 70°C.

6. Conclusions

It can be concluded from the experimental results that early-age compressive strength of cement-only concrete cured at higher temperature is higher than that of concrete cured at lower temperature. However, the compressive strength of cement-only concrete cured at higher temperature will be lower than that of concrete cured at lower temperature at later ages according to poorer pore structure. In case of concrete incorporating fly ash, early-age compressive strength of fly ash concrete cured at higher temperature is higher than that of concrete cured at lower temperature. Moreover, it can be seen obviously that at later ages the differences of compressive strength are larger compared between normal temperature and elevated temperature because of slow rate of Pozzolanic reaction.

The proposed equations can be used to predict early-age compressive strength with satisfactory accuracy

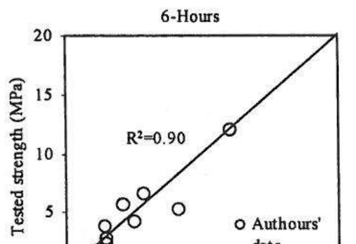

Figure.9 Verification of 6 hours compressive strength at 30°C, 45°C and 70°C.

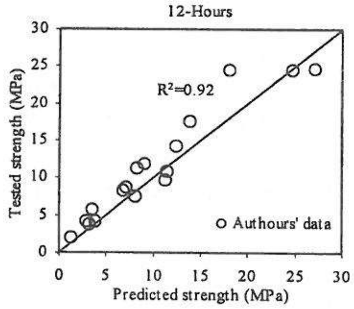

Figure.10 Verification of 12 hours compressive strength at 30°C, 45°C and 70°C.

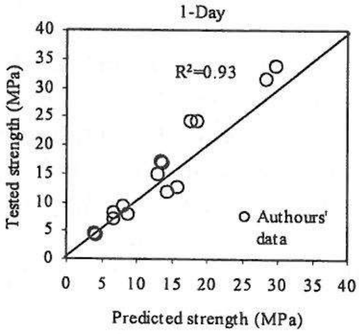

Figure.11 Verification of 1 day compressive strength at 30°C, 45°C and 70°C.

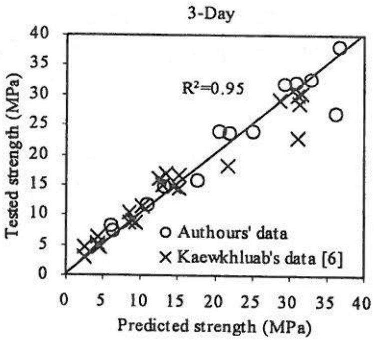

Figure.12 Verification of 3 days compressive strength at 30°C, 45°C and 70°C.

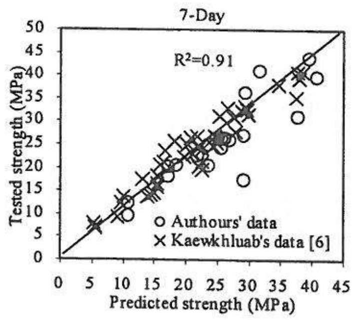

Figure.13 Verification of 7 days compressive strength at 30°C, 45°C and 70°C.

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