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Prediction model of compressive strength development of fly-ash concrete

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Abstract

Based on experimental results concerning the compressive strength development of concrete containing fly ash, the authors derived an estimation equation for compressive strength development. The equation can express coefficient α, which indicates the activity of fly ash as a binder, in the form of a function of age, fly-ash content, and Blaine specific surface area of fly ash.

This equation is capable of explaining the increases in the early strength due to fly ash in place of part of fine aggregate, the decreases in the early strength due to fly ash in place of part of cement, the increases in the long-term strength due to pozzolanic reaction, the relationship between the fly-ash replacement ratio and the ratio of strength increase/decrease, and the effect of fly ash's Blaine specific surface area on the strength.

Keywords: Fly ash; Pozzolanic reaction; Compressive strength; Prediction model

1. Introduction

Power stations firing coal, an economical fuel of which there is a steady supply, have increased in recent years to meet the increasing demand for electric power. Such power stations, which now produce 6.4 million tons of coal ash annually, are expected to emit some 12.8 million tons in 2010 [1] in Japan. Whereas half the amount is currently used for cement materials and concrete admixtures, the rest is dumped. However, environmental situations will not permit the dumping of a large amount of waste fly ash, which will increase every year. It is therefore crucial to increase the amount and area of the fly-ash use. To cope with this problem, a number of studies have been conducted in the architectural field in recent years on applying a large amount of fly ash to concrete [2–4].

The authors investigated the compressive strength properties of concrete with a high fly-ash content and found the following [5,6].

At early ages, the cement–water ratio and the compressive strength correlated, but the correlation between the powder–water ratio and the compressive strength was not evident. On the other hand, the correlation between the cement–water ratio and the compressive strength became less evident at later ages, whereas the correlation between the powder–water ratio and the compressive strength became highly evident, regardless of the presence/absence and mixing method of fly ash. In other words, fly ash induces pozzolanic reactions as the age increases, acting as a binder.

The compressive strength-developing behavior of concrete containing fly ash widely differs from that of concrete with no fly ash while depending on the method and amount of fly-ash addition. An equation model is therefore considered necessary, when proportioning concrete containing fly ash, to estimate the compressive strength development, taking account of its properties.

Akram Tahir and Nimityongskul [7] proposed an equation for calculating the compressive strength of such concrete from the aspect of interaction between the hydration of C_3S and C_2S and the pozzolanic reaction based on a hypothesis that the compressive strength of fly-ash concrete results from the formation of $C_3S_2H_3$. Babu et al. proposed a function of the fly-ash replacement ratio to determine the contribution of fly ash to the compressive strength of concrete at an age of 7 days [8]. However, these cannot express the long-term compressive strength development of fly-ash concrete.

The authors propose an equation for estimating the compressive strength development of concrete containing fly ash incorporating the pozzolanic effect of fly ash with

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the aim of establishing a technique of proportioning concrete with a high fly-ash content.

2. Experiment procedure

2.1. Mixture proportions

Table 1 gives the mixture proportions under analysis. The first two characters indicate the state of fly-ash addition (PL: no fly ash; EX: addition in place of part of fine aggregate; IN: addition in place of part of cement). The following two digits indicate the water–cement ratio (W/C) in the case of PL and EX and the water–powder ratio [W/(C + fly ash)] in the case of IN. The last two digits indicate the fly-ash percentage by mass of cement in the case of IN and the fly-ash percentage by volume of fine aggregate in the case of EX.

In the case of addition in place of part of fine aggregate (EX), concrete was proportioned by determining the fly ash and fine aggregate contents according to the predetermined volumetric ratio after determining the unit water, cement, and coarse aggregate contents referring to the proportioning design method specified in JASS 5 (the water–cement ratio was constant). In the case of addition in place of part of cement (IN), concrete was proportioned by replacing part of cement with fly ash according to the predetermined mass ratio and then reducing the fine aggregate content corresponding to the increase in the powder volume resulting from the difference between the specific gravities of cement and fly ash (the water–powder ratio was constant). The target slumps were set at 21 ± 2.5 and 18 ± 2.5 cm for water–cement ratios of 40% or less and 50% or more, respectively.

2.2. Materials

The properties of the materials used for the experiment were as follows: Normal Portland cement having the physical properties as given in Table 2 was used as the cement. Fly ash conforming to JIS A 6201 had the properties as given in Table 3. Sand from Oigawa River was used as the fine aggregate. Crushed hard sandstone from Ohme was used as the coarse aggregate. Their physical properties are given in Table 4. As for chemical admixtures, a naphthalene-based, air-entraining, and high-range water-reducing admixture and lignosulfonate-based, air-entraining, and water-reducing admixture were used for W/C of 40% or less and 50% or more, respectively.

2.3. Test procedure

Concrete was mixed with a temperature of 20 °C and a relative humidity of 60% or more. The slump was adjusted by changing the chemical admixture dosage. The slump, air content, mass, and compressive strength were measured in accordance with JIS A 1116, JIS A 1128, JIS A 1116, and JIS A 1108, respectively. Compression specimens 10 cm in diameter and 20 cm in length were demolded at an age of 1 day and were standard cured.

The pore volume and $Ca(OH)_2$ content were measured to investigate the space-filling effect of fly ash and the

Table 1
Mixture proportions and fresh properties

	W/C (%)	W/P (%)	FA/C	s/a (%)	Weight (kg)					AE agents (%)	Slumps (cm)	Air contents (%)
					W	FA	C	S	G			
PL35	35	35.0	0	43.4	175	0	500	760	991	1.7	21.3	3.1
EX35-20		27.8	0.26	38.0		129		608		2.5	20.4	1.6
PL40	40	40.00	0	45.3	175	0	438	811	991	1.6	22.8	3.6
EX40-10		34.5	0.16	42.4		69		730		1.8	21.8	1.6
EX40-20		30.4	0.31	39.8		137		649		2.0	21.1	1.9
EX40-30		27.2	0.47	36.4		206		568		2.5	19.7	1.5
PL50	50	50.0	0	47.1	175	0	350	884	991	1.5	19.5	3.3
EX50-10		41.2	0.21	44.5		75		795		1.4	18.0	2.3
EX50-20		35.0	0.43	41.6		150		707		1.7	18.1	2.3
EX50-30		30.5	0.64	38.0		224		607		2.1	11.5	2.3
IN50-10	55.6	50.0	0.11	46.8	175	35	315	871	991	1.4	19.5	2.7
IN50-20	62.5		0.25	49.5		70	280	842		1.4	19.0	2.6
IN50-30	71.4		0.43	46.0		105	245	845		1.8	20.0	3.6
PL60	60	60.1	0	48.0	175	0	291	914	991	1.4	18.1	2.3
EX60-10		47.3	0.27	45.8		79		839		1.5	20.5	1.7
EX60-20		39.0	0.54	42.5		158		732		1.6	18.5	1.6
EX60-30		33.2	0.81	39.7		237		653		2.2	11.6	2.0
PL70	70	70.0	0	48.9	175	0	250	948	991	1.5	18.1	3.0
EX70-10		52.7	0.33	46.7		82		870		1.5	19.5	1.5
EX70-20		42.3	0.65	43.3		164		758		1.7	19.8	2.2
EX70-30		35.3	0.98	40.6		245		676		1.9	18.7	1.6

W/C: water–cement ratios; s/a: rate of fine aggregate; W: water; C: cement; S: fine aggregate; G: coarse Aggregate; FA: fly ash; W/P: water–powder ratio; and FA/C: fly ash–cement ratio.

Table 2
Properties of cement

Specific gravity	Blaine specific surface area (cm^2/g)	Setting time (h–min)		Soundness test
		Initial	Final	
3.16	3370	2–20	3–25	Good

effect of pozzolanic reaction on the pore structure and hydrate content. Concrete specimens cured for 28 days and for 6 months in water, at a temperature of 20 ± 2 °C, were crushed and immersed in acetone to discontinue hydration and were then dried by the D-dry. The pore volume was measured by mercury penetration [9], while the $Ca(OH)_2$ content was measured by the TG-DSC method [10], with corrections for the aggregate content made by the insol method [10].

3. Results and discussion

3.1. Compressive strength development

Fig. 1 shows the compressive strength development over time. Without fly ash, PL, the rate of strength development significantly decreased after an age of 28 days. When fly ash was added in place of part of cement, IN, the early strength was lower than that of the non-fly-ash concrete, but strength gains continued for a long time. On the other hand, fly ash in place of part of fine aggregate, EX, increased the strength starting from an early age over a long period.

3.2. Pore structure

Fig. 2 (a) to (d) shows the pore size distribution at 28 days and at 6 months. At 28 days, fly ash in EX specimens led to a lower total pore volume, whereas fly ash in IN specimens led to a higher total pore volume, than non-fly-ash concrete did. The pore volume of EX specimens decreased, whereas that of IN specimens increased, as the fly-ash content increased. At 6 months, the total pore volumes of NO, IN, and EX specimens were lower than those at 28 days, but the differences between the methods and contents of fly-ash addition were smaller than at 28 days.

3.3. $Ca(OH)_2$ content

Fig. 3 (a) and (b) shows the $Ca(OH)_2$ content detected at 28 days and at 6 months. At 28 days, nearly the same

Table 3
Properties of fly ash

Ig. loss (%)	Specific gravity	Fineness		Percentage of flow [%]
		45-μm Sieve residual quantity [%]	Surface area (Blaine Method) [cm^2/g]	
0.9	2.27	2.3	3890	110

Table 4
Properties of sand and coarse aggregate

	Specific gravity	Rate of water absorption (%)	Percentage of solid volume	Fineness modulus
Fine aggregate	2.63	1.67	66.2	2.74
Coarse aggregate	2.66	0.64	60.9	6.75

$Ca(OH)_2$ content was detected for all methods of addition and content of fly ash. At 6 months, the $Ca(OH)_2$ content in PL specimens was higher than at 28 days, but the $Ca(OH)_2$ content in both IN and EX specimens was lower than at 28 days, and the decrease was larger as the fly-ash content increased.

In the process of hydrate structure formation, the large deposit phase of $Ca(OH)_2$ begins to grow at an age of 1 day and nearly ceases to grow at 7 days. $Ca(OH)_2$ deposits thereafter in the form of small crystals coexisting with C-S-H and hydrates of monosulfates [11,12]. Accordingly, fly-ash particles in place of part of fine aggregate occupy and reduce the spaces for hydrate deposits normally occupied by free water in the process of setting and hardening, permitting the formation of only small and dense hydrates [13]. This not only causes the matrix to be dense but also inhibits large $Ca(OH)_2$ deposits, contributing to early strength gains.

When fly ash is mixed with water, together with cement, it induces pozzolanic reaction, in which glass phase silica (SiO_2) and alumina (Al_2O_3) progressively react with $Ca(OH)_2$ formed by cement hydration, forming hydrates of calcium silicate, as given in Eq. (1). This reduces the $Ca(OH)_2$ content, which is a weakness in concrete strength, while increasing C-S-H gel, which is responsible for the formation of the structure of hardened cement. Therefore, in concrete containing fly ash, the hydration of cement forms the hardened structure, and the pozzolanic reaction of fly

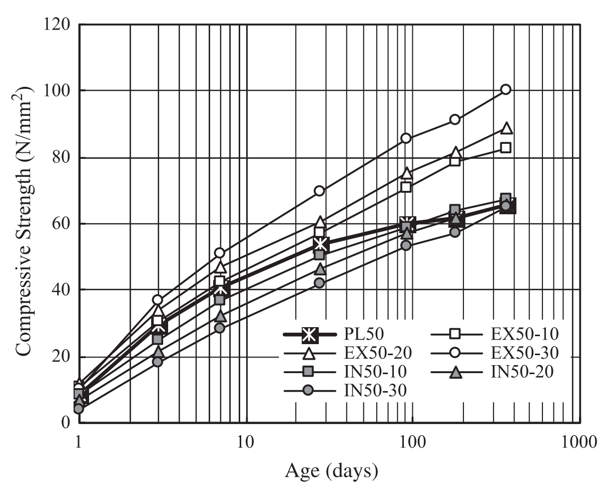

Fig. 1. The compressive strength development over time with age.

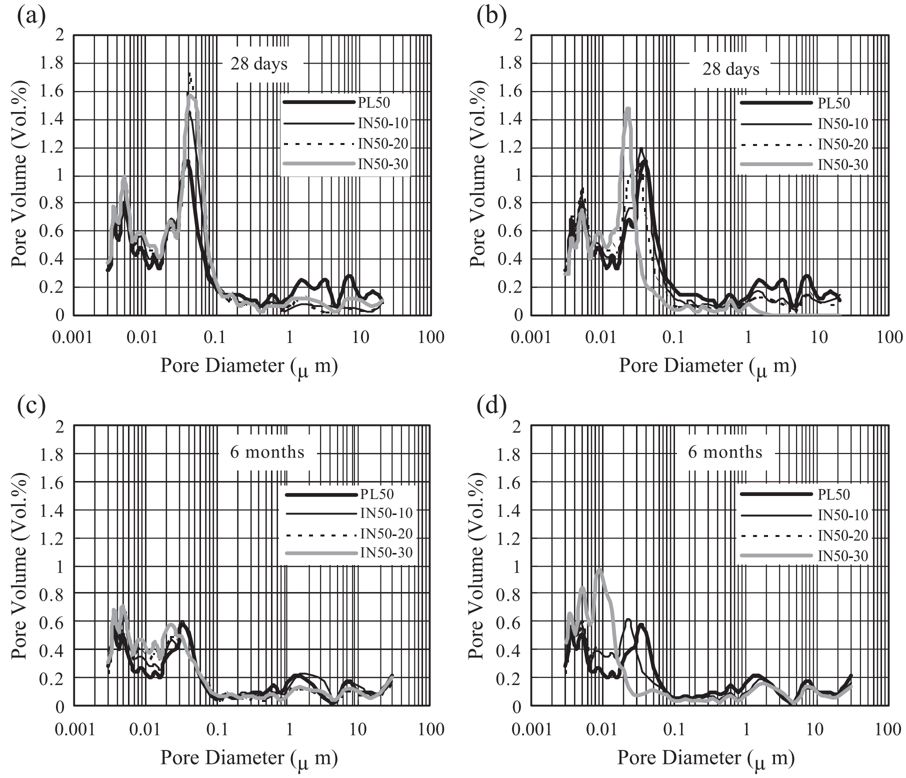

Fig. 2. Pore size distribution at 28 days and at 6 months. (a) Fly ash in place of part of cement (age 28 days). (b) Fly ash in place of part of fine aggregate (age 28 days).(c) Fly ash in place of part of cement (age 6 months). (d) Fly ash in place of part of fine aggregate (age 6 months).

ash improves the structure, ensuring strength development for a long time.

$$Ca(OH)_2+[SiO_2, Al2O_3] \rightarrow \begin{cases} 3CaO \cdot 2SiO_2 \cdot 3H_2O \\ 3CaO \cdot Al_2O_3 \cdot 6H_2O \\ 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O \end{cases} \quad (1)$$

4. Strength development estimation equation

It is considered highly useful for establishing the proportioning technique for concrete containing fly ash to derive an equation to quantitatively estimate the above-mentioned compressive strength development of such concrete. This article proposes a strength development estimation equation paying attention to the fact that the compressive strength of concrete with no fly ash is a linear function of the cement–water ratio and that fly ash gradually begins its pozzolanic reaction as the age increases, assuming the role of a binder.

Fig. 4 shows the relationship between the cement–water ratio and the compressive strength of non-fly-ash concrete at different ages. Compressive strength is a linear function of cement–water ratio, and their relationship can be expressed as Eq. (2). The values of $A(t)$ and $B(t)$ are as given in Table 5. Fig. 4 and Table 5 reveal that the values of $B(t)$ can be judged as being constant, regardless of the age. For the cement used in the present tests, the average of the values of Table 5, $B=18.2$, was adopted as $B(t)$.

$$f_c(t) = A(t)(C/W) + B(t) \quad (2)$$

where $f_c(t)$ = compressive strength at t days (N/mm^2), C = cement content (kg/m^3), W = unit water content (kg/m^3), $A(t)$ = function of age (t days), and $B(t)$ = constant.

Fig. 5 shows the relationship between the cement–water ratio and the 28-day compressive strength of concrete with and without fly ash. As fly ash contained in the concrete plays a role of a binder, Eq. (2) can be modified as Eq. (3).

$$f_c(t) = A(t)\left(\frac{\alpha FA + C}{W}\right) + B \quad (3)$$

Where α = fly ash's contribution to strength and FA = fly ash content (kg/m^3).

The α in the equation, which indicates fly ash's contribution to the strength, is a value expressing the effect of fly ash as a binder when added with cement into concrete. In prEN 206, a similar value referred to as the K value is used to indicate the degree of contribution of a mineral admixture to the ultimate strength, durability, etc., in comparison with cement. A constant $K=0.2$ or 0.4 is assigned depending on the cement type. However, α should be changed with age to express the changing strength development of concrete containing fly ash with age. In other words, α is also a

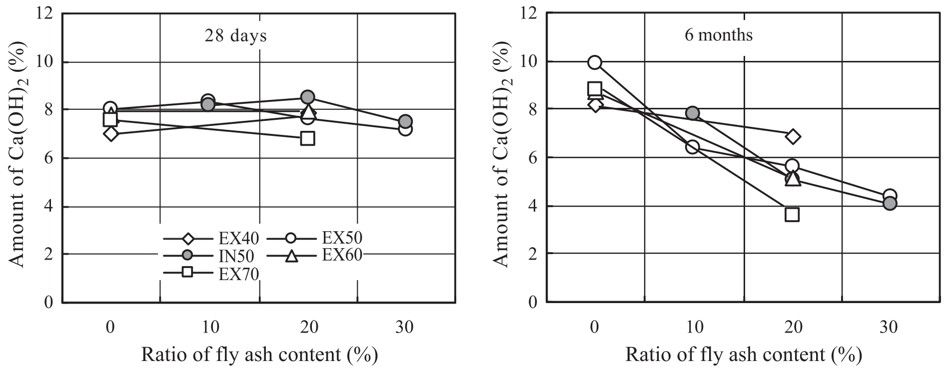

Fig. 3. $Ca(OH)_2$ content detected at 28 days and at 6 months.

coefficient that changes with the progress of pozzolanic reaction.

The case without fly ash (FA = 0) is considered in the beginning. Coefficient $A(t)$, which indicates the strength development of concrete over time, is expressed as Eq. (4), according to the ACI equation [14]. Their relationship is found to be expressed by a linear equation by determining $A(t)$ at each age from Fig. 6 and by plotting $1/A(t)$ over $1/t$, as shown in Fig. 7. Constants a and b are calculated as 0.049 and 0.0255, respectively. These are experiment constants that depend on the cement type, curing method, etc.

$$A(t) = \frac{t}{a + bt} \qquad (4)$$

where a and b = experiment constants.

The α is obtained by determining the values of coefficient $A(t)$ from Eq. (4), the constant B from Eq. (2), as well as C, W, and FA from the mixture proportions, and substituting them into Eq. (3) and calculating it. Fig. 8 shows the plots of the values of α against age. According to Uchikawa [15], the ratio of pozzolanic reaction of fly ash is between 1% and 2%, 5% and 10%, and 15% and 20% at 1, 28, and 180 days, respectively, with a fly-ash replacement ratio of 40%. Another report states that the strength gains continue for 18 years under standard curing [16]. When plotted against FA/C for each age, α exhibits a clear correlation with FA/C. In other words, α is a function of t (age) and FA/C. Accordingly, this was expressed as Eq. (5).

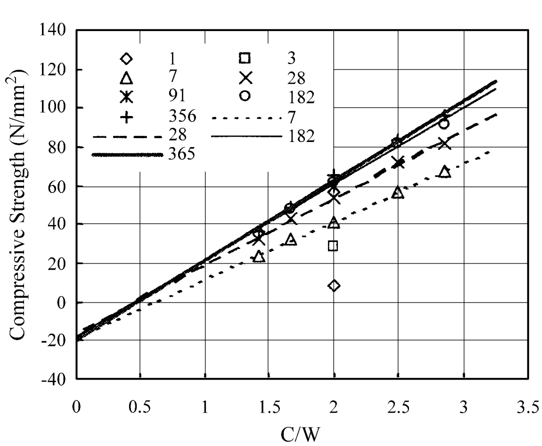

Fig. 4. Relationships between cement–water ratio and compressive strength.

Fly-ash hydrates with $Ca(OH)_2$, alkalis, etc., and hardens, forming such hydrates as C-S-H, $C_3A \cdot CaOH_3 \cdot 12H$ (C_4AH_{13}), and $C_3A \cdot SH_8$, as well as hydrogarnet, in the long range. The reaction of SiO_2 and Al_2O_3 in fly ash depends on the concentration and content of $Ca(OH)_2$ supply. The higher the $Ca(OH)_2$ concentration, the higher the rate of pozzolanic reaction. At late ages, the higher the $Ca(OH)_2$ content, the longer that the pozzolanic reaction of fly ash lasts [15].

Such pozzolanic reactivity of fly ash is expressed by Eq. (5).

$$\alpha = k_1(t)\exp\{k_2(t) \cdot (\mathrm{FA}/C)\} \qquad (5)$$

where $k_1(t)$ and $k_2(t)$ = functions of t (age).

According to Fig. 8, the value of α at an age of 1 day is distinguishable from the tendencies thereafter. This indicates that fly ash contributes to the strength by a different mechanism at 1 day. At 1 day, the addition of fly ash increases the locations for hydrate deposits, while the Ca^{2+} concentration in the liquid phase decreases, increasing the rate of C_3S deposition [17]. This accelerates the cement reaction and is apparently expressed as α in Eq. (3). On the other hand, the mechanism of fly ash's contribution to the strength at 2 days and thereafter is governed by its pozzolanic reaction (Fig. 9).

Table 5
Values of $A(t)$ and $B(t)$

Age	7 Days	28 Days	6 Months	1 Year
$A(t)$	30.1	35.0	39.2	41.2
$B(t)$	– 18.6	– 16.3	– 18.1	– 19.9

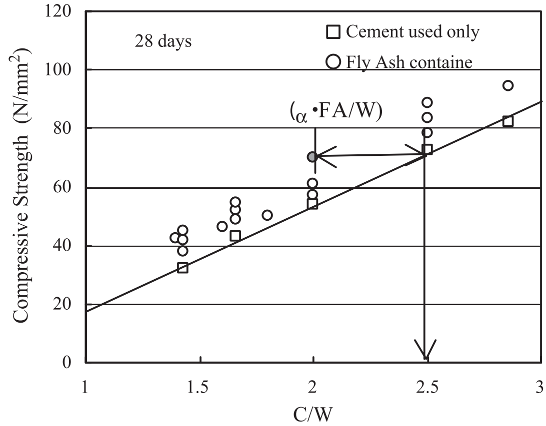

Fig. 5. Relationship between cement–water ratio and compressive strength.

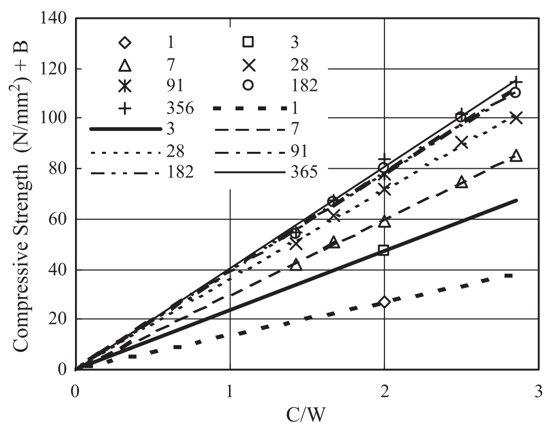

Fig. 6. Relationships between cement water–ratio and compressive strength + B.

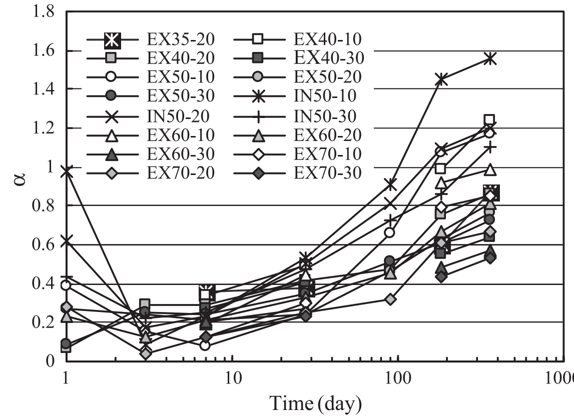

Fig. 8. Relationship between α and age.

It is therefore necessary that the values of α at 1 day should be treated separately from those at later ages to express both fly ash's early space filling and its later pozzolanic reaction effects. At 1 day, $k_1 = 0.73$ and $k_2 = -2.43$ (Table 6), whereas at later ages, k_1 and k_2 are considered to be functions of time t, as shown in Fig. 10. These are expressed by Eqs. (6) and (7), respectively.

$$k_1 = m_1\{1 - \exp(-m_2 t) + m_3 \tag{6}$$

$$k_2 = n_1\{1 - \exp(-n_2 t) + n_3 \tag{7}$$

where m_1, m_2, m_3, n_1, n_2, n_3 = experiment constants, $m_1 = 1.55$, $m_2 = 0.0075$, $m_3 = 0.156$, $n_1 = -0.750$, $n_2 = 0.01$, and $n_3 = -0.371$.

On one hand, k_1 is an increasing function of t, indicating that fly ash's contribution, α, increases as its pozollanic reaction proceeds. On the other hand, k_2 is a reducing function of t, indicating that as FA/C increases, $Ca(OH)_2$ relatively decreases, inhibiting fly ash to begin pozzolanic reaction.

Fly ash's contribution to strength, α, was calculated as a function of FA/C and time. However, the effect of fly-ash quality should be calculated, as α depends on fly-ash quality. According to our previous study [13], the compressive strength of concrete containing fly ash highly correlates with the specific surface area by Blaine but scarcely correlates with the ignition loss of fly ash. Accordingly, fly ash's contribution to the strength, α, can be expressed as Eq. (8) by replacing α, which takes account of

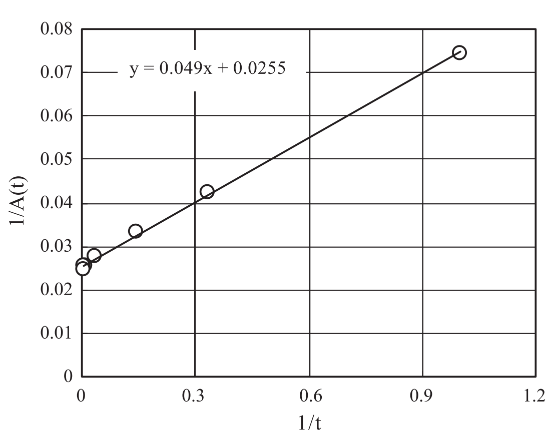

Fig. 7. Relationship between $1/A(t)$ and $1/t$.

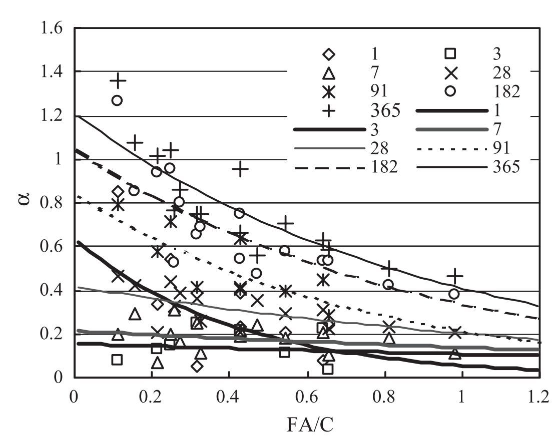

Fig. 9. Relationships between α and FA/C.

Table 6
Functions of α

Age	1 Day	3 Days	7 Days	28 Days	91 Days	6 Months	1 Year
$k_1(t)$	0.63	0.16	0.21	0.42	0.85	1.05	1.21
$k_2(t)$	− 2.43	− 0.37	− 0.43	− 0.72	− 1.36	− 1.13	− 1.09

the effect of FA/C, expressed as Eq. (5), with α_1 and incorporating α_2, which expresses the effect of the specific surface area by Blaine.

$$\alpha = \alpha_1 \alpha_2 \tag{8}$$

where $\alpha_1 = \alpha$ in Eq. (3), a function of FA/C, and α_2 = a function of specific surface area by Blaine.

Using Eq. (3), α was calculated from compression test results of fly ashes having different Blaine specific surface areas. To determine α_2 ($=\alpha/\alpha_1$), α_1 was then calculated from Eq. (5). Fig. 11 shows the plots of α_2 against the specific surface area by Blaine. As shown in Fig. 11, fly ash's contribution increases as the specific surface area by Blaine increases, and the relationship is expressed as Eq. (9).

$$\alpha_2 = k_3 \cdot \text{Blaine} + 0.71 \tag{9}$$

where Blaine = specific surface area by Blaine (cm^2/g), $k_3 = 1.14 \times 10^{-4}$.

To determine the effect of specific surface area by Blaine, α_2, on fly ash's contribution to the strength, α, Eq. (3) is rewritten based on 2500 cm^2/g, a value specified in JIS A 6201 (fly ash for use in concrete), as given in Eq. (10).

$$\alpha_2 = k_3(\text{Blaine} - 2500) + 1 \tag{10}$$

Accordingly, the estimation equation for the strength development of concrete containing fly ash is expressed as given in Eq. (11).

$$f_c(t) = \left(\frac{t}{a + bt}\right)\left(\frac{\alpha_1 \alpha_2 \text{FA} + C}{W}\right) + B \tag{11}$$

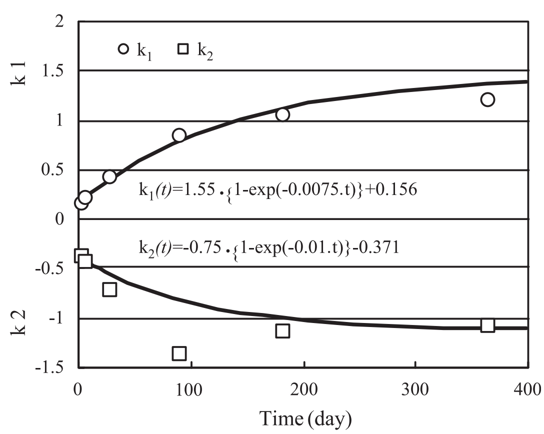

Fig. 10. Relationships between k_1, k_2, and age.

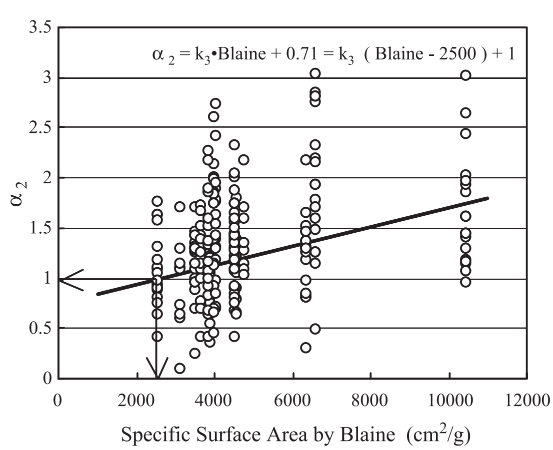

Fig. 11. Relationship between Blaine specific surface area and α_2.

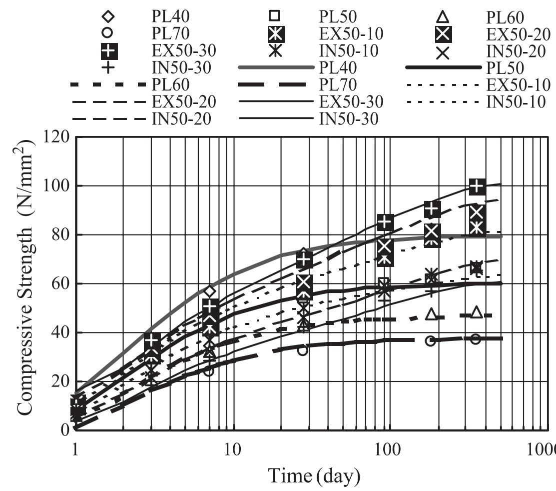

Fig. 12. Relationships between calculation value and experimental value.

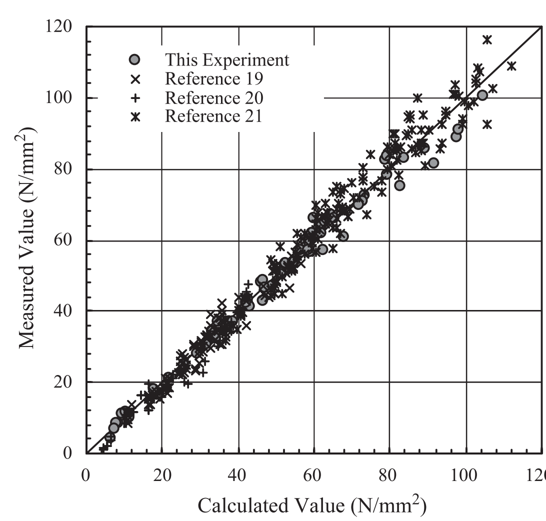

Fig. 13. Relationship between calculation value and experimental value.

Figs. 12 and 13 show the relationships between the measurements and the values calculated using Eq. (11). The measurements of Fig. 13 are values given in Refs. [18–21]. Coefficients a, b, and B of this equation are inherent values that depend on such factors as cement types and are independent of the fly-ash properties. These were therefore recalculated using the data given in Refs. [19–21].

As shown in Figs. 12 and 13, Eq. (11) accurately expresses the strength development of concrete containing fly ash. It is considered useful as an estimation equation for strength development incorporating the effects of long-range pozzolanic reactivity and specific surface area by Blaine.

5. Conclusions

Based on test results concerning the compressive strength development of concrete containing fly ash, the authors derived an estimation equation for compressive strength development. The equation can express coefficient α, which indicates the activity of fly ash as a binder, in the form of a function of age, fly ash content, and Blaine specific surface area of fly ash as follows: where $f_c(t)$ = compressive strength at t days (N/mm^2), t = age (days), a and b = experiment constants, α_1 = function of FA/C, α_2 = function of specific surface area by Blaine, FA = fly-ash content (kg/m^3), C = cement content (kg/m^3), W = unit water content (kg/m^3), and B = constant.

This equation is capable of explaining the increases in the early strength due to fly ash in place of part of fine aggregate, the decreases in the early strength due to fly ash in place of part of cement, the increases in the long-term strength due to pozzolanic reaction, the relationship between the fly-ash replacement ratio and the ratio of strength increase/decrease, and the effect of fly ash's Blaine specific surface area on the strength.

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