-Technical Paper-

RELATIONSHIP BETWEEN SPLITTING TENSILE STRENGTH AND COMPRESSIVE STRENGTH OF CONCRETE AT EARLY AGE WITH DIFFERENT TYPES OF CEMENTS AND CURING TEMPERATUREHISTORIES

Soty ROS*1and Hiroshi SHIMA*2

ABSTRACT

This study investigates the interrelations among splitting tensile strength f_{spt}, compressive strength f_c', and Young's modulus E_c of early age concrete cured under different temperature histories. The concrete of cylindrical specimens were mixed with the same water to cement ratio and with different types of cements, OPC, BB, and LH cements. It was found that f_{spt}-f_c' relationship and E_c-f_{spt} relationship of early age concrete were unique regardless of types of cements and curing temperature histories. Accordingly, new equations of the two relationships were developed and proposed.

Key words: Early age concrete, splitting tensile strength, compressive strength, Young's modulus, curing temperature history

1. INTRODUCTION

Predictions of splitting tensile strength f_{spt} and Young's modulus E_c of concrete at early age are significant among other parameters for thermal stress analysis of massive concrete. The analysis is known to be complicated because the mechanical properties and the thermal properties of the concrete are developing during hydrations [1]. In terms of concrete compressive strength f_c' at early age, it could be predicted by means of a strength model based on hydration of cement constituent mineral proposed by Kato and Kishi [2]. Therefore, the developments f_{spt} and E_c of early age concrete could be indirectly predicted from the heat of hydration if the interrelations among f_{spt}, E_c, and f_c' were established. Meanwhile, based on the Guidelines for Control of Cracking of Mass Concrete 2008 [3], the equation to predict f_c' which can take into account the age, the temperature history dependence, type of cement and so on was also given. Then, the corresponding f_{spt}-f_c' and E_c-f_c' relationships were also provided [3].

Moreover, many equations have been proposed for f_{spt}-f_c' relationships [3-13] and E_c-f_c' relationships [3-8] whose equations are generally accepted in a form of Eqs.1 and 2, respectively.

$$f_{spt} = k\times(f_c')^n \quad (1)$$
$$E_c = \alpha\times(f_c')^\beta \quad (2)$$

where,

f_{spt} : split tensile strength (N/mm^2);
E_c : Young's modulus (kN/mm^2);
f_c' : compressive strength (N/mm^2); and
k, n, α, and β: are non-dimensional coefficients.

Different values of k, n, α, and β were previously given by different researchers and institutions as summarized in Table 1.

The value of n of 0.5 and 2/3 given by [4] and [8], and by [5], [7], and [9-10], respectively have been proposed for f_{stp}-f_c' relationships of concrete at all ages. However, it has been reported that 0.5 and 2/3 of n gave less accuracy in the prediction of f_{sct} at early age, and Oluokun et al. [11] subsequentially proposed the value of n of 0.79 for the early age concrete. On the other hand, it has been observed that the proposed equation of [11] was developed based on only the test results of 150×300 mm cylindrical concrete specimens with Type I cement cured in a moist room of constant temperature of 22^{o}C. Based on the research results of Gardner [10], type of cement and curing temperature effect on the developments of both strengths and E_c, but not f_{spt}-f_c' relationships. Still, only a method of constant curing temperatures of 0, 10, 20, and 30^{o}C until the testing age were examined by Gardner [10].

In the real concrete structures, the temperature in concrete after casting increase and decrease with time respectively before and after removing the form works. It means that the equations to predict f_{spt} and E_c of early

Table 1 Values of k, n, α, and β given by [3-12]

Source	k	n	α	β
JCI [3]	0.13	0.85	6.3	0.45
JSCE [4]	0.44	0.5	4.7	1/2
JSCE [5]	0.23	2/3	9	1/3
AIJ [6]	0.18	0.75	8.56	1/3
CEB-FIB [7]	0.3	2/3	9.5	1/3
ACI318-11 [8]	0.56	0.5	4.73	1/2
Raphael [9]	0.313	2/3	-	-
Gardner [10]	0.33	2/3	3.24	0.63
Oluokun et al. [11]	0.216	0.79	-	-
Oluokun [12]	0.2	0.7	-	-
Arioglu et al. [13]	0.387	0.63	-	-

*1 Phd, Dept. of Infrastructure System Engineering, Kochi University of Technology, JCI Member
*2 Professor, Dept. of Infrastructure System Engineering, Kochi University of Technology, JCI Member

Table 2 Concrete mixes proportions

Mixes	f_{c28}' (N/mm^2)	Slump (cm)	w/c (%)	s/a (%)	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Gravel(kg/m^3) 05-15mm	15-20mm	WA (kg/m^3)	AE (kg/m^3)
OPC1, 2,3	30	12	67	43.5	244	163	824	536	536	2.44	1.72
BB2,3,4	28.9	12	67	43.5	244	163	821	539	539	2.44	1.72
LH4	27.5	12	67	43.5	244	163	820	532	532	2.44	1.72

Note: OPC: Ordinary Portland Cement (3.15g/cm^3); BB: Blast Furnace Cement type B (3.04g/cm^3); LH: Low Heat Cement (3.24g/cm^3). The difference among the mixes 1, 2, 3 and 4 is the curing temperature histories given in Fig.1.

age concrete which could adapt to the wide ranges of temperature histories and curing conditions, and to different types of cements are required for rational thermal stress analysis of massive concrete at early age.

Fortunately, the values of k, n, α, and β given by JCI codes 2008 [3] were confirmed to be suitable for this purpose. This is because the equation of f_c' given by JCI [3] in Eqs. 1 and 2 could take into account the aforementioned conditions. However, some parameters required to calculated f_c' were available only in case of specimens curing under water [3]. This may lead to a limitation of f_{spt}-f_c' and E_c-f_c' relationships predictions in case of other curing conditions. Meanwhile, effects of size of cylindrical specimens on these relationships were not discussed.

Accordingly, this paper presents and proposes the interrelations among f_{spt}, E_c, and f_c' of early age concrete not only with different types of cements and with wide ranges of curing temperature histories, but also with different curing conditions and size of cylindrical specimens. The proposed equations were found to fit well with other researchers' test results of early age concrete regardless of type of cement, temperature history, curing condition and cylinder size.

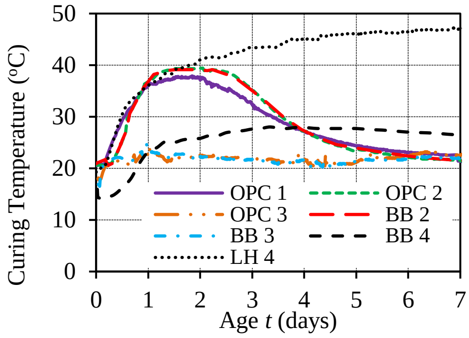


Fig.1 Curing Temperatures


(a) Splitting test (b) Compressive strength test

Photo.1 Details of test set up

2. EXPERIMENT

2.1 Specimens

A total of 180 of 100x200 mm cylindrical specimens were constructed. Three different types of cements namely OPC (Ordinary Portland Cement), BB (Blast Furnace Slag Cement type B), and LH (Low Heat Cement) were used in this study. The details of concrete mix proportions of each type of cement are given in Table 2. All mixes were designed to have the same w/c, the same s/a, and the same maximum size of 20mm of coarse aggregate. Crushed-limestone aggregate with 2.70g/cm^3 of specific gravity was used as coarse aggregate while crushed-limestone sand with 2.57g/cm^3 of specific gravity and 2.75cm^2/g of fineness was used as fine aggregate. Meanwhile, 1% and 0.5% of cement content was respectively used for water reducing agent (WA) and Air Entraining Agent (EA) in all mixes.

2.2 Casting and Curing

Fresh mixed concrete was casted into the cylindrical molds of 100×200 mm following the method of JIS A 1132. Moreover, three specimens were sampled per age of strength. In terms of curing method, the specimens OPC1, OPC2, and BB2 were cured by storing in a temperature-controlled room with a relative humidity of 67%. The temperature history in the room was controlled to be the same as that developed in a 600mm thick wall. Meanwhile, an air-cured condition was applied on the specimens OPC3 and BB3 by storing the specimens in a common room with an air temperature from 20^{o}C to 25^{o}C. Differently, an isolate-cured condition was made on the specimens BB4 and LH4. These specimens were kept in a semi-adiabatic temperature controlled chamber in which the temperature was controlled to be the same as the temperature in the concrete. Unfortunately, an isolate-cured was successfully done only for LH4 specimens. It was due to the failure of manual temperature controlling for BB4 specimens. The histories of curing temperatures of all specimens are illustrated in Fig.1. The surfaces of all specimens were completely sealt and all specimens were cured until the age of testing.

2.3 Testing of Hardened Concrete

Compressive strength and splitting tensile strength tests were performed on three cylindrical specimens of 100×200 mm according to a method of test for compressive strength of concrete of JIS A 1108 and for splitting tensile strength of concrete of JIS A 1113, respectively. Meanwhile, the Young's modulus of concrete was measured by means of a test method for static modulus of elasticity of concrete of JIS A 1149. The illustrations of the test setup are given in Photo.1.

3. RESULTS AND DISCUSSIONS

3.1 Effect of Temperature and Type of Cement

Figs.2, 3, and 4 gives the development of f_c', f_{spt},

Table 3 Test results of f_{spt} (N/mm^2), f_c' (N/mm^2), and E_c (kN/mm^2)

Age	OPC1			OPC2			BB2			BB3			OPC3			BB4			LH4		
(days)	f_{spt}	f_c'	E_c	f_{spt}	f_c'	E_c	f_{spt}	f_c'	E_c	f_{spt}	f_c'	E_c	f_{spt}	f_c'	E_c	f_{spt}	f_c'	E_c	f_{spt}	f_c'	E_c
0.3	0.20	0.64	3	0.19	0.81	-	0.08	0.30	-	0.02	0.19	-	0.12	0.82	0.9	0.02	0.09	-	-	-	-
0.5	0.59	3.08	8	0.46	2.25	-	0.32	1.31	-	0.18	0.72	4	0.31	2.34	6.1	0.06	0.55	-	0.21	0.83	-
0.8	0.85	5.61	14	0.74	5.00	10	0.55	3.50	6	0.45	4.0	8	0.66	5.07	10.5	0.17	1.14	-	0.57	3.92	10.43
1.0	1.13	8.11	16	1.15	7.92	14	0.95	6.16	14	0.57	5.12	-	0.71	6.41	-	0.38	3.26	7.55	0.61	4.66	11.62
1.2	-	-	-	-	-	-	-	-	-	-	-	-	1.20	9.72	23.9	-	-	-	0.64	5.5	13.06
1.5	1.46	11.73	23	-	-	-	-	-	-	0.86	7.82	-	1.17	10.4	16.1	0.78	6.77	14.1	0.75	6.62	13.79
2.0	1.85	15.28	27	1.74	14.18	25	1.44	11.52	18	1.21	10.1	18	1.54	13.5	25.5	1.15	9.50	20.7	1.12	10.71	-
2.5	2.10	18.82	29	-	-	-	-	-	-	-	-	-	1.69	15.6	21.7	1.6	12.8	25.7	1.46	15.06	-
3.0	2.16	19.55	31	2.15	19.25	28	1.77	14.92	25	1.49	14.0	25	1.89	17.7	29.3	1.81	14.1	28.4	1.72	-	-
4.0	2.36	21.41	32	2.20	19.55	32	1.96	17.35	28	1.71	15.1	29	2.14	19.9	29.4	2.08	17.4	-	1.68	-	-
5.0	2.40	22.92	34	2.48	22.08	33	2.09	20.08	29	1.73	18.2	-	-	-	-	2.4	23.0	-	-	-	-
6.0	2.46	23.83	36	2.49	23.46	32	2.16	20.46	30	1.74	21.3	31	-	-	-	-	-	-	-	-	-
7.0	2.57	23.46	34	2.47	23.60	35	2.29	21.10	31	1.81	23.4	-	1.98	22.0	35.9	2.62	25.9	-	-	-	-

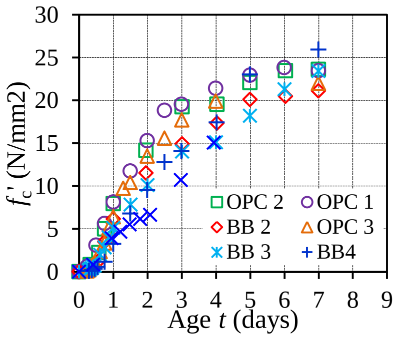


Fig.2 Compressive strength f_c'

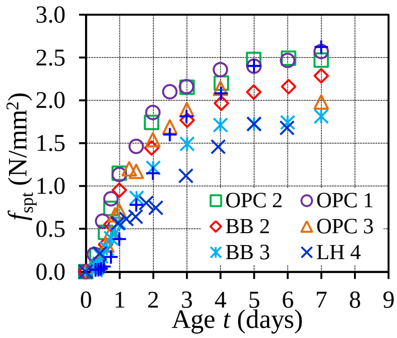


Fig.3 Splitting tensile strength f_{spt}

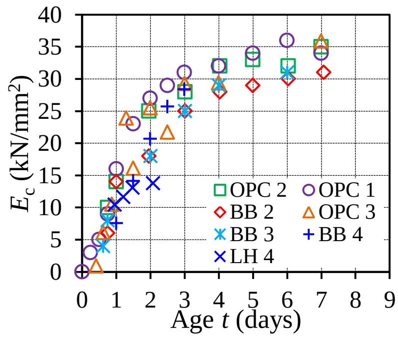


Fig.4 Young's modulus E_c

and E_c of all specimens within 7 days age, respectively. The test results suggested that the developments of f_c', f_{spt}, and E_c of early age concrete are dependence of curing temperature and type of cement. Similar results were also found by Gardner [10]. With the same type of cement, the higher curing temperature was found to result in a higher strength and Young's modulus at early age. It was because the chemical reactions of hydration were speeded up by a rise of curing temperature [14].

As given in Table 3 and Figs. 2 and 3, it can be observed in specimens OPC2, BB2, and LH4 whose temperature histories during the first 2 days were almost identical that the developments of strengths with ages were different. It is generally accepted that with the same mix proportions, strength developed in BB concrete is respectively slower and faster than in OPC concrete and LH concrete; and it appeared in the authors' test results. It is due to the differences of heats of hydrations given by the chemical compounds in the cements [14]. Similar tendency was also observed for E_c regardless of the temperature history.

3.2 Relationship between f_{spt} and f_c'

The experimental results of f_{spt} and f_c' were plotted against the calculation results by means of the existing equations listed in Table 1 as shown in Figs.5a and 5b. It can be seen in Fig.5a that f_{spt} of early age concrete were not proportional to 0.5 power of f_c'. Similar commentaries were also given by [10], [11], and [14]. Meanwhile, 2/3 power of f_c' seems to fit more with the test results. However, it was found that the existing equations did not give a high accuracy in the prediction of f_{spt} of early age concrete with different types of cements and curing temperatures.

Additionally, as shown in Fig.5a, the predicted results of f_{spt} from f_c' based on the equations given by JCI 2008 [3] were found to be lower than the authors' test results whose specimens were cured under sealt cured and air-cured conditions. Similar conditions were also observed in case of the test results of [10-11] and [15-21] as shown in Fig.6a and 6b.

Moreover, f_{spt}-f_c' relationship of early age concrete was found to remain unique and independent of type of cement and curing temperature history. Meanwhile, the relationships fitted best with the following equation:

$$f_{spt} = 0.2\times(f_c')^{0.8} \qquad (3)$$

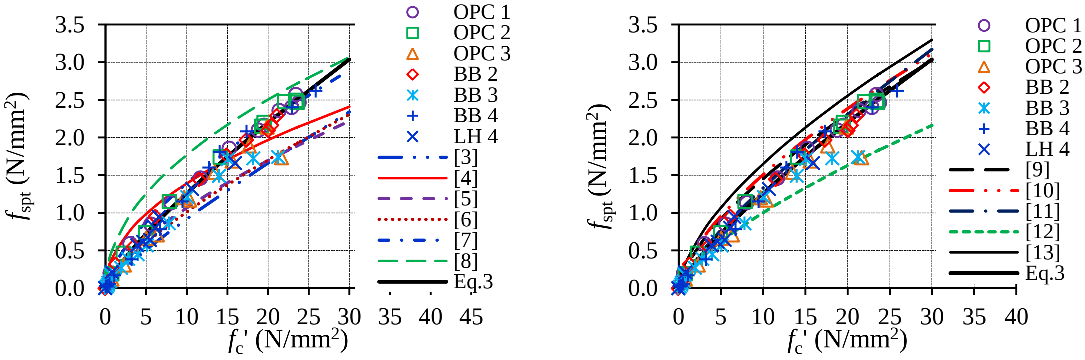
where,

f_{spt} : splitting tensile strength of concrete at early age ($t \leq$ 7days) (N/mm^2); and

f_c' : compressive strength of concrete at early age ($t \leq$ 7days) (N/mm^2).

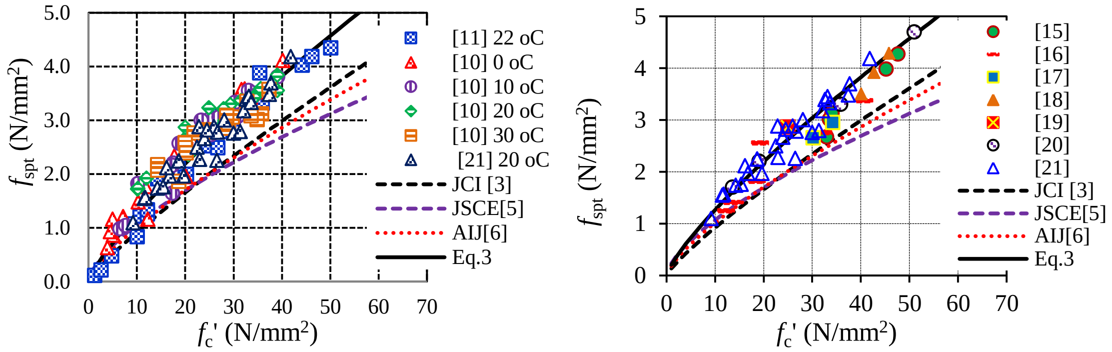
As shown in Figs.5a and 5b, f_{spt} of early age concrete calculated by means of Eq.3 agreed well with the test results regardless of type of cement (OPC, BB, and LH) and temperature history of the concrete.

The accuracy and the applicable ranges of Eq.3 were also examined by comparing the calculations results with the test results of f_{spt} of early age concrete of the literatures [10-11] and [15-21] whose data were listed in Tables 4, 5, and 6. The tested values of f_c' in Tables 4, 5, and 6 were used to calculate f_{spt} by means of Eq.3 and compare with the tested f_{spt} as plotted in Figs.6a and 6b. Consequently, it was confirmed that Eq.3 could precisely predict f_{spt} of early age concrete



(a) (b)

Fig.5 f_{spt}-f_c' relationships



(a) (b)

Fig.6 Verifications of Eq.3 with previous test results

Table 4 Test results of f_{spt} (N/mm^2) and f_c' (N/mm^2) from [9] (cylinder size 150×300mm)

Source	Curing Temp.	Age (days)	Mix1 (w/c = 0.55) Cement type I/fly ash		Mix 2 (w/c = 0.35) Cement type I/fly ash		Mix 3 (w/c = 0.55) Cement type I		Mix 4 (w/c = 0.35) Cement type I		Mix 5 (w/c = 0.55) Cement type III		Mix 6 (w/c = 0.35) Cement type III	
			f_c'	f_{spt}	f_c'	f_{spt}	f_c'	f_{spt}	f_c'	f_{spt}	f_c'	f_{spt}	f_c'	f_{spt}
[10]	0 °C	1	5.12	0.86	4.51	0.93	3.95	0.63	11.83	1.77	7.17	1.21	5.02	1.16
		3	10.27	1.48	17.73	2.33	12.24	1.16	26.38	2.95	32.24	3.57	31.65	3.57
		7	21.65	2.58	33.5	3.43	20.14	1.95	32.33	3.58	40.16	4.11	36.33	3.53
	10 °C	1	6.53	0.98	10.19	1.82	7.71	1.04	17.39	2.16	23.34	3.00	18.78	2.57
		3	17.58	2.20	25.07	3.01	17.36	1.64	27.04	3.06	33.11	3.55	30.34	3.33
		7	25.33	2.73	30.87	3.07	24.92	3.01	34.04	3.5	39.11	3.81	34.14	3.45
	20 °C	1	10.12	1.72	11.97	1.92	10.22	1.73	20.65	2.36	27.94	3.21	22.14	2.77
		3	20.17	2.67	28.19	2.99	19.99	2.87	29.31	3.29	35.65	3.59	31.6	3.37
		7	24.9	3.23	34.6	3.47	27.72	2.91	39.06	3.55	39.09	3.84	34.33	3.43
	30 °C	1	14.29	2.17	18.68	1.86	14.31	2.07	20.21	2.39	29.7	3.06	24.63	2.78
		3	21.87	2.76	28.59	2.85	20.02	2.58	28.92	2.95	33.65	3.08	28.58	3.09
		7	28.8	3.04	35.8	3.12	24.21	2.82	34.87	3.01	37.36	3.57	32.75	3.35

Table 5 Test results of f_{spt} (N/mm^2), and f_c'(N/mm^2) from [14-20] (cylinder size 100×200mm)

Source	Age (days)	f_{spt}	f_c'	f_{spt}	f_c'	f_{spt}	f_c'	f_{spt}	f_c'	Remarks
[15]	7	2.67	32.95	3.13	38.12	2.67	32.95	3.37	40.75	Concrete containing silica fume
		3.01	37.56	3.98	45.19	4.27	47.68	-	-	
[16]	7	2.55	19.27	2.75	34.3	3.26	56.27	1.4	13.5	Concrete containing high-volume fly ash roller
		1.81	18.6	1.24	12.29	-	-	-	-	
[17]	7	30.2	2.65	34.2	2.95	-	-	-	-	Concrete containing rice husk ash
[18]	7	48.7	3.91	45.1	3.5	-	-	45.8	4.28	-
[19]	3	2.86	25.01	-	-	-	-	-	-	Concrete with oil palm shell as coarse aggregate
[20]	3	1.7	13.6	-	-	-	-	-	-	Concrete without silica fume
	7	2.2	19.1	3.3	40.9	4.7	51	-	-	Concrete with 5 to 10% of silica fume
[21]	3	1.54	11.53	2.88	25.96	2.50	22.49	3.45	33.15	Concrete with natural sand
	7	2.24	18.67	3.18	32.11	2.76	29.98	3.48	37.44	
	3	1.10	9.21	2.88	22.87	1.74	14.24	2.78	26.72	Concrete with bottom ash
	7	1.76	15.42	3.01	28.09	1.97	19.65	3.33	33.64	
	3	1.57	11.77	2.24	18.67	-	-	2.66	23.98	Concrete with bottom ash and natural sand
	7	2.12	16.16	2.82	24.52	-	-	-	-	
	3	1.97	16.79	3.39	32.62	2.25	26.52	3.70	37.71	-
	7	2.28	22.98	2.79	31.38	4.19	41.85	-	-	

Table 6 Test results of f_{spt} (N/mm^2) and f_c' (N/mm^2) from [10] (cylinder size 150×300mm)

Source	Curing Temp.	Age (days)	Mix A (w/c=0.388) Cement type I		Eq.3	Mix B (w/c=0.763) Cement type I		Eq.3	Mix C (w/c=0.534) Cement type I		Eq.3	Mix D (w/c=0.329) Cement type I		Eq.3
			f_c'	f_{spt}	$f_{spt.cal}$	f_c'	f_{spt}	$f_{spt.cal}$	f_c'	f_{spt}	$f_{spt.cal}$	f_c'	f_{spt}	$f_{spt.cal}$
[11]	22 °C	0.3	10.67	1.22	1.33	1.30	0.11	0.25	2.63	0.21	0.43	10.07	0.83	1.27
		0.6	20.28	1.99	2.22	4.82	0.48	0.70	12.22	1.33	1.48	26.77	2.49	2.77
		1	24.79	2.52	2.61	7.82	1.07	1.04	18.68	1.94	2.08	35.93	3.32	3.51
		2	27.43	2.79	2.83	12.19	1.25	1.48	23.90	2.86	2.53	44.22	4.02	4.14
		3	29.92	2.90	3.03	14.31	1.91	1.68	26.48	3.08	2.75	46.21	4.19	4.29
		7	35.69	3.50	3.49	18.57	2.10	2.07	35.44	3.88	3.47	50.11	4.34	4.58

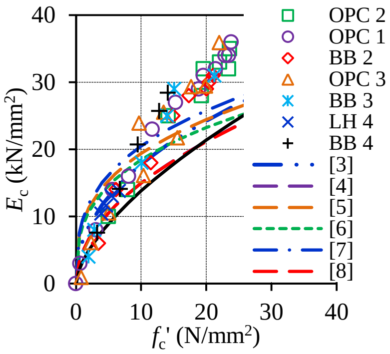


Fig.7 E_c-f_c' relationship

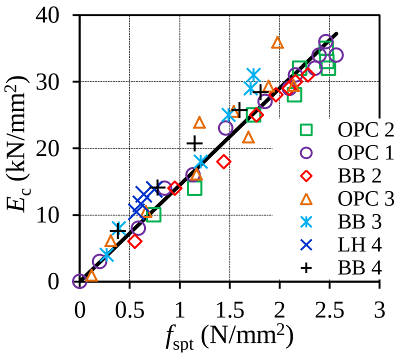


Fig.8 E_c-f_{spt} relationship

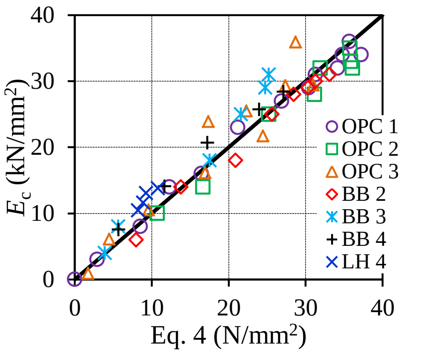


Fig.9 Verification of Eq.4

regardless of size of cylinder, type of cement, mix proportions, curing temperature, and curing conditions.

Based on [22], f_{spt} of concrete decreases when the size of cylinder increases within a range of cylinder diameter of 50, 80, 100, 125 and 150mm. However, this study confirmed that f_{spt}-f_c' relationship is independent of size of cylinder.

3.3 Young's Modulus of Early Age Concrete

The relationships between E_c and f_c' of all specimens were plotted in Fig.7. It can be observed that E_c-f_c' remained unique and independent of type of cement and curing temperature history. Similar findings were also presented by Gardner [10] in the ranges of constant curing temperatures of 0, 10, 20, and 30 °C.

It has been reported that the development of concrete E_c is proportional to $(f_c')^{0.5}$ and $(f_c')^{1/3}$ which was given by [4] and [8], and by [5-7], respectively. As illustrated in Fig.7, the test results of E_c of concrete at early age were found to be higher than the calculation results by means of the existing equations given by [3-8] and [10] especially within the ranges of f_c' between 10 N/mm^2 to 26 N/mm^2 (1day $\leq t \leq$ 7days).

In a view point of thermal cracking analyses of early age concrete under external restraint, it was reported that E_c, f_{spt} and tensile Young's modulus E_{ct} of concrete are the main parameters which directly control the cracking phenomena; and the interrelations among them are significance to be discussed [23-24].

According to the experimental results of [24-25], E_c and E_{ct} of concrete were found to be identical when $f_c' \geq 15$N/mm^2, corresponding to $3 \leq t \leq$ 7days. Meanwhile, E_{ct} was found to be greater than E_c at very early age ($t <$ 3days). On the contrary, based on the test results of [26], E_c was found to be greater than E_{ct} when $t \leq$ 3days. However, the values of E_c and E_{ct} were also found to be identical by [26] when t>3days. Nevertheless, Kanstad et al. [27] and Pane and Hansen [28] found that E_c and E_{ct} of early age concrete $t \geq 18$ hours (0.75day) are almost the same. Therefore, the research results of [24-28] are the supportive proofs showing that E_c is equivalent to E_{ct}.

Accordingly, the relationship between E_c and f_{spt} of early age concrete were examined as illustrated in Fig.8. The test results suggested that E_c-f_{spt} relationship of early age concrete is linear and unique regardless of type of cement and curing temperature. Meanwhile, the relationships fitted best with the following equation:

$$E_c = 14.5 \times f_{spt} \tag{4}$$

where,

E_c : Young's modulus (kN/mm^2), which is equivalent to E_{ct}; and

f_{spt} : Splitting tensile strength of concrete (N/mm^2) with ($t \leq$ 7days).

As shown in Fig.9, good agreement between test results of E_c and the calculation results by means of Eq.4 was observed. These agreements implied that prediction of E_c of early age concrete ($t \leq$ 7days) from f_{spt} gives more accuracy than from f_c' using the existing equations given by [3-10]. Meanwhile, since E_{ct} is equivalent to E_c, it also implied that E_{ct} could be also predicted from f_{spt} by means of Eq. 4.

Moreover, the unique equation of E_c-f_{spt} relationships (Eq.4) and f_{spt}-f_c' relationships (Eq.3) regardless of type of cement, temperature history, and curing conditions of the concrete found in this study could allow E_c, f_{spt} and E_{ct} to be indirectly and precisely calculated from the total heat of cement hydration of early age concrete through f_c'. It was because f_c' at early age could be predicted by means of a strength model based on hydration of constituent mineral proposed by Kato and Kishi [2].

5. CONCLUSIONS

The following conclusions can be derived from this study.

(1) Splitting tensile strength and compressive strength relationship of concrete at early age ($t \leq 7$ days) was found to be unique regardless of type of cement and temperature history of the concrete.

(2) The relationship between splitting tensile strength and compressive strength of concrete at early age ($t \leq 7$ days) is proposed as follows:

$$f_{spt} = 0.2\times(f_c')^{0.8}$$

(3) Young's modulus of concrete at early age ($t \leq 7$ days) was found to have a linear relationship with the splitting tensile strength regardless of the type of cement and temperature history of the concrete. The equation was established and proposed as followings:

$$E_c = 14.5\times f_{spt}$$

Meanwhile, E_{ct} could be also predicted by means of this equation since E_{ct} and E_c are equivalent.

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