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Mechanical Properties of Energy Efficient Concretes Made with Binary, Ternary, and Quaternary Cementitious Blends of Fly Ash, Blast Furnace Slag, and Silica Fume

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Abstract: When the energy performance of concrete is substantially higher than that of normal type concrete, such concrete is regarded as energy efficient concrete (WBSCSD 2009). An experimental study was conducted to investigate mechanical properties of energy efficient concrete with binary, ternary and quaternary admixture at different curing ages. Slump test for workability and air content test were performed on fresh concretes. Compressive strength, splitting tensile strength were made on hardened concrete specimens. The mechanical properties of concrete were compared with predicted values by ACI 363R-84 Code, NZS 3101-95 Code, CSA A23.3-94 Code, CEB-FIP Model, EN 1991, EC 2-02, AIJ Code, JSCE Code, and KCI Code. The use of silica fume increased the compressive strengths, splitting tensile strengths, modulus of elasticities and Poisson's ratios. On the other hand, the compressive strength and splitting tensile strength decreased with increasing fly ash.

Keywords: energy efficient concrete, compressive strength, splitting tensile strength, modulus of elasticity, Poisson's ratio, fly ash, blast furnace slag, silica fume.

1. Introduction

The cement industry accounts for approximately 5 % of current anthropogenic carbon dioxide (CO_2) emissions worldwide (WBSCSD 2009). World cement demand and production are increasing; annual world cement production is expected to grow from approximately 2540 million tones (Mt) in 2006 to between 3680 Mt (low estimate) and 4380 Mt (high estimate) in 2050. The largest share of this growth will take place in India, China, and other developing countries on the Asian continent (Liu et al. 2016). This significant increase in cement production is associated with a significant increase in the cement industry's absolute energy use and CO_2 emissions.

The major difference between normal concrete and energy efficient concrete (EEC) is essentially the use of chemical and mineral admixtures. EEC is the concrete which meets special performance and uniformity requirements that cannot always be achieved by normal materials, normal mixing, placing and curing practices. There have been a number of attempts to develop a method for the proportioning of mixes with cement replacement materials which could be classified as fly ash or blast furnace slag.

Limbachiya et al. (2012) conducted experimental studies of use of recycled concrete aggregate (RCA) in fly-ash concrete. It shows that the use of fly ash in RCA concrete may significantly improve the resistance to chloride ingress. Zain et al. (2002) conducted research work to determine relationship between compressive strength and splitting tensile strength of concrete. Vilanova et al. (2011) evaluated the mechanical properties of self-compacting concrete (SCC) using current estimating models estimating the modulus of elasticity, tensile strength, and modulus of rupture of SCC. It shows that all the models evaluated are suitable for the estimating the modulus of elasticity, tensile strength, and modulus of rupture of SCC.

2. Materials and Mixture Proportions

Commercial Type I Portland cement that complies with the requirements of ASTM C 150 (ASTM Standards 2016) was used as a testing cement. A commercial Class F coal fly ash,

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Table 1 Physical properties of cement.

Physical properties	Unit	Cement	Fly ash	Blast furnace slag	Silica fume
Specific gravity	g/cm^3	3.15	2.35	2.94	2.32
Blaine	cm^2/g	3.376	5.102	4.444	250,653

Table 2 Chemical composition.

Chemical properties	Unit	Cement	Fly ash	Blast furnace slag	Silica fume
SiO_2	%	21.23	64.02	36.04	94.91
Al_2O_3		5.23	19.89	15.79	1.89
Fe_2O_3		3.51	4.45	0.45	0.36
CaO		60.32	3.82	42.16	0.79
MgO		3.68	1.09	3.94	0.26
SO_3		1.92	–	1.95	–
F-CaO		1.66	–	–	–
K_2O		1.06	1.13	0.50	0.57
Na_2O		0.13	1.04	0.22	0.34
T.A		0.83	–	–	–
LOI		1.26	4.55	0.70	0.88

Table 3 Physical properties of aggregate.

	Density (g/cm^3)	Water absorption (%)	Max size D_{max} (%)	Unit weight (kg/m^3)
Fine aggregate	2.68	2.80	5	1662
Coarse aggregate	2.78	1.33	20	1702

blast furnace slag and silica fume was used as a material. The physical properties and chemical composition, as supplied by the fly ash distributor, blast furnace slag and silica fume, are listed in Tables 1 and 2. Coarse and fine aggregate were crushed aggregate and sea sand, respectively. The densities of fine aggregate and coarse aggregate were 2.68 and 2.78, as listed in Table 3. Three levels of energy efficient concrete were designed using the different mixture proportions. Three different mixture group were prepared to achieve the nominal compressive strength. The mix proportions for the three mixture group are listed in the Table 4.

3. Specimen and Test Method

Energy efficient concrete mixtures were mixed in a high-speed shear mixer. For each batch, cylindrical molds of size 100 mm × 200 mm (4 × 8 in.) were cast for the determination of compressive strength, splitting tensile strength and modulus of elasticity of energy efficient concrete. After casting, all the molded specimens were taken to a room at 23 ± 2 °C and humidity and covered with a plastic sheet. When the mixing procedure was completed, tests were conducted on the fresh concrete to determine slump flow and air content. The slump flow tests were performed according to ASTM C 143 (ASTM Standards 2016). The slump flow test measures the horizontal free flow of energy efficient concrete by using a regular slump cone. Air content test method ASTM C 231 (ASTM Standards 2016) was used in this project. Compressive strength and splitting tensile strength tests were performed on cylindrical specimens. Compressive strength of the cylinder specimens was determined in ASTM C 39 (ASTM Standards 2016). Splitting tensile strength testing was conducted in accordance with ASTM C 496 (ASTM Standards 2016). The modulus of elasticity tests was measured following ASTM C 469 (ASTM Standards 2016). These specimens were tested at 7, 28, 56 and 91 days. Three cylinders were tested at each age, and the presented results are an average of the three cylinders.

4. Results and Discussion

4.1 Slump Flow and Air Content

The slump test of concretes was measured for workability of concrete in the fresh state. In addition, the air contents of concretes in its fresh state were measured using pressure gauge method. The test results of slump flow and air content are listed in Table 5. As listed in Table 5, the slump values of for Group I and Group II were 135–210 and 180 to 215 mm, respectively.

Table 4 The details of mix proportions.

Specimen name		W/B	S/a	W	C	FA	BS	SF	S	G
		(Unit: %)		(Unit: kg/m^3)						
Group I	FA15	40	43	162	324	81	–	–	750	1027
	FA25			155	291	97	–	–	762	1044
	SF5			155	368	–	–	19	772	1057
	BS25 + FA25			155	194	97	97	–	760	1041
	BS30 + FA30			155	155	116	116	–	757	1037
	BS50			155	194	–	194	–	769	1054
	BS65 + SF5			155	116	–	252	19	765	1048
Group II	FA25	34	39	155	342	114	–	–	667	1078
	SF5			155	433	–	–	23	677	1094
	BS25 + FA25			155	228	114	114	–	664	1073
	BS30 + FA30			155	182	137	137	–	661	1069
	BS50			155	228	–	228	–	674	1090
	BS65 + SF5			155	137	–	296	23	670	1083
Group III	FA25 + SF5	28	39	155	388	138	–	28	628	1016
	SF5			155	526	–	–	28	644	1041
	BS25 + FA20 + SF5			155	277	111	138	28	628	1016
	BS30 + FA25 + SF5			155	221	138	166	28	624	1009
	BS45 + SF5			155	277	–	249	28	638	1032
	BS65 + SF5			155	137	–	296	23	670	1083

Table 5 Slump flow and air content.

Specimen name		Slump (Unit: mm)	Air content (Unit: %)
Group I	FA15	135	3.8
	FA25	180	4.4
	SF5	180	3.5
	BS25 + FA25	185	3.3
	BS30 + FA30	210	3.7
	BS50	210	3.5
	BS65 + SF5	170	4.0
Group II	FA25	215	4.0
	SF5	180	3.6
	BS25 + FA25	210	3.3
	BS30 + FA30	215	3.2
	BS50	205	4.0
	BS65 + SF5	190	4.0
Group III	FA25 + SF5	530	3.9
	SF5	510	3.6
	BS25 + FA20 + SF5	580	3.3
	BS30 + FA25 + SF5	530	3.7
	BS45 + SF5	510	3.2
	BS65 + SF5	600	3.3

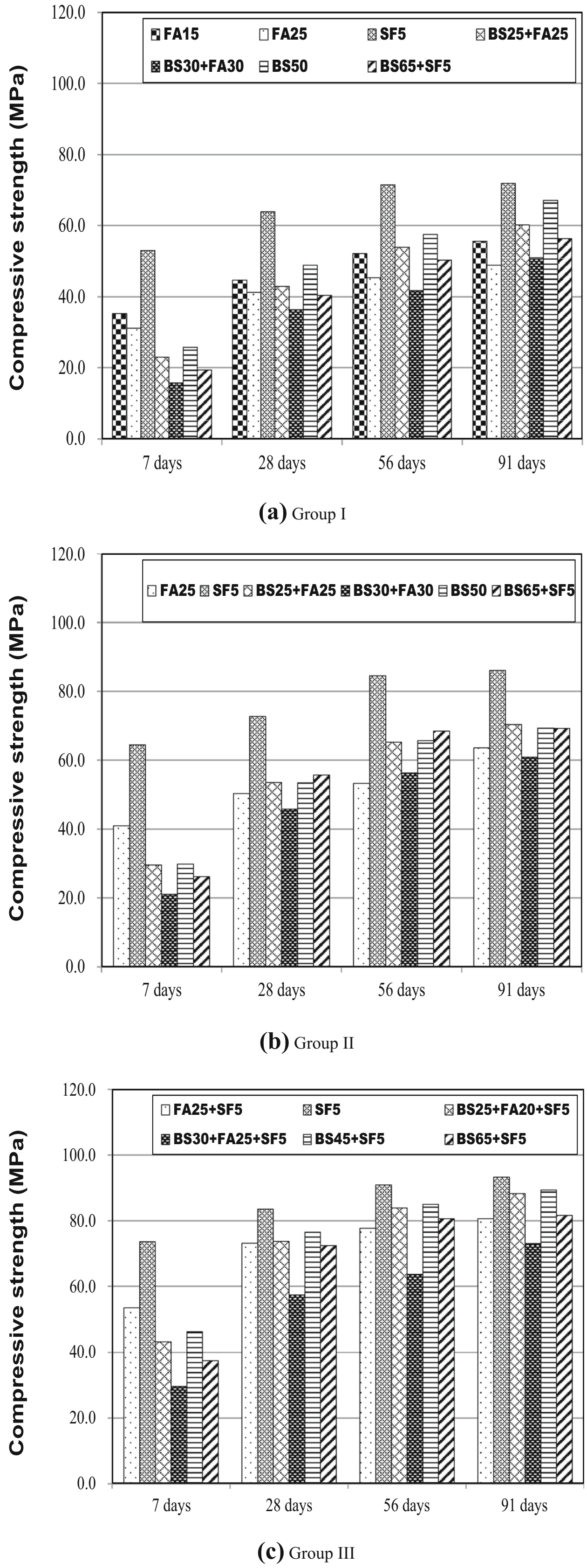


Fig. 1 Compressive strength.

In addition, the slump flow values of for Group III was 510–600 mm. The air contents for Group I, Group II and Group III, as vindicated values in the pressure gauge, were 3.3–4.4 %, 3.2–4.0 %, and 3.2–3.9 %, respectively.

4.2 Concrete Compressive Strength

Figure 1 shows the variation of the compressive strength of energy efficient concrete with binary and ternary admixture at different curing ages. The compressive strength depends mainly on the water-binder (W/B) ratio. It is also affected by the quality of the constituent materials, mixing and curing methods (Gao et al. 2005).

The compressive strength development of the EEC mixes should be affected because of the different properties and replacement levels of the mineral admixtures. For all curing days, compressive strengths of SF5 specimens were higher than those of other specimens, as shown in Fig. 1. As expected, the compressive strength of concrete containing silica fume are higher than control concrete at all curing ages.

The lower the value of W/B ratio, the higher is the compressive strength of concrete, as listed in Table 6. The average values of 7, 28, 56 and 91 days compressive strength in Group I series was ranged with 15.8–53.0 MPa, 36.3–63.9 MPa, 45.3–71.5 MPa and 48.8–71.9 MPa, respectively. The ratio of compressive strength at 7 days to strength at 28, 56 and 91 days were ranged with 0.44–0.83, 0.38–0.74, 0.31–0.74, respectively. For all the different concrete mixes prepared, 28 days cylindered compressive strengths were found to range between 36.3 and 63.9 MPa. In particular, Specimens BS30 + FA30 and SF 5 concrete mixed in Group I exhibited the lowest and highest 28 days compressive strength, as shown in Fig. 1, respectively. In addition, the compressive strength decreased with increasing fly ash at all ages, compared with Specimens FA 15 and FA 25 in Group I. This is attributed to the fact that pozzolanic reaction depending on contents of fly ash could develop compressive strength slowly.

The average values of 7, 28, 56 and 91 days compressive strength in Group II series was ranged with 21.1–64.5 MPa, 45.8–72.8 MPa, 53.3–84.6 MPa and 60.9–86.1 MPa, respectively. The ratio of compressive strength at 7 days to strength at 28, 56 and 91 days were ranged with 0.46–0.89, 0.37–0.77, 0.35–0.75, respectively. These values in Group II series are similar to those in Group I series. In addition, the trends of 28 days compressive strength for Specimens BS30 + FA30 and SF 5 concrete mixed in Group II series are almost the same to those in Group I series, as shown in Figs. 1a and 1b.

The average values of 7, 28, 56 and 91 days compressive strength for Group III series was ranged with 29.6–73.6 MPa, 57.4–83.6 MPa, 63.7–90.9 MPa and 73.0–93.2 MPa, respectively. The ratio of compressive strength at 7 days to strength at 28, 56 and 91 days were ranged with 0.52–0.88, 0.46–0.81, 0.41–0.81, respectively. These values in Group III series are slightly higher than those in Group I and Group II series. In particular, Specimens BS30 + FA25 + SF5 and SF5 concrete mixed in Group III exhibited the lowest and highest 28 days compressive strength, as shown in Fig. 1.

In all the Group I, II and III, the compressive strength of specimen SF5, binary admixture containing 5 % silica fume, are still much higher than those of specimens FA15, FA 25, BS25 + FA25, BS30 + FA30, BS50 containing fly ash or/and

Table 6 Compressive strength test results.

Specimen name		Water-binder (W/B) ratio (%)	Compressive strength (Unit: MPa)				Ratio of compressive strength at 7 days to strength at 28, 56 and 91 days		
			7 days	28 days	56 days	91 days	7/28	7/56	7/91
Group I	FA15	40	35.2	44.6	52.2	55.6	0.79	0.67	0.63
	FA25		31.1	41.2	45.3	48.8	0.75	0.69	0.64
	SF5		53.0	63.9	71.5	71.9	0.83	0.74	0.74
	BS25 + FA25		23.0	42.9	53.9	60.2	0.54	0.43	0.38
	BS30 + FA30		15.8	36.3	41.7	51.0	0.44	0.38	0.31
	BS50		25.8	48.9	57.5	67.1	0.53	0.45	0.38
	BS65 + SF5		19.4	40.4	50.2	56.4	0.48	0.39	0.34
Group II	FA25	34	41.0	50.4	53.3	63.6	0.81	0.77	0.64
	SF5		64.5	72.8	84.6	86.1	0.89	0.76	0.75
	BS25 + FA25		29.5	53.5	65.3	70.4	0.55	0.45	0.42
	BS30 + FA30		21.1	45.8	56.3	60.9	0.46	0.37	0.35
	BS50		29.8	53.4	65.7	69.3	0.56	0.45	0.43
	BS65 + SF5		26.2	55.7	68.4	69.3	0.47	0.38	0.38
Group III	FA25 + SF5	28	53.6	73.2	77.7	80.6	0.73	0.69	0.67
	SF5		73.6	83.6	90.9	93.2	0.88	0.81	0.81
	BS25 + FA20 + SF5		43.2	73.7	83.9	88.3	0.59	0.51	0.49
	BS30 + FA25 + SF5		29.6	57.4	63.7	73.0	0.52	0.46	0.41
	BS45 + SF5		46.3	76.5	85.0	89.4	0.61	0.54	0.52
	BS65 + SF5		37.4	72.5	80.6	81.6	0.52	0.46	0.46

blast furnace slag at all ages and various admixture. This is attributed to the fact that silica fume consisted of ultra fine particles and increased the bond strengths between cement paste and aggregate by making the interfacial zone denser. In addition, the compressive strength of specimens BS30 + FA30, BS30 + FA25 + SF5 decreased with increasing fly ash and blast furnace slag at all ages, compared with Specimens BS25 + FA25, BS25 + FA20 + SF5 in Group I, Group II and Group III. This is attributed to the fact that pozzolanic reaction of fly ash and latent hydraulic activity of blast furnace slag could develop compressive strength slowly.

4.3 The Relationship Between 7 and 28 days Compressive Strength

It may be necessary to predict the compressive strength of concrete not only at an early age but also at later ages. The number of researchers and Codes (Power and Brownyard 1946; Nevile 1997; Hassoun and Choo 2003; Kim et al. 2015) have attempted to predict the relationship between 7 and 28 days compressive strength. The relationship could be expressed by the following equations.

(1) DIN Code

In Germany, DIN Code proposed a simple equation to predict the relationship between 7 and 28 days compressive strength

$$f_{28} = 1.4f_7 + 1.0 \sim f_{28} = 1.7f_7 + 5.9(\text{MPa}) \tag{1}$$

where, f_7 and f_{28} are the compressive strengths at 7 and 28 days.

(2) Pineiro et al.

Pineiro et al. proposed equation to predict the relationship of compressive strength between 7 and 28 days.

$$f_{28} = k_2(f_7)^{k_1} \tag{2}$$

where, f_7 and f_{28} are the compressive strengths at 7 and 28 days. k_1 and k_2 are the coefficients, which were ranged from 0.3 to 0.8 and 3 to 6, respectively.

(3) Hassoun et al.

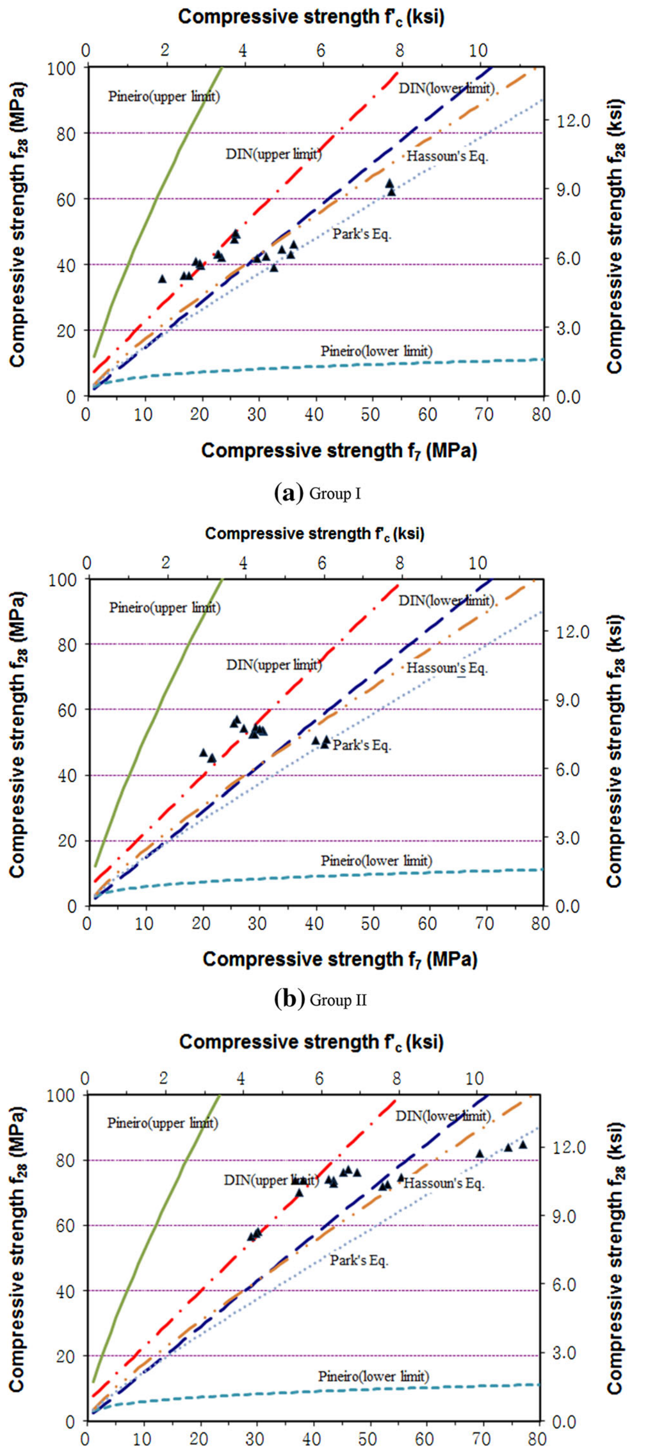
Hassoun et al. recommended the following equation for the relationship of compressive strength between 7 and 28 days.

$$f_{28} = f_7 + 2.4\sqrt{f_{ck}}(\text{MPa}) \tag{3}$$

where, f_7 and f_{28} are the compressive strengths at 7 and 28 days, respectively.

(4) Park et al.

Park et al. recommended the following equation for the relationship of compressive strength between 7 and 28 days.



(a) Group I

(b) Group II

(c) Group III

Fig. 2 7 days strength versus 28 days strength.

$$f_{28} = f_7 + 2.4\sqrt[3]{f_{ck}}(\text{MPa}) \tag{4}$$

Figure 2 shows the relationship of compressive strength between 7 and 28 days. 7 days compressive strength in Group I were ranged with 15.8–53.0 MPa, which values are 0.44–0.74 times of 28 days compressive strength. In addition, 7 days compressive strength in Group II and Group III were ranged with 21.1–64.5 and 29.6–73.6 MPa, which values are 0.46–0.89 times and 0.52–0.88 times of 28 days compressive strength. Compared with Pineiro' Eq. (1) and Hassoun's Eq. (3), the predicted values by DIN code show good agreement with observed values less than 30 MPa and Park's Eq. (4) over 30 MPa in Group I. Compared with Pineiro' Eq. (1) and Hassoun's Eq. (3), the predicted values by DIN code show good agreement with observed values less than 35 MPa and Park's Eq. (4) over 35 MPa in Group II. This trend is similar to that of Group I. The predicted values by DIN are in a good agreement with measured values less than 50 MPa and Hassoun's Eq. (3) for 50–70 MPa in Group III. In addition, the predicted values by Park's Eq. (4) are in a good agreement with measured values over 70 MPa.

4.4 Splitting Tensile Strength

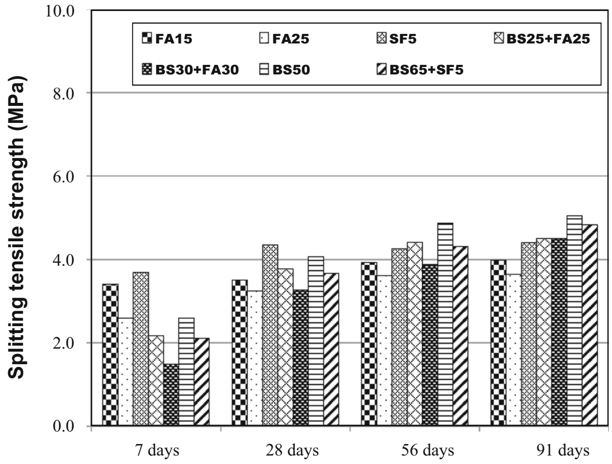
Figure 3 shows the variation of the splitting tensile strength of energy efficient concrete with binary and ternary admixture at different curing ages. The tensile strength of EEC is much lower than the compressive strength, largely because of the ease with which cracks can propagate under tensile loads.

As listed in Table 7, the average values of 7, 28, 56 and 91 days splitting tensile strengths for Group I were ranged with 1.5–3.7 MPa, 3.2–4.3 MPa, 3.6–4.9 MPa, 3.6–5.0 MPa, respectively. The ratio of tensile strength at 7 days to strength at 28, 56 and 91 days were ranged with 0.45–0.97, 0.38–0.87, 0.33–0.85, respectively. The ratio of tensile strength of FA15 specimens were higher than that of other specimens, while BS30 + FA30 specimens were lower than that of other specimens. In particular, the splitting tensile strength decreased with increasing fly ash at all ages, compared with specimens FA 15 and FA 25 in Group I. Although the trend in splitting tensile strength gain is almost similar with that of compressive strength, the 28 days splitting tensile strength lies in the range of 5–10 % of compressive strength.

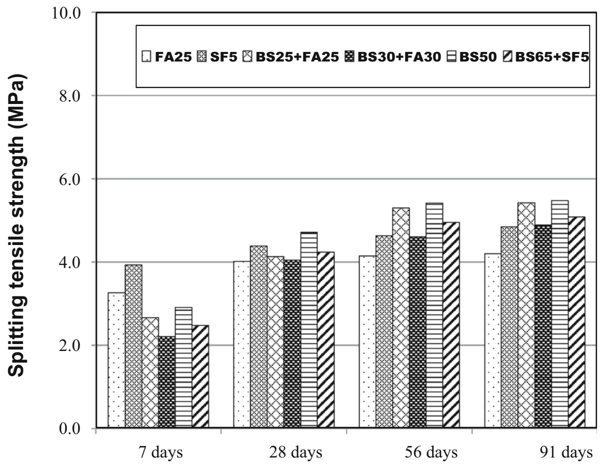
The average values of 7, 28, 56 and 91 days splitting tensile strengths for Group II series were ranged with 2.2–3.9 MPa, 4.0–4.7 MPa, 4.1–5.4 MPa, 4.2–5.5 MPa, respectively. The ratio of tensile strength at 7 days to strength at 28, 56 and 91 days were ranged with 0.55–0.87, 0.48–0.85, 0.45–0.81, respectively. The ratio of tensile strength of SF5 specimens were higher than that of other specimens, while BS30 + FA30 specimens were lower than that of other specimens.

Splitting tensile strength of SF5 specimens for Group I and II were higher than that of other specimens at 7 and 28 days. However, 57 and 91 days splitting tensile strength of BS50 specimens were higher than those of SF5. Even though compressive strength of SF5 specimens were higher than those of other specimens, the splitting tensile strength showed different trends.

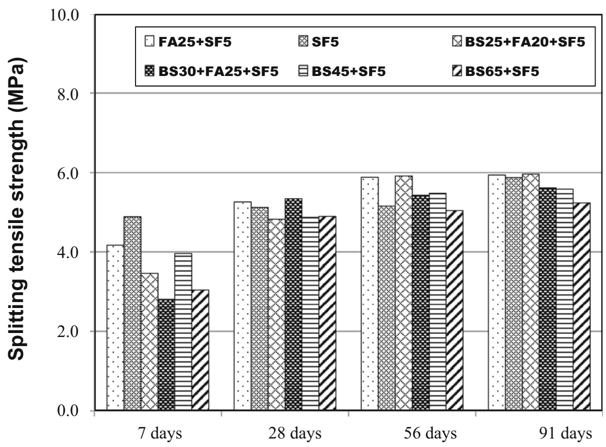
In addition, the average values of 7, 28, 56 and 91 days splitting tensile strengths for Group III series were ranged with 2.8–4.9 MPa, 4.8–5.3 MPa, 5.0–5.9 MPa, 5.2–6.0 MPa, respectively. The ratio of tensile strength at 7 days to strength at 28, 56 and 91 days were ranged with 0.53–0.96, 0.52–0.94, 0.50–0.83, respectively. The ratio of tensile strength of SF5 specimens were higher than that of other specimens, while BS30 + FA25 + SF5 specimens were lower than that of other specimens.



(a) Group I

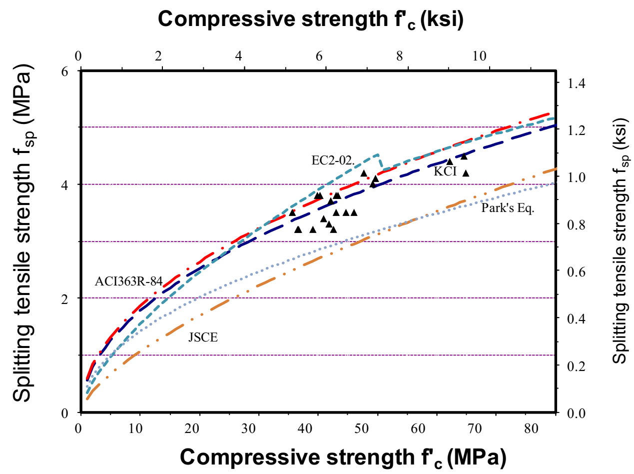


(b) Group II

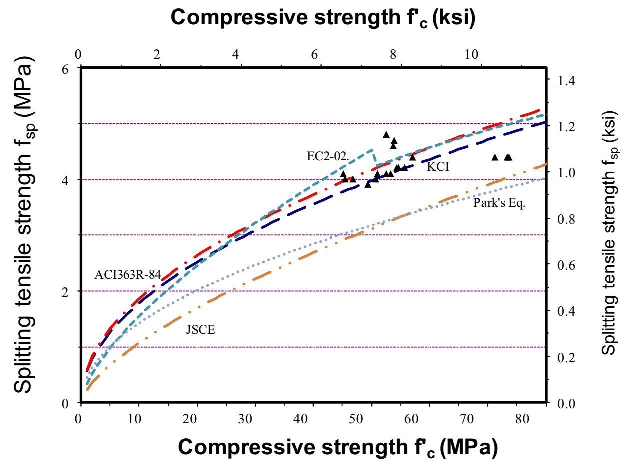


(c) Group III

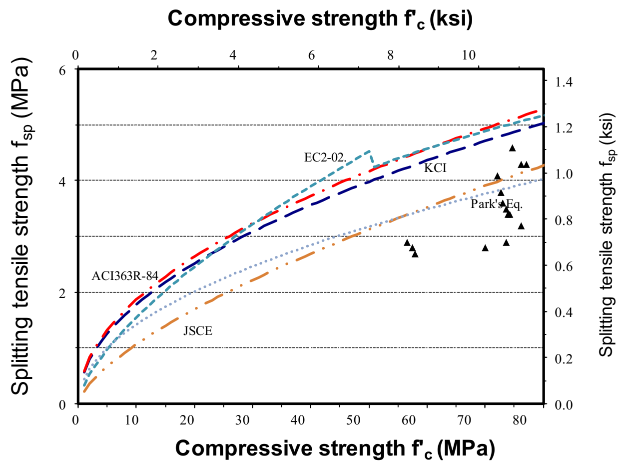
Fig. 3 Splitting tensile strength.



(a) Group I



(b) Group II



(c) Group III

Fig. 4 Compressive strength versus splitting tensile strength.

4.5 The Relationship Between Compressive Strength and Splitting Tensile Strength

The splitting tensile strength generally increases with the compressive strength. The following equation is recommended by KCI Code for prediction of the splitting tensile strength of normal-weight concrete.

(1) KCI Code

In Korea, KCI Code (2011) proposed a simple equation to predict the relationship between compressive strength and splitting tensile strength

$$f_{sp} = 0.563\sqrt{f_{ck}}(\text{MPa}) \tag{5}$$

(2) ACI 363R-84 Code

Table 7 Splitting tensile strength test results.

Specimen name		Splitting tensile strength (Unit: MPa)				Ratio of tensile strength at 7 days to strength at 28, 56 and 91 days		
		7 days	28 days	56 days	91 days	7/28	7/56	7/91
Group I	FA15	3.4	3.5	3.9	4.0	0.97	0.87	0.85
	FA25	2.6	3.2	3.6	3.6	0.81	0.72	0.72
	SF5	3.7	4.3	4.3	4.4	0.86	0.86	0.84
	BS25 + FA25	2.2	3.8	4.4	4.5	0.58	0.50	0.48
	BS30 + FA30	1.5	3.3	3.9	4.5	0.45	0.38	0.33
	BS50	2.6	4.1	4.9	5.0	0.63	0.53	0.52
	BS65 + SF5	2.1	3.7	4.3	4.8	0.57	0.49	0.44
Group II	FA25	3.3	4.0	4.1	4.2	0.83	0.80	0.79
	SF5	3.9	4.4	4.6	4.8	0.87	0.85	0.81
	BS25 + FA25	2.7	4.1	5.3	5.4	0.67	0.51	0.50
	BS30 + FA30	2.2	4.0	4.6	4.9	0.55	0.48	0.45
	BS50	2.9	4.7	5.4	5.5	0.62	0.54	0.53
	BS65 + SF5	2.5	4.2	5.0	5.1	0.60	0.50	0.49
Group III	FA25 + SF5	4.2	5.3	5.9	5.9	0.79	0.71	0.71
	SF5	4.9	5.1	5.2	5.9	0.96	0.94	0.83
	BS25 + FA20 + SF5	3.5	4.8	5.9	6.0	0.73	0.66	0.58
	BS30 + FA25 + SF5	2.8	5.3	5.4	5.6	0.53	0.52	0.50
	BS45 + SF5	4.0	4.9	5.5	5.6	0.82	0.73	0.71
	BS65 + SF5	3.0	4.9	5.0	5.2	0.61	0.60	0.58

In America, ACI 363R-84 Code (ACI Committee 363 1984) proposed a simple equation to predict the relationship between compressive strength and splitting tensile strength based on a study by Carrasquillo et al. (1981).

$$f_{sp} = 0.59\sqrt{f_{ck}}(\text{MPa}) \quad 21\,\text{MPa} < f_c' < 83\,\text{MPa} \tag{6}$$

(3) EC2-02 Code
In Europe, EC2-02 Code (European committee 2012) recommended the following equation for the relationship between compressive strength and splitting tensile strength
(a) $f_{ck} \le 50$ MPa

$$f_{sp} = \frac{1}{3}(f_{ck})^{2/3}(\text{MPa}) \tag{7}$$

(b) $f_{ck} > 50$ MPa

$$f_{sp} = 2.35\ln\left(1 + \frac{f_{cm}}{10}\right)(\text{MPa}) \tag{8}$$

(4) JSCE Code
In Japan, JSCE Code (Japan Society of Civil Engineers 2008) recommended the following equation for the relationship between compressive strength and splitting tensile strength

$$f_{sp} = 0.23(f_{ck})^{2/3}(\text{MPa}) \tag{9}$$

Figure 4 shows the relationship between the compressive strength and the splitting tensile strength of the concrete. The splitting tensile strength can be related to compressive strength, water/binder (W/B) ratio and concrete age. Predicted values by ACI 363R-84, EC 2-02 and KCI Code slightly overestimated observed value, as shown in Fig. 4. Predicted values by Park's Eq. (4) and JSCE Code show good agreement with observed value in Group I. In addition, predicted values by KCI show good agreement with observed value in Group I and Group II. Predicted values by ACI 363R-84, EC 2-20, KCI and JSCE Code overestimated observed values in Group III.

4.6 Modulus of Elasticity

The modulus of elasticity of concrete is one of the most important factors to determine the strain distributions and deformation. The modulus of elasticity of concrete, E_c, is an indicator of the resistance to deformation of concrete, which is subjected to compressive load. The modulus of elasticity can be estimated by Equations listed in Table 8. The modulus of elasticity of energy efficient concrete with binary and ternary admixture at different curing ages are listed in Table 9. As listed in Table 9, the average values of 7, 28, 56 and 91 days modulus of elasticities for Group I were ranged with 13.8–27.8 MPa, 21.7–30.2 MPa, 21.0–33.8 MPa,

Table 8 Estimating equations of the different models.

Mechanical property	Code	Estimating model
Modulus of elasticity	ACI 318-11	$E_c = 4733\sqrt{f'_c}$
	CEB-FIP, KCI-11	$E_c = 8500 \cdot \sqrt{f'_c + 8}$
	EN 1991	$E_c = 22(f_{cm}/10)^{0.3}$
	NZS 3101:1995	$E_C = 3320\sqrt{f'_c} + 6900$
	CSA A23.3-04	$E_C = 4500\sqrt{f'_c}$

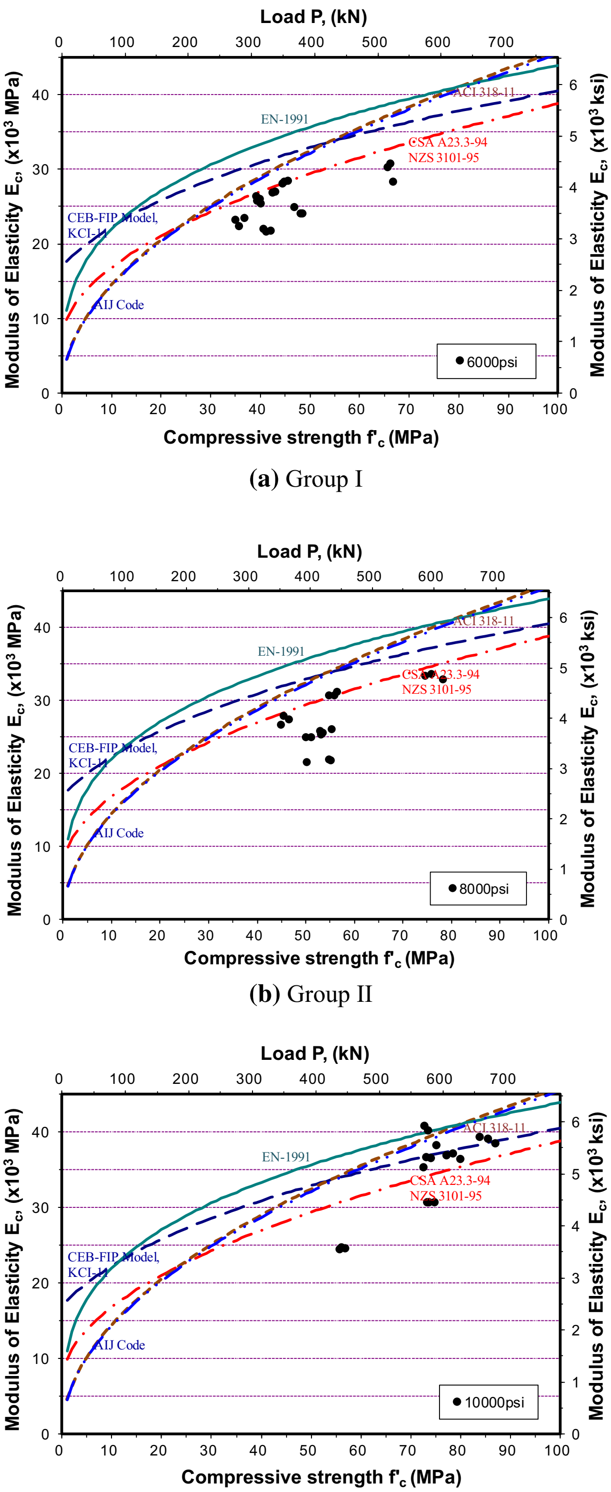
* At the time of testing.
E_c: Modulus of elasticity of concrete at 28 days.
f_c': Compressive strength of concrete at 28 days.
f_{cm}: Mean compressive strength of concrete at 28 days.

Table 9 Modulus of elasticity.

Specimen name		Modulus of elasticity				Ratio of modulus of elasticity at 7 days to observed values at 28, 56 and 91 days		
		7 days	28 days	56 days	91 days	7/28	7/56	7/91
Group I	FA15	24.9	26.3	27.1	28.0	0.95	0.92	0.89
	FA25	23.6	25.5	29.8	30.8	0.93	0.79	0.77
	SF5	27.8	30.2	33.8	34.2	0.92	0.82	0.81
	BS25 + FA25	20.4	26.8	21.0	32.2	0.76	0.97	0.63
	BS30 + FA30	13.8	22.9	25.1	26.9	0.60	0.55	0.51
	BS50	21.9	24.2	29.7	31.2	0.90	0.74	0.70
	BS65 + SF5	19.6	21.7	26.0	28.1	0.90	0.75	0.70
Group II	FA25	25.9	27.1	30.9	32.4	0.96	0.84	0.80
	SF5	33.0	33.4	35.7	36.0	0.99	0.92	0.92
	BS25 + FA25	20.7	31.0	32.3	32.6	0.67	0.64	0.63
	BS30 + FA30	18.0	24.1	28.8	30.2	0.75	0.63	0.60
	BS50	19.0	25.8	30.8	32.0	0.74	0.62	0.59
	BS65 + SF5	20.1	21.7	28.3	30.2	0.93	0.71	0.67
Group III	FA25 + SF5	27.9	30.2	31.2	33.2	0.92	0.89	0.84
	SF5	33.3	35.9	35.9	36.7	0.93	0.93	0.91
	BS25 + FA20 + SF5	26.5	34.6	34.7	35.0	0.77	0.76	0.76
	BS30 + FA25 + SF5	18.7	24.6	31.5	33.2	0.76	0.59	0.56
	BS45 + SF5	25.1	30.8	33.6	35.2	0.81	0.75	0.71
	BS65 + SF5	21.4	30.7	34.3	34.6	0.70	0.62	0.62

26.9–34.2 MPa, respectively. The ratio of modulus of elasticity at 7 days to those at 28, 56 and 91 days were ranged with 0.60–0.95, 0.55–0.97, 0.51–0.89, respectively.

The average values of 7, 28, 56 and 91 days modulus of elasticities for Group II were ranged with 18.0–33.0 MPa, 21.7–33.4 MPa, 28.3–35.7 MPa, 30.2–36.0 MPa, respectively.

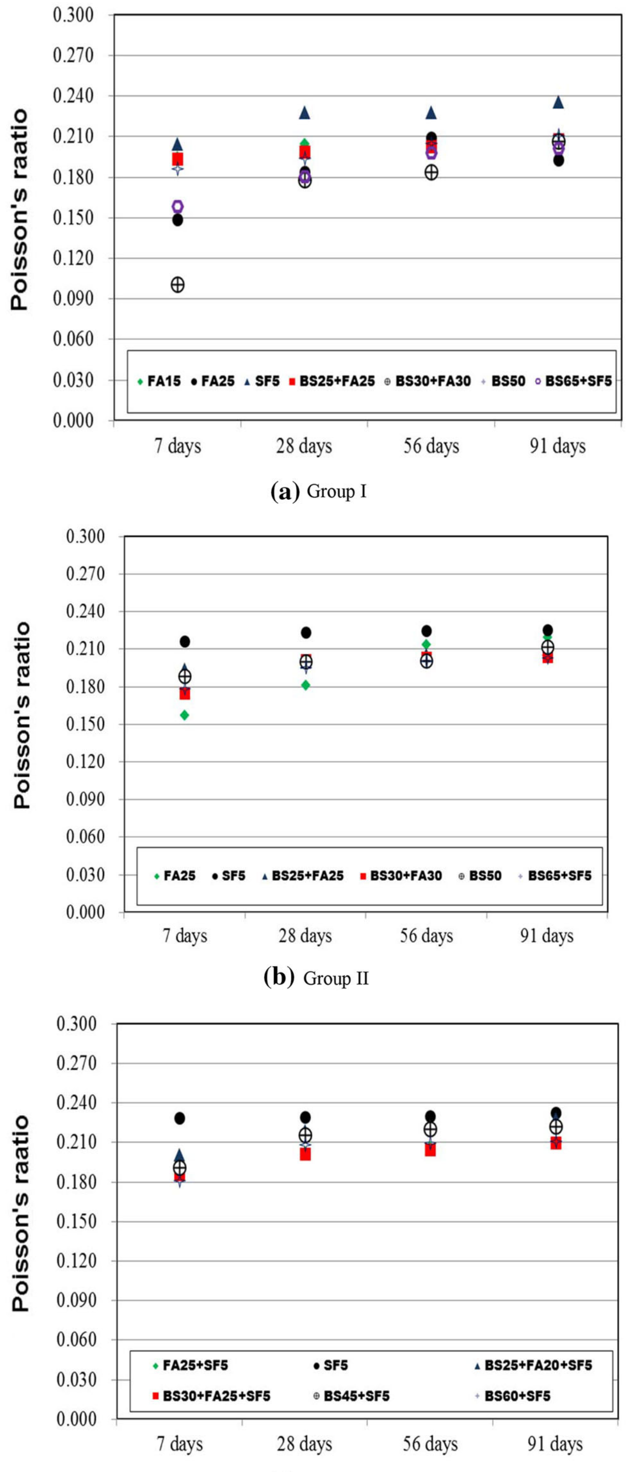


(a) Group I

(b) Group II

(c) Group III

Fig. 5 Modulus of elasticity.



(a) Group I

(b) Group II

(c) Group III

Fig. 6 Poisson's ratio.

The ratio of modulus of elasticity at 7 days to those at 28, 56 and 91 days were ranged with 0.67–0.99, 0.62–0.92, 0.59–0.92, respectively.

The average values of 7, 28, 56, and 91 days modulus of elasticities for Group III were ranged with 18.7–33.3 MPa, 24.6–35.9 MPa, 31.2–35.9 MPa, 33.2–36.7 MPa, respectively. The ratio of modulus of elasticity at 7 days to those at 28, 56 and 91 days were ranged with 0.70–0.93, 0.59–0.93, 0.56–0.91, respectively. In particular, the modulus of elasticity of SF5 specimens for all the Group I, II and III were higher than that of other specimens. This trend is similar to that of compressive strength.

The relationship between compressive strength and modulus of elasticity is shown in Fig. 5. Predicted values by ACI 318-11 (ACI Committee 2011), CEB-FIP Model (CEB-FIP 1993) and KCI Code, EN 1991 Code (EN 1991 1991) NZS 3101 (New Zealand Standard 1995), CSA A 23.3 (CSA Technical Committee 2004) overestimated observed values

Table 10 Poisson's ratio.

Specimen name		Poisson's ratio			
		7 days	28 days	56 days	91 days
Group I	FA15	0.195	0.205	0.209	0.209
	FA25	0.149	0.184	0.209	0.193
	SF5	0.205	0.228	0.228	0.236
	BS25 + FA25	0.194	0.199	0.203	0.208
	BS30 + FA30	0.101	0.178	0.184	0.207
	BS50	0.187	0.195	0.206	0.211
	BS65 + SF5	0.159	0.181	0.199	0.201
Group II	FA25	0.157	0.181	0.214	0.220
	SF5	0.216	0.224	0.225	0.226
	BS25 + FA25	0.195	0.200	0.206	0.210
	BS30 + FA30	0.175	0.202	0.204	0.204
	BS50	0.188	0.200	0.201	0.212
	BS65 + SF5	0.179	0.195	0.201	0.204
Group III	FA25 + SF5	0.195	0.203	0.207	0.220
	SF5	0.229	0.230	0.230	0.233
	BS25 + FA20 + SF5	0.201	0.219	0.222	0.228
	BS30 + FA25 + SF5	0.186	0.202	0.205	0.210
	BS45 + SF5	0.191	0.216	0.220	0.222
	BS65 + SF5	0.181	0.209	0.210	0.211

in Group I and II. However, predicted values by CEB-FIP Model and KCI Code show good agreement with observed value in Group III.

4.7 Poisson's Ratio

The Poisson ratio is a basic factor in analyzing, designing and important attribute of the mechanical response of any materials. Poisson's ratio is defined as the ratio of the transverse extension strain to the longitudinal contraction strain in compression. The Poisson's ratios are listed in Table 10. Tests were performed on specimens with strain gauge units and tensile strain gauge units. Poisson's ratio in this study were ranged from 0.101 to 0.236. This values are slightly larger than those of normal concrete. As it can be seen from Fig. 6, the Poisson's ratio of SF5 specimens were larger than those of other specimens. This trend is similar to that of compressive strength. This is attributed to the fact that silica fume particles are very small, compared with fly ash and blast furnace slag particles. The ultra fine silica fume particles enter the relatively coarse cement inter-particle space. Thus components fineness was effected by particle size of silica fume.

5. Conclusions

The following conclusions were derived from the experimental results of mechanical properties of EEC with binary and ternary admixture, such as fly-ash, blast furnace slag and silica fume.

(1) The compressive strengths, splitting tensile strengths, modulus of elasticities and Poisson's ratios of Specimen SF5 for Group I, II and III showed higher values. This is attributed to the fact that silica fume particles are very small, compared with fly ash and blast furnace slag particles. The ultra fine silica fume particles enter the relatively coarse cement inter-particle space. Thus components fineness was effected by particle size of silica fume.
(2) The predicted values by DIN code and Park's Eq. (4) for relationship of compressive strengths between 7 and 28 days show good agreement with observed values in Group I and II. The predicted values by DIN are in a good agreement with measured values less than 50 MPa, Hassoun's Eq. (3) for 50–70 MPa and Park's Eq. (4) over 70 MPa in Group III.

(3) Predicted values by Park's Eq. (4) and JSCE Code for relationship between compressive strength and splitting tensile strength days show good agreement with observed value in Group I. Predicted values by KCI show good agreement with observed values in Group I and Group II. In addition, predicted values by ACI 363R-84, EC 2-20, KCI and JSCE Code overestimated observed values in Group III.
(4) The predicted values by ACI 318-11, CEB-FIP Model, EN-1991, NZS 3101, CSA A 23.3 and KCI Code to estimate modulus of elasticity overestimated observed values in Group I and II. However, predicted values by CEB-FIP Model and KCI Code show good agreement with observed value in Group III.
(5) The Poisson's ratios in this study were ranged from 0.101 to 0.236. This values are slightly larger than those of normal concrete. In particular, the Poisson's ratio of SF5 specimens were larger than those of other specimens.

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