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Mechanical Properties of Hwangtoh-Based Alkali-Activated Concrete

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Abstract

This study presents the testing of 15 hwangtoh-based cementless concrete mixes to explore the significance and limitations of the development of eco-friendly concrete without carbon dioxide emissions while maintaining various beneficial effects. Hwangtoh, which is a kind of kaolin, was incorporated with inorganic materials, such as calcium hydroxide, to produce a cement-less binder. The main variables investigated were the water-to-binder ratio and fine aggregate-to-total aggregate ratio to ascertain the reliable mixing design of hwangtoh-based cement-less concrete. The variation of slump with elapsed time was recorded in fresh concrete specimens. Mechanical properties of hardened concrete were also measured: including compressive strength gain, splitting tensile strength, moduli of rupture and elasticity, stress-strain relationship, and bond resistance. In addition, mechanical properties of hwangtoh-based cement-less concrete were compared with those of ordinary portland cement (OPC) concrete and predictions obtained from the design equations specified in ACI 318-05 and CEB-FIP for OPC concrete, wherever possible. Test results show that the mechanical properties of hwangtoh-based concrete were significantly influenced by the water-to-binder ratio and to less extend by fine aggregate-to-total aggregate ratio. The moduli of rupture and elasticity of hwangtoh-based concrete were generally lower than those of OPC concrete. In addition, the stress-strain and bond stress-slip relationships measured from hwangtoh-based concrete showed little agreement with the design model specified in CEB-FIP. However, the measured moduli of rupture and elasticity, and bond strength were higher than those given in ACI 318-05 and CEB-FIP. Overall, the test results suggest that the hwangtoh-based concrete shows highly effective performance and great potential as an environmental-friendly building material.

Keywords : Hwangto, Cement-less Concrete, Slump, Mechanical Properties, Eco-friendly Material

1. INTRODUCTION

Ordinary portland cement (OPC) is generally known as an essential component of concrete. However, the production of OPC generates excessive carbon dioxide and cause massive environmental pollution. Recent survey(Malhotra, 2002) shows that approximately 7% of total emission of greenhouse gases (GHS) in the earth's atmosphere is produced because of the production of OPC. Thus, production of cement-less binder using pozzolan materials, such as fly-ash, ground granulated blast-furnace slag, and condensed silica fumes has attracted the concrete industry to minimize carbon dioxide emissions. Alkali-activated or geopolymer binder has been commonly regarded as a new class of engineering materials for use in the production of environmental friendly mortar and concrete((Wang, 1995; Xu, 2000). Extensive studies(Wang, 1995; Xu, 2000; Pacheco-Torgal, 2007; De Silva, 2007; Xu, 2002) on geopolymers or alkaline activations of pozzolans clearly showed that calcined materials with abundant silicon oxide (SiO_2) and aluminum oxide (Al_2O_3) are suitable source materials of a cement-less binder as the mechanism of the hydration process commonly involves chemical dissolution of silicon and aluminum atoms in the source material by a high-alkaline activator with soluble alkali metal silicates. In particular, Shi and Day(2001) showed that chemical activators such as Na_2SO_4 and $CaCl_2$ are more effective on the compressive strength development of fly ash pastes with 20% lime than thermal activation techniques. Xu and van Deventer(2000) also proved out that single use or various combinations of fly ash, kaolinite and albite can produce cement-less pastes having compressive strength more than 20 MPa through the geopolymerisaton process by adding an alkaline activator.

Hwangtoh, whose physical characteristics and activation process are fully covered in a companion paper(Yang, 2007), is the primary clay created by the weathering of rocks and is mainly available in South Korea. Hwangtoh is commonly known as an eco-friendly material with various beneficial properties, including high absorbency, self-purification, and radiation of far infrared rays. As proved by Yang et al.(2007), the main ingredients in hwangtoh are kaolinite and halloysite, which have a few layers containing linked Si-tetrahedral sheets and Al-octahedral sheets, indicating that hwangtoh is a kind of kaolin having a 1:1 layer structure with an amorphous microstructure. Therefore, hwangtoh has been considered for production of inorganic cement-less pastes. Since 1997, it has been suggested(Hwang, 1997; Choi, 2006) that hwangtoh could possibly be used as an admixture for enhancement of mechanical properties of OPC concrete. In addition, Yang et al.(2007) showed that hwangtoh-based cement-less mortars have various applications as an environmental friendly building material, and proposed empirical formulas to evaluate the initial flow and 28-day compressive strength of hwangtoh-based mortars.

In the present study, 15 concrete mixes were produced and tested to explore the significance and limitations of the development of hwangtoh-based cement-less concrete. The main variables investigated were the water-binder ratio by weight and fine aggregate-to-total aggregate ratio by volume. The amount of high-range water-reducing admixture added to meet the designed initial slump and slump loss with time were recorded for fresh concrete. Different properties of hardened concrete, such as compressive strength gain with age, splitting tensile strength, moduli of elasticity and rupture, stress-strain relation, and bond resistance, were also measured. Mechanical properties of hwangtoh-based cement-less concrete were compared with those of OPC concrete examined from the database established by Yang et al.(2007). In addition, mechanical properties of concrete tested were compared, whenever possible, with the predictions obtained from the design equations specified in ACI 318-05(2005) or CEB-FIP(1999) for OPC concrete.

2. EXPERIMENTAL DETAILS

2.1 Materials

The chemical compositions of hwangtoh evaluated by x-ray fluorescence (XRF) analysis are given in Table 1. Hwangtoh has very low calcium oxide (CaO) content, but is rich in silicon oxide (SiO_2) and aluminum oxide (Al_2O_3), so the SiO_2-to-Al_2O_3 ratio by mass is 1.6. The hwangtoh used as source material belong to zeolite but reveal an amorphous microstructure(Yang 2007). Hwangtoh was incorporated with inorganic materials, such as calcium hydroxide, to produce a cement-less binder.

The physical properties of hwangtoh and aggregates used were also measured. The specific gravity and specific surface area of the hwangtoh were 2.48 and 5800 cm^2/g, respectively. The specific gravity and fineness modulus for sand used as a fine aggregate were 2.54 and 2.82, respectively, and those for crushed granite used as coarse aggregate having maximum size of 25 mm were 2.61 and 7.06, respectively.

2.2 Mixture Proportions

Fifteen cement-less concrete mixtures using the hwangtoh-based binder were prepared. Table 2 provides the details of the mixture proportions of designed concrete mixtures. Workability and compressive strength of OPC concrete are significantly influenced by various mixing properties such as the water-cement ratio, fine aggregate-to-total aggregate ratio, and total volume of aggregate(Neville, 1995). In the present investigation, the water-binder (W/B) ratio by weight varied between 20 and 70% when the volumetric fine aggregate-to-total aggregate (S/A) ratio was fixed at 40%, whereas for different W/B ratios of 30% and 50%, the S/A ratio varied from 30 to 50% with 5% intervals as given in Table 2. All aggregates were batched in a saturated surface dried state. To meet the designed initial slump of 180±10 mm polycarboxylate-based, high-range water-reducing admixture, whose threshold dosage recommended to minimize the change of concrete properties was 2% with respect to the weight of binder, was added.

Table 1. Chemical composition of hwangtoh (mass %)

SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	F_2O_3	TiO_2	MnO	LOI*
52.5	32.9	4.31	4.37	0.4	0.7	0.69	0.24	3.89

* Loss on ignition.7

The concrete specimen notation given in Table 2 includes two parts: the first of which refers to W/B ratio and the latter identifies S/A. For example, the 2-40 specimen indicates a concrete mixture having W/B ratio of 20% and S/A ratio of 40%.

2.3 Casting, curing and testing

Fine and coarse aggregates together with the hwangtoh-based binder were dry-mixed in a 0.35m^3 capacity mixer pan for 1 minute and then water was added and mixed for another 1 min. If the initial slump of concrete did not meet the designed value, high-range water-reducing admixture was added until the designed slump was obtained.

Various steel moulds were cast to evaluate the mechanical properties of each concrete mix. Immediately after casting, all specimens were cured at a constant temperature and relative humidity of 23 ± 2 °C and 70 ± 5%, respectively, until tested at a specified age. All steel moulds were removed at the age of one day.

The slump of fresh concrete was measured at 0 (initial), 30, 60, 90, and 120 minutes after mixing of concrete to evaluate the workability loss of hwangtoh-based concrete. Compressive and splitting tensile strengths, stress-strain relation, and modulus of elasticity were measured using 100×200 mm cylinder specimens. A compressor meter having dial gages and electrical resistance strain gages (ERS) was mounted on the cylinder specimens, as shown

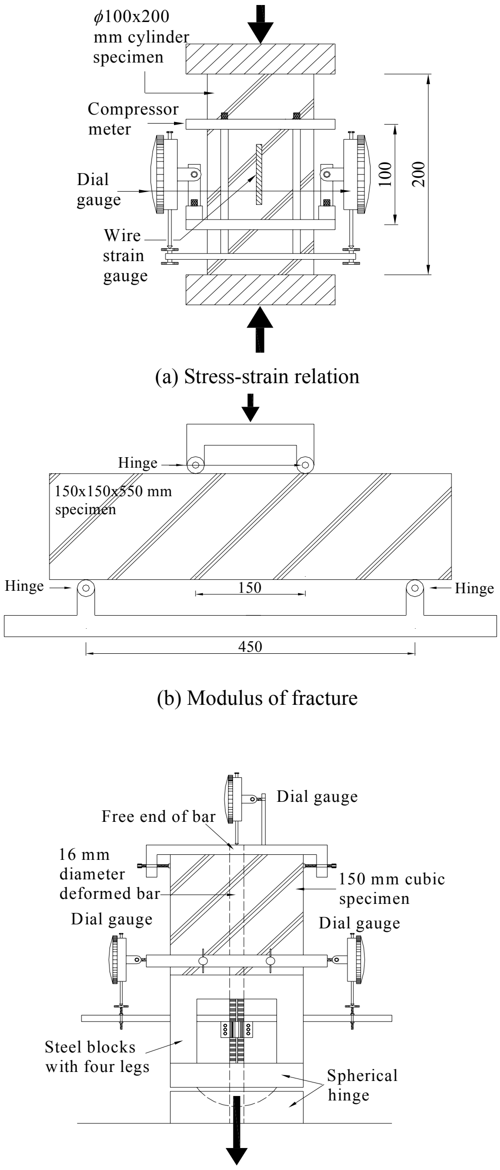
Table 2. Details of concrete mixes tested

Speci-men	W/B (%)	S/A (%)	Unit weight (kg/m^3)					R_{sp}* (%)
			W	B	S	G	SP	
2-40	20	40	175	875	487	750	2.36	2.0
2.5-40	25			700	551	849	1.50	1.59
3-40	30			583	594	915	0.80	1.02
4-40	40			437	647	998	0.50	0.85
5-40	50			350	679	1047	0.24	0.5
6-40	60			291	701	1080	0.10	0.25
7-40	70			250	716	1104	0.06	0.17
3-30	30	30		583	445	1068	0.80	1.01
3-35		35			520	991	0.83	1.05
3-45		45			668	839	0.86	1.09
3-50		50			742	763	0.88	1.12
5-30	50	30		350	509	1222	0.15	0.32
5-35		35			594	1134	0.21	0.45
5-45		45			764	960	0.30	0.63
5-50		50			849	873	0.33	0.69

Note: W, B, S, G and SP indicate water, hwangtoh-based binder, fine aggregate, coarse aggregate, and superplasticizer, respectively.

*R_{sp}= ratio of superplasticizer to binder by weight.

in Fig. 1 (a), to obtain the stress-strain relationship and modulus of elasticity of concrete, which was calculated at 45% peak stress(ACI Committee 318, 2005). The modulus of rupture of concrete was also measured using prismatic beams of 150×150×550 mm dimensions under a symmetrical two-point top loading system as shown in Fig. 1 (b). The bond stress-slip relationship of a 16 mm diameter deformed bar with yield strength of 820 MPa incorporated in a cubic specimen of 150 mm was measured from the pullout test under monotonic loads as shown in Fig. 1 (c). The above tests of hardened concrete specimens were conducted using a 500 kN capacity universal testing machine with a servo-control system. The compressive strength of concrete specimens was measured at 1, 3, 7, 28, 56 and 91 days, while other properties were measured at the age of 28 days only.



(a) Stress-strain relation

(b) Modulus of fracture

(c) bond stress-slip relation

Figure 1. Testing procedures for different properties of concrete

The testing procedure was carried out in accordance with the specifications of the KS(KS F 2402-KS F 2414, 2006) for testing OPC concrete.

3. TEST RESULTS AND DISCUSSION

Splitting tensile strength, and moduli of elasticity and rupture of OPC concrete are generally proportional to the square root of compressive strength in the range of normal concrete strength(ACI Committee 318, 2005; Neville, 1995; MacGregor2005). Thus, these mechanical properties of hwangtoh-based (HB) concrete tested also need to be normalized by square root of the compressive strength. As there is little, if any, available test results on HB concrete, the effects of main variables on different properties of the concrete specimen is compared with that recorded for OPC concrete database compiled by Yang et al(2007). In addition, various measured properties of HB concrete are compared, wherever possible, with the predictions obtained from design equations specified in ACI 318-05 or CEB-FIP building codes for OPC concrete.

3.1. Amount of high-range water-reducing admixture added

The amount of high-range water-reducing admixture added to obtain the designed initial slump of a concrete specimen is given in Table 2. Specimen 2-40 failed to meet the designed initial slump, although high-range water-reducing admixture was added to the recommended critical value of 2%. The amount of added high-range water-reducing admixture increased with the decrease of the W/B ratio and the increase of the S/A ratio. This result indicated that the lower the W/B ratio and the higher the S/A ratio, the lower the initial slump of the HB concrete.

3.2. Slump loss

The slump loss $S_L(t)/(S_L)_i$ of concrete with elapsed time is shown in Fig. 2: Fig. 2 (a) demonstrates the effect of W/B ratio, while Fig. 2 (b) displays the effect of S/A ratio for W/B ratio= 50%, where $S_L(t)$ and $(S_L)_i$ are the slump values at a specified time (in minutes) and initial slump, respectively. The slump of specimens 2-40 and 2.5-40 after 30 minutes and 60 minutes, respectively, could not be measured due to the rapid setting. Therefore, the variation of slump for specimen 2-40 is not presented in Fig. 2 (a). The slump of the HB concrete decreased linearly with time, regardless of W/B and S/A ratios. The decreasing rate was more notable with the decrease of W/B ratio and the increase of S/A ratio. The increase of S/A ratio induces increase of the total surface area of aggregates mixed in concrete, which results in a lower initial slump and rapid slump loss of the concrete. Therefore, if water content and W/B ratio are constant, a lower S/A ratio is required to achieve high workability of HB concrete. In addition, HB concrete with a W/B ratio less than 30% would be more suitable for precast concrete owing to its steep slump loss.

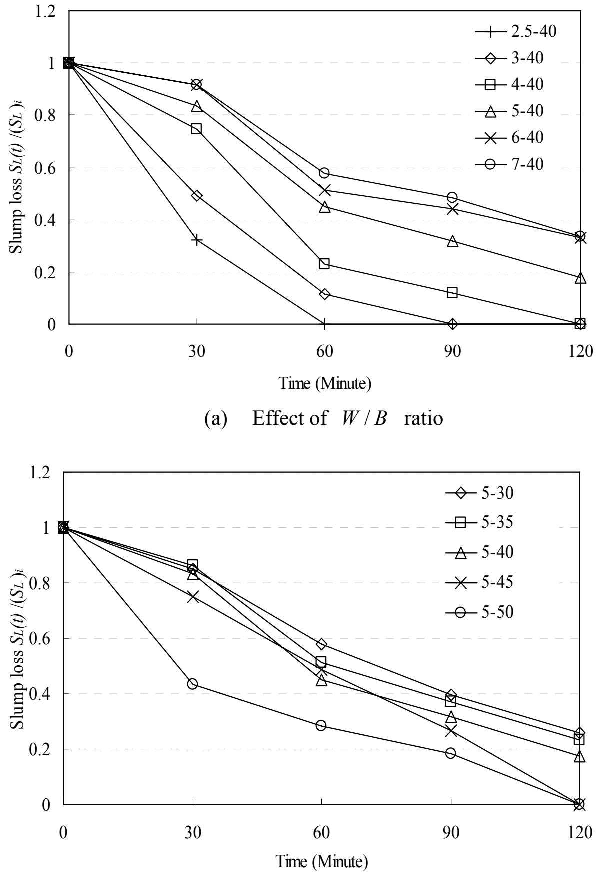
3.3. Compressive strength at 28 days

The effect of W/B ratio and S/A ratio on the 28-day compressive strength f_{ck} of HB concrete is plotted in Fig. 3. On the same figure, the test results of OPC concrete and best fit curves obtained from nonlinear regression analysis are also given. The compressive strength of concrete specimens tested increased with the decrease of W/B ratio, showing that the W/B ratio is one of the most important factors that affect the compressive strength of HB concrete. This is also true for OPC concrete[13] and HB mortar[8]. The increasing rate of the compressive strength against the W/B ratio was slightly lower for HB concrete than for OPC concrete. In addition, for the same W/B ratio, a lower compressive strength generally developed in HB concrete than in OPC concrete. A compressive strength greater than 20 MPa was not achieved in HB concrete with W/B ratios above 40%. Therefore, W/B ratio should be less than 40% for structural application of HB concrete.

The variation of compressive strength of HB concrete against S/A ratio showed a trough shape having a low point at S/A ratio of 40%. The compressive strength of HB concrete decreased as S/A ratio increased up to a certain limit (S/A=40%), beyond which it gradually increased. On the other hand, the compressive strength of OPC concrete increased with the increase of S/A ratio up to a certain limit (S/A=35~40%), beyond which it remained more or less constant. Therefore, S/A ratio is a secondary factor affecting the compressive strength of HB concrete, though further research would be required to ascertain the effect of the amount of fine aggregates on the microstructure of HB concrete.

3.4. Compressive strength development

To examine the compressive strength gain of HB concrete with age, the relative compressive strength $f_{ck}(t)/f_{ck}$ with age is shown in Fig. 4: Fig. 4 (a) for different W/B ratios, and Fig. 4 (b) for different S/A ratios when the W/B ratio is 50%, where $f_{ck}(t)$ is the compressive strength at age t (in days). The effect of the S/A ratio on the compressive strength development is nearly independent of W/B ratio. Thus, the relative compressive strengths of specimens with W/B= 30% is not provided in the Fig. 4 (b).



(a) Effect of W/B ratio

(b) Effect of S/A ratio (W/B =50%)

Figure 2. Slump loss with time

Table 3. Test Results

Specimen	Slump (mm)					f_{ck} (MPa)						f_{sp} (MPa)	f_r (MPa)	E_c (GPa)	τ_b (MPa)	$\frac{f_{sp}}{\sqrt{f_{ck}}}$	$\frac{f_r}{\sqrt{f_{ck}}}$	$\frac{E_c}{\sqrt{f_{ck}}}$	$\frac{\tau_b}{\sqrt{f_{ck}}}$
	Initial (0 Min)	30 Mins	60 Mins	90 Mins	120 Mins	1 day	3 days	7 days	28 days	56 days	91 days								
2-40	140	-	-	-	-	17.6	30.4	42.8	48.1	55.1	58.5	4.16	4.50	31.3	15.4	0.60	0.65	4518	2.22
2.5-40	185	60	-	-	-	14.7	24.3	32.4	36.1	40.0	42.6	3.33	4.02	27.6	14.6	0.55	0.67	4594	2.44
3-40	185	91	21	-	-	11.2	19.5	26.8	29.9	33.2	34.8	2.93	3.32	24.7	11.5	0.55	0.61	4508	2.09
4-40	185	138	42	22	-	8.1	12.6	16.9	18.8	21.3	22.1	2.20	2.22	19.8	8.6	0.51	0.51	4571	1.99
5-40	180	150	81	57	32	5.8	8.8	12.0	13.5	14.4	14.4	1.78	1.83	16.5	6.7	0.48	0.50	4501	1.83
6-40	175	160	90	77	58	4.0	6.5	8.9	10.0	10.3	10.6	1.44	1.48	14.0	5.6	0.45	0.47	4425	1.77
7-40	180	165	104	87	60	3.3	5.6	7.5	8.4	8.7	9.1	1.13	1.12	12.7	4.4	0.39	0.39	4403	1.52
3-30	186	105	41	-	-	10.6	21.2	27.8	34.2	37.4	39.2	3.50	3.65	25.6	12.4	0.60	0.62	4370	2.12
3-35	179	100	35	-	-	10.1	19.5	25.5	31.7	35.7	37.2	3.42	3.42	24.9	11.6	0.61	0.61	4415	2.06
3-45	184	95	30	-	-	9.0	20.1	27.2	32.7	37.5	39.2	3.31	3.34	25.0	11.2	0.58	0.58	4364	1.95
3-50	178	85	24	19	-	9.5	19.1	25.4	32.1	36.9	38.9	3.36	3.32	24.8	11.5	0.59	0.59	4383	2.03
5-30	187	159	108	74	48	7.5	11.8	13.6	14.2	14.5	14.9	1.76	2.25	17.4	7.2	0.47	0.60	4623	1.91
5-35	180	155	92	67	42	6.6	12.1	14.7	15.2	15.7	15.9	1.93	2.40	18.5	7.3	0.49	0.62	4744	1.88
5-45	180	135	88	48	-	6.4	11.8	14.0	15.2	15.6	16.2	1.95	2.02	18.1	7.4	0.50	0.52	4650	1.89
5-50	173	75	49	32	-	7.3	14.0	17.9	19.0	20.5	21.6	2.20	2.25	21.4	8.4	0.50	0.52	4900	1.93

Note: '–' indicates that the slump was not measured due to quick setting time.

The development of the compressive strengths of different HB concretes according to age showed a typical parabolic shape, indicating that the increasing rate of compressive strength development decreased with the increase of age. The compressive strength at age of 1 day ranged between 25% and 45% of the 28-day strength, and more than 80% of the 28-day strength developed within age of 7 days. The compressive strength development at age of 1 day was slightly increased with the increase of W/B ratio and the decrease of S/A ratio. On the other hand, the compressive strength development at age of 91 days increased minimally with the decrease of the W/B ratio and the increase of the S/A ratio.

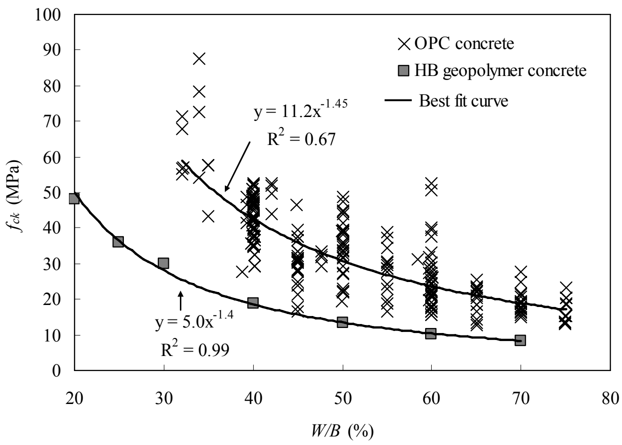
The ACI 209(ACI 209R-92, 1994) proposed that concrete develops compressive strength with age according to:

$$\frac{f_{ck}(t)}{f_{ck}} = \frac{t}{A_1 + B_1 t} \tag{1}$$

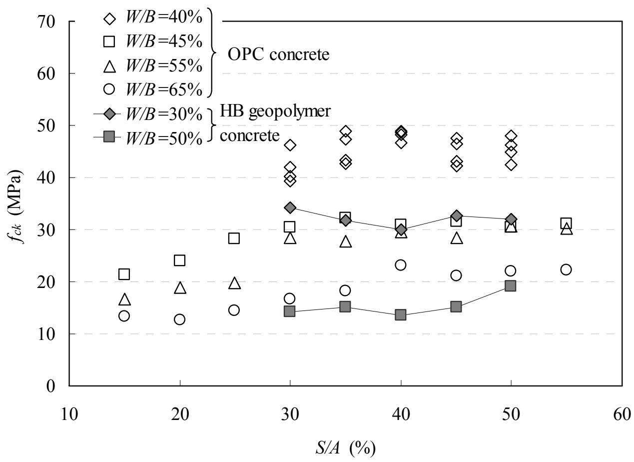
The two constants A_1 and B_1 in Eq. (1) generally represent the strength gain at early and long-term ages, respectively. In particular, lower values of A_1 and B_1 indicate higher compressive strength at early age and long-term age, respectively. Based on test results, the ACI 209 specifies the two constants A_1 and B_1 for OPC concrete as 4.0 and 0.85, respectively. Eq. (1) shows a parabolic gain of strength with time, which agrees with the observation in Fig. 4. The constants A_1 and B_1 obtained from nonlinear regression analysis of the test results using SPSS

Table 4. Regression analysis results for A_1 and B_1 constants of Eq. (1)

Specimen	A_1	B_1	R^2	Specimen	A_1	B_1	R^2
2-40	2.10	0.84	0.97	3-30	2.37	0.88	0.99
2.5-40	1.74	0.87	0.98	3-35	2.44	0.86	0.99
3-40	1.90	0.87	0.99	3-45	2.61	0.84	0.99
4-40	1.71	0.87	0.97	3-50	2.73	0.83	0.98
5-40	1.58	0.92	0.99	5-30	0.86	0.95	0.99
6-40	1.63	0.93	0.99	5-35	1.11	0.94	0.97
7-40	1.63	0.92	0.99	5-45	1.25	0.93	0.99
				5-50	1.54	0.89	0.98

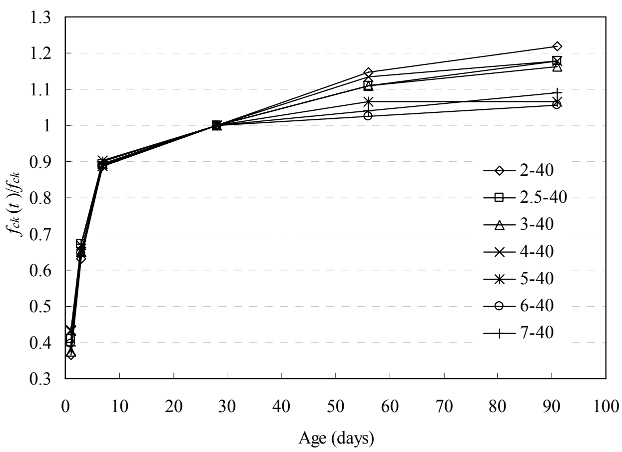


(a) Effect of W/B ratio



(b) Effect of S/A ratio

Figure 3. Compressive strength at age of 28 days



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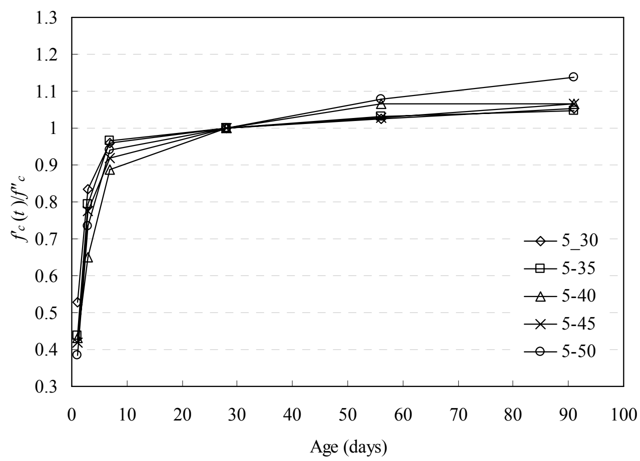


(b) Effect of S/A ratio (W/B =50%)

Figure 4. Compressive strength development versus age

software(SPSS 13.0) are presented in Table 4. Correlation coefficients between the strength development predicted from Eq. (1) using A_1 and B_1 obtained from the nonlinear regression analysis and the measured strength development with age for different specimens are also given in Table 4. High correlation coefficients of more than 0.95 were observed for all specimens. Therefore, the compressive strength development of HB concrete can be properly evaluated by Eq. (1) with appropriate constants A_1 and B_1. The constant A_1 in HB concrete decreased with the increase of W/B ratio and decrease of S/A ratio. The constant A_1 varies between 0.86 and 2.61, as given in Table 4, which is lower than the value of 4.0 specified in ACI 209 for OPC concrete. These lower values indicate that HB concrete experiences rapid and high strength development at an early age. Unlike the constant A_1, the constant B_1 whose values ranged between 0.83 and 0.95 decreased very slightly with the decrease of the W/B ratio and the increase of the S/A ratio. The constant B_1 of HB concrete was slightly higher than the value of 0.85 specified in ACI 209 for the OPC concrete by an average of 5%, indicating that the compressive strength development of HB concrete at long-term age was similar to that of the OPC concrete.

3.5. Splitting tensile strength

Fig. 5 shows the normalized splitting tensile strengths $f_{sp}/\sqrt{f_{ck}}$ of HB concrete and OPC concrete. The $f_{sp}/\sqrt{f_{ck}}$ of HB concrete decreased with the increase of the W/B ratio, but that of the OPC concrete was nearly independent of the W/B ratio. On the other hand, the S/A ratio had little influence on the $f_{sp}/\sqrt{f_{ck}}$ of HB concrete, which is the same as OPC concrete. In general, a lower $f_{sp}/\sqrt{f_{ck}}$ appears in HB concrete than in OPC concrete. When the W/B ratio was below 30%, however, the $f_{sp}/\sqrt{f_{ck}}$ of HB concrete was higher than 0.53, which is the empirical value proposed by Oluokun[18] based on test results of OPC concrete.

3.6. Modulus of rupture

The effect of W/B and S/A ratios on the normalized modulus of rupture $f_r/\sqrt{f_{ck}}$ of HB concrete is shown in Fig. 6. Test data obtained from OPC concrete database are given in Fig. 6 (a), and the modulus of rupture specified in ACI 318-05 for OPC concrete is also given in Fig. 6. The $f_r/\sqrt{f_{ck}}$ of HB concrete decreased with the increase of the W/B ratio, but was nearly independent of the S/A ratio, which is similar behavior to the $f_{sp}/\sqrt{f_{ck}}$. In addition, when the W/B ratio was above 30%, the $f_r/\sqrt{f_{ck}}$ of HB concrete was lower than that of OPC concrete and the design equation of ACI 318-05. Based on Fig. 5 and Fig. 6, the tensile resistance capacity of HB concrete is commonly lower than that of OPC concrete.

3.7. Modulus of Elasticity

Fig. 7 shows the normalized modulus of elasticity $E_c/\sqrt{f_{ck}}$ of HB concrete with the increase of W/B ratio (Fig. 7 (a)) and S/A ratio (Fig. 7 (b)). $E_c/\sqrt{f_{ck}}$ of OPC concrete against W/B ratio is plotted in Fig. 7 (a) and that of the design equation of ACI 318-05 for OPC concrete is also given in Fig. 7. $E_c/\sqrt{f_{ck}}$ of HB concrete was independent of W/B and S/A ratios. The average value of $E_c/\sqrt{f_{ck}}$ of HB concrete tested was about 4540, indicating that the modulus of elasticity of HB concrete is generally lower than the predictions obtained from ACI 318-05 by an average of 3.5%.

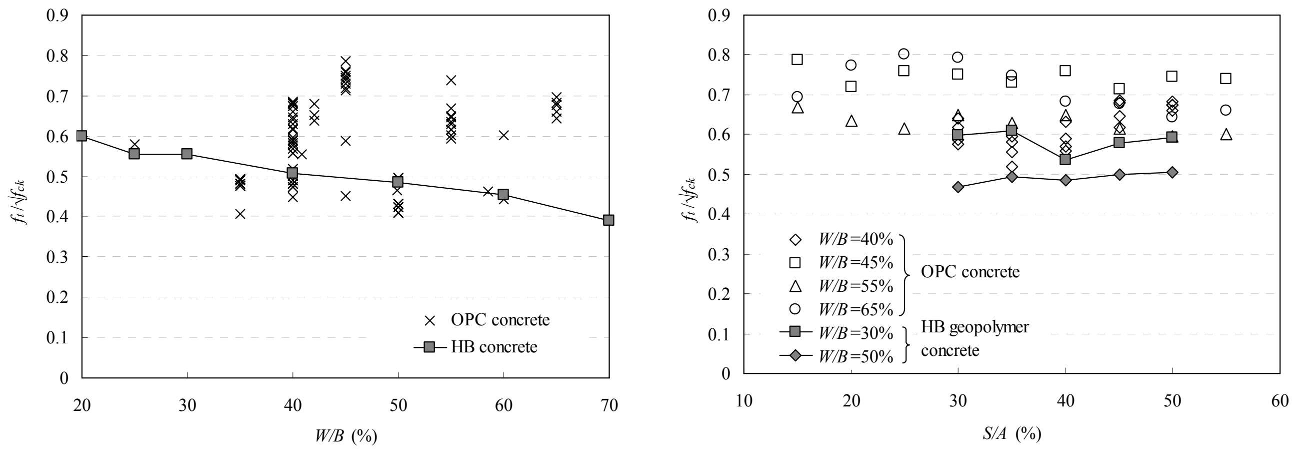
3.8. Stress-strain relationship

Typical stress-strain curves of different HB concrete mixes are plotted in Fig. 8. On the same figure, predictions obtained from formulas specified in CEB-FIP for OPC concrete are also given for comparison purposes. The characteristic of the stress-strain curve of HB concrete was significantly influenced by W/B ratio, which has a significant effect on the compressive strength. With the decrease of W/B ratio, that is, the increase of compressive strength, the initial stiffness and strain at the peak stress of HB concrete increased. For W/B ratio below 30% (for medium strength), the descending branch of the stress-strain curve dropped sharply showing the brittleness failure mode, and the dropping rate was more prominent for high concrete strengths as shown in Fig. 8 (a). However, the descending branch for HB concrete having W/B ratios greater than 30% (for low strength lower than 20 MPa) showed ductile behavior, as shown in Fig. 8 (b). On the other hand, the effect of S/A ratio on the shape of the stress-strain curve for HB concrete was negligible when the compressive strength was of similar grade, as shown in Fig. 8 (c).

The characteristic of the stress-strain curve measured for HB concrete generally disagreed with the predictions of the CEB-FIP model. Lower stiffness in the ascending branch and larger strain at the peak stress were observed for the test specimens than for the CEB-FIP model, showing an increase of discrepancy with the increase of W/B ratio. In addition, the slope of the descending branch of the stress-strain curve was slower for the test specimens than for the CEB-FIP model, showing an increase of discrepancy with the decrease of W/B ratio.

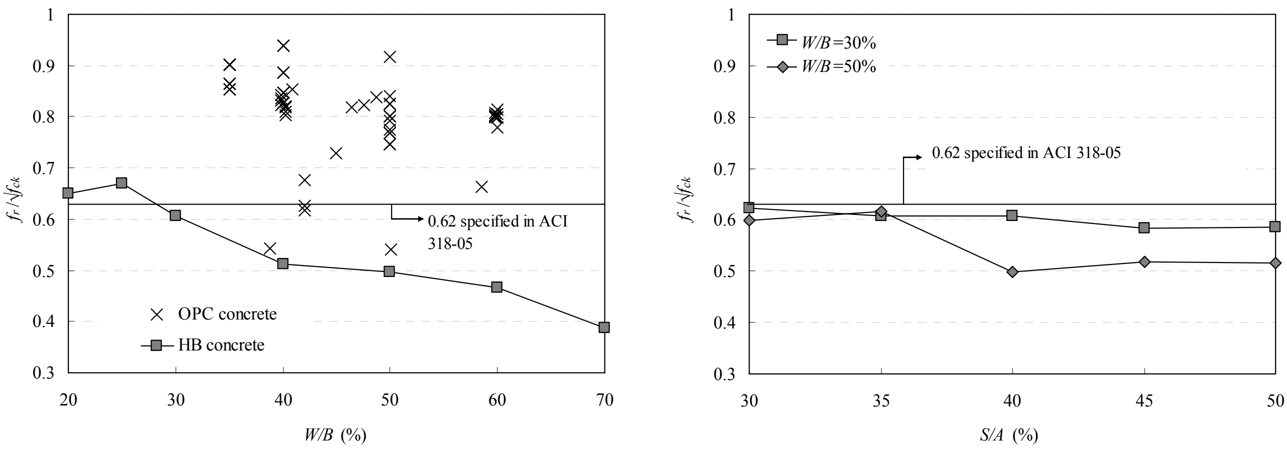
3.9. Bond stress-slip relationship

Fig. 9 shows the bond stress-slip relation of steel reinforcement installed in the HB concrete. The amount of slip recorded from the dial gage attached at the free end of steel reinforcement was used. On the same figure, predictions obtained from the design model of CEB-FIP for OPC concrete are also presented. The bond stress-slip relation in HB concrete was influenced by W/B ratio, as the compressive strength of concrete was greatly dependent on W/B ratio, as shown in Fig. 3 (a). As W/B ratio decreases bond strength of HB concrete improves owing to the increase in compressive strength, as shown in Fig. 9 (a), Fig. 9 (b) and Table (3). In addition, the slip resistance in the ascending branch of the bond stress-slip curve increased with the decrease of the W/B ratio, resulting in a smaller amount of slip at the peak stress. On the other hand, the bond stress-slip curve of the reinforcement installed in HB concrete was hardly influenced by the S/A ratio when the compressive strength was of similar grade, as shown in Fig. 9 (c). After the peak bond stress, the amount of slip of reinforcement installed in HB concrete increased sharply, regardless of the W/B and S/A ratios. The normalized bond strength $\tau_b/\sqrt{f_{ck}}$ of HB con



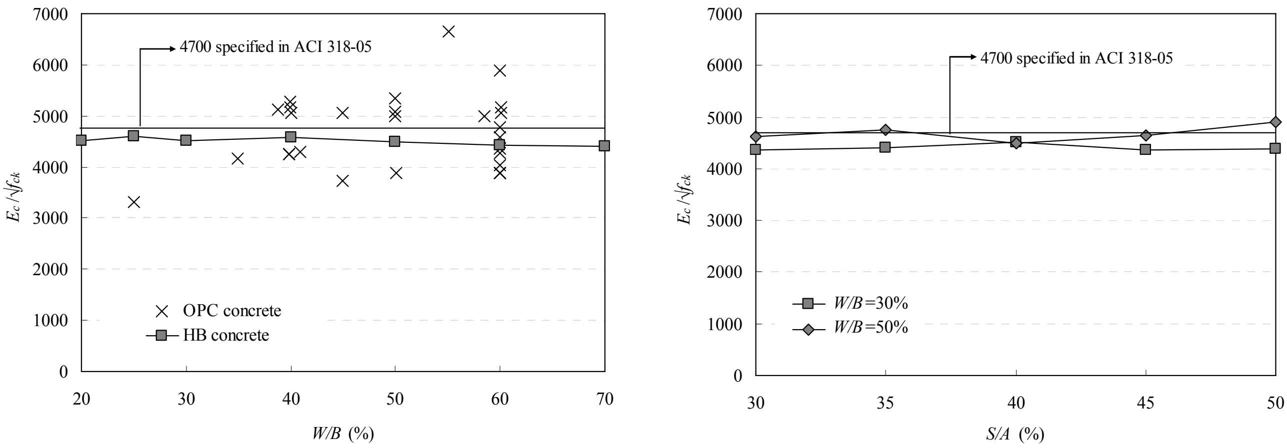
(a) Effect of W/B ratio (b) Effect of S/A ratio

Figure 5. Normalized splitting tensile strength



(a) Effect of W/B ratio (b) Effect of S/A ratio

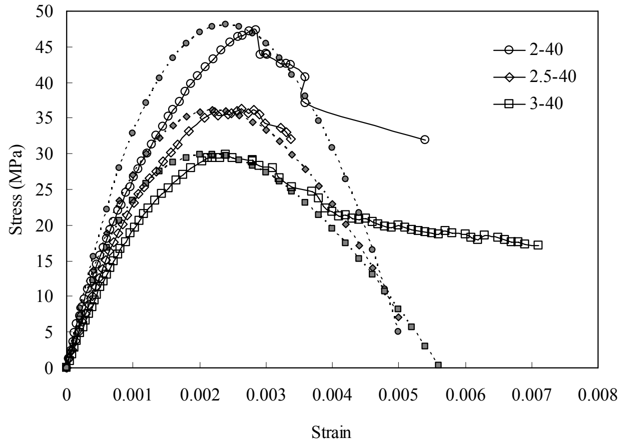
Figure 6. Normalized modulus of rupture



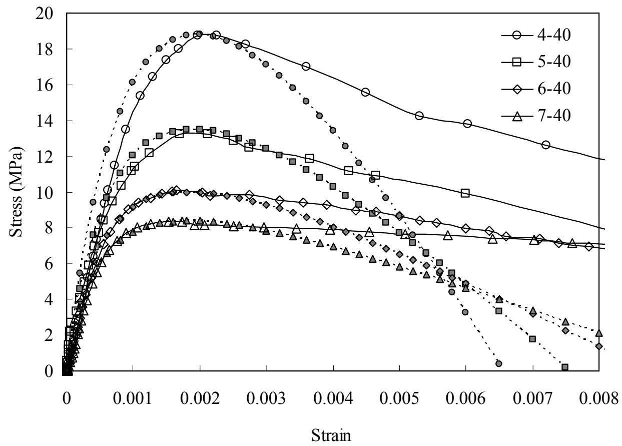
(a) Effect of W/B ratio (b) Effect of S/A ratio

Figure 7. Normalized modulus of elasticity

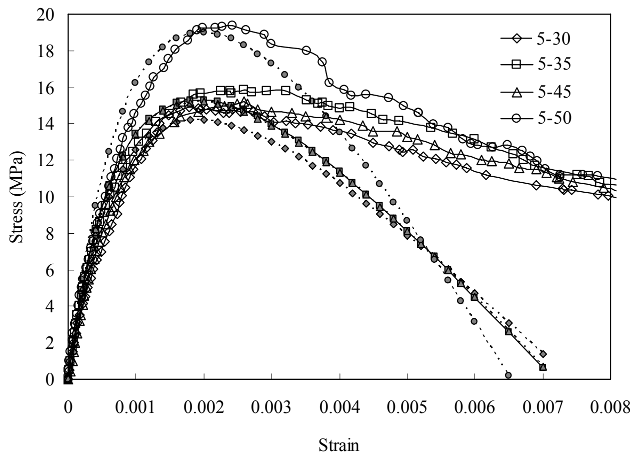
crete decreased with the increase of the W/B ratio but was independent of the S/A ratio, as given in Table 3. Agreement between the measured and predicted bond stress-slip relations was dependent on the compressive strength of concrete tested, though the average value of 1.97 of the measured $\tau_b/\sqrt{f_{ck}}$ showed good agreement with the value 2.0 specified in CEB-FIP for OPC concrete.



(a) Effect of W/B ratio for medium strength



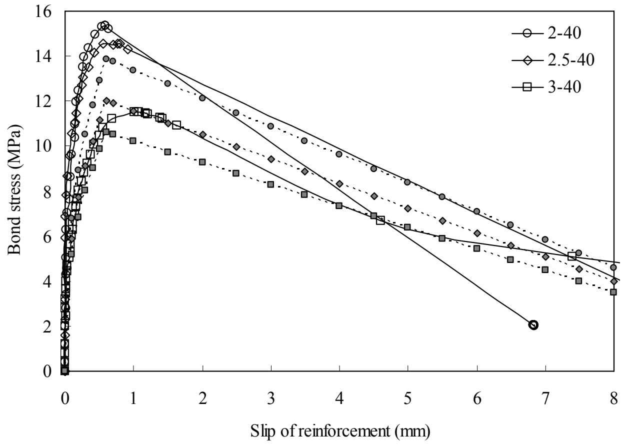
(b) Effect of W/B ratio for low strength



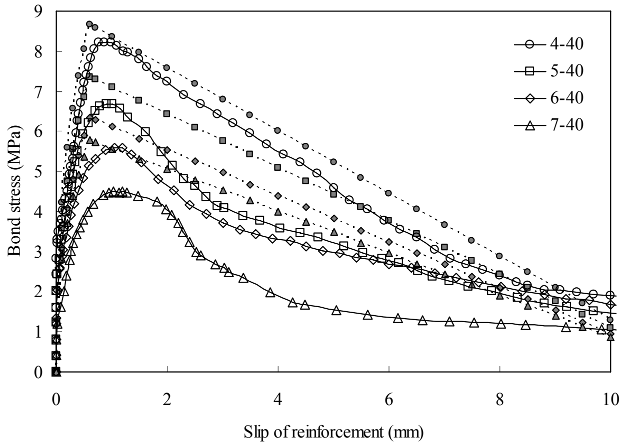
(c) Effect of S/A ratio (W/B =50%)

Figure 8. Stress-strain curves of HB concrete

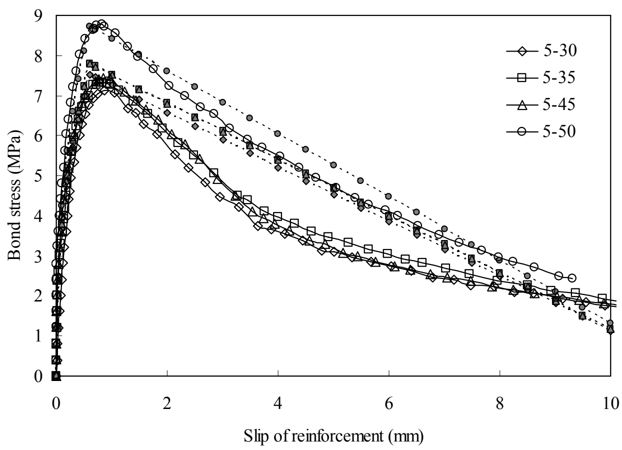
(White symbol with solid line and black symbol with dotted line indicate test results and predictions obtained from CEB-FIP for OPC concrete, respectively.)



(a) Effect of W/B ratio for medium strength



(b) Effect of W/B ratio for low strength



(c) Effect of S/A ratio (W/B =50%)

Figure 9. Bond stress-slip relation of reinforcement installed in HB concrete

(White symbol with solid line and black symbol with dotted line indicate test results and predictions obtained from CEB-FIP for OPC concrete, respectively.)

When W/B ratio was below 30%, the bond strength of HB medium strength concrete was higher than that predicted from CEB-FIP model as shown in Fig. 9 (a). For W/B ratios greater than 30% (for low strength), however, the measured bond strength was lower than that predicted by the CEB-FIP model, indicating that the discrepancy increased with the increase of the W/B ratio, as shown in Fig. 9 (b) and Fig. 9 (c). The descending branch slope of the bond stress-slip relationship of reinforcement installed in HB concrete was similar to the predicted slope.

4. CONCLUSIONS

The following conclusions are deduced from the study presented above:

(1) The slump of HB concrete decreased linearly with time, regardless of the water-to-binder ratio and fine aggregate-to-total aggregate ratio. The decreasing rate was more notable with the decrease of water-to-binder ratio and the increase of fine aggregate-to-total aggregate ratio.

(2) The compressive strength of HB concrete slightly decreased with the increase of the fine aggregate-to-total aggregate ratio until the fine aggregate-to-total aggregate ratio reached 40%, beyond which it gradually increased.

(3) HB concrete showed rapid and high strength development at an early age, but the compressive strength development at long-term age was similar to that of OPC concrete.

(4) The normalized splitting tensile strength, normalized modulus of rupture and normalized bond strength of HB concrete decreased with the increase of water-to-binder ratio, but were nearly independent of fine aggregate-to-total aggregate ratio.

(5) Slip resistance in the ascending branch of the bond stress-slip curve in HB concrete increased with the decrease of the water-to-binder ratio, resulting in a smaller amount of slip at the peak stress, whereas the bond stress-slip relation was little influenced by fine aggregate-to-total aggregate ratio when the compressive strength was of similar grade.

(6) The moduli of rupture and elasticity of HB concrete with water-to-binder ratios above 40% were generally lower than those of OPC concrete and predictions obtained from design equation specified in ACI 318-05 for OPC concrete. In addition, the stress-strain relation and bond stress-slip relation measured for HB concrete showed little agreement with the predictions obtained from the design model specified in CEB-FIP.

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