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STRENGTH PROPERTIES OF DURABLE CONCRETE MADE WITH VARIOUS ALTERNATIVE CEMENTITIOUS MATERIALS

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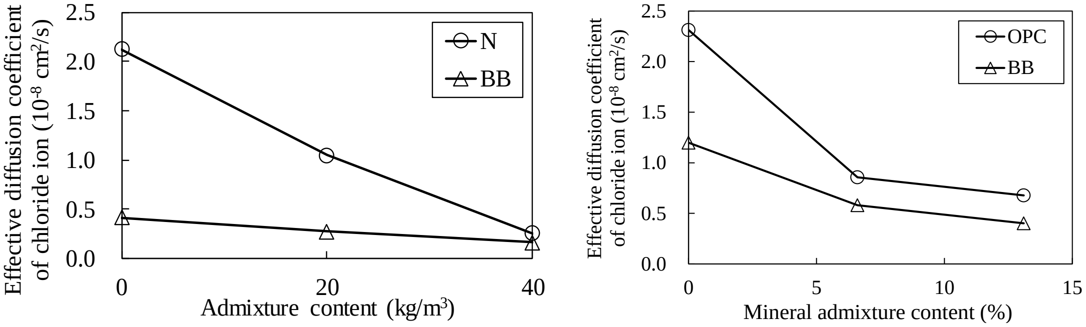
Many researchers investigated various concrete made with the cementitious materials, hence the effects of various admixture are well known. Most researches focused on an alternative cementitious material, tested concrete properties by varying the cement-replacement ratio. The optimum cement-replacement ratio may be different by each admixture. The present study examined the strength properties of concrete incorporating various admixtures. The cementitious materials tested in this study were fly-ash, blast furnace slag powder, silica-fume, limestone powder, and an artificial admixture which has high resistance to chloride attack. First, fundamental properties of the concrete incorporating the admixture were summarized referring to previous durability tests. Second, the strength properties of concrete made with some cement-replacement ratios by the cementitious materials were examined. In addition, alternative cement efficiency factors (***k***) of each cementitious material were estimated.

Keywords: Admixture, Durability, Alternative cement efficiency factor, Chloride resistance admixture.

1 INTRODUCTION

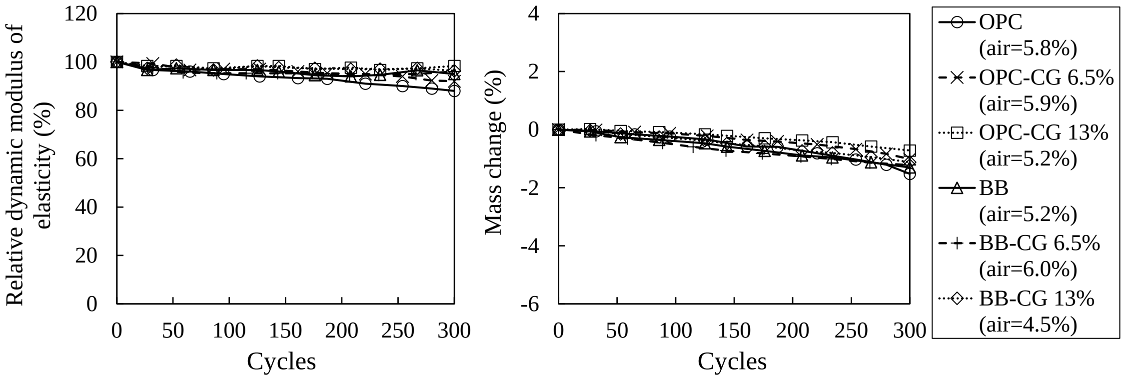
Alternative cementitious materials such as fly-ash and blast-furnace slag are often used in concrete to improve strength and durability in addition to the reduction of CO_2 emission from cement production. Many researchers investigated various concrete made with the cementitious materials, hence the effects of various admixture on strength and durability are well known. Most researches focused on an alternative cementitious material, tested concrete properties by varying the cement-replacement ratio. The optimum cement-replacement ratio may be different by each admixture. Hence it is not easy to compare the effect of admixture under a certain test condition. To compare and quantify the effect of the admixture, the present study examined strength properties and durability of concrete incorporating various admixtures. The cementitious materials tested in this study were fly-ash, blast furnace slag powder, silica-fume, limestone powder. In addition, the study tested on an artificial admixture developed in recent years. The admixture has unique properties which are high-resistance for chloride attack and high-early-strength (Chloroguard 2018).

Yamato *et al.* (2017, 2018) conducted various durability tests using artificial admixture. They examined chloride penetration resistance, carbonation, sulfate resistance, and freeze-thaw resistance of the concrete incorporating the admixture. Their test results confirmed that the durability properties are comparable with or higher than that of conventional concrete without the admixture. For example, effective diffusion coefficients of steam-cured and water-cured concrete incorporating the admixture are presented in Figure 1 (a) (b), respectively. In addition, Figure 2 shows the relative dynamic moduli of elasticity and mass-change of the water-cured concrete subjected to freeze-thaw cycles. In these graphs, N or OPC was used for concrete using ordinary Portland cement, and BB was used for concrete made with blast-furnace slag cement. As well, it is well known that general concrete made with admixtures such as fly-ash, blast-furnace slag powder and silica-fume indicates excellent durability (Berry and Malhotra 1980, Özbay *et al*. 2016, Khan and Siddique 2011). The study focuses on strength properties of concrete containing such mineral admixtures which improve concrete durability and indicates fundamental properties for the designing of optimum mixture proportion of concrete made with admixture.



(a) steam-cured concrete (Yamato *et al*. 2017). (b) standard-cured concrete (Yamato *et al*. 2018).

Figure 1. Effective diffusion coefficients of concrete incorporating the developed admixture.



(a) Relative dynamic moduli of elasticity. (b) Mass change.

Figure 2. Freeze-thaw test of concrete incorporating the admixture (Yamato *et al*. 2018).

2 MATERIALS AND CONCRETE MIXTURE

2.1 Chloride Resistance Admixture

The chloride-resistance admixture (C) is a pozzolanic mineral powder incorporating SiO_2 and Al_2O_3, and it has a Brunauer–Emmett–Teller (BET) specific surface area of 13000 m^2/kg or higher. It was confirmed that the admixture contributes to improve concrete durability and strength development at an early age in the previous investigations (Yamato *et al.* 2017, Yamato *et al*. 2018, Yamato 2018). The fundamental properties of the admixture are given in Table 1. It is remarkable that the admixture (C) has higher Al_2O_3 than silica-fume (S). Further details of the admixture (C) cannot be released here because of a commercial contract with the manufacturer.

Table 1. Chloride resistance admixture.

	Density (kg/m^3)	**Fineness (m^2/kg)**	**SiO_2 (%)**	**Al_2O_3 (%)**	**Na_2O (%)**	**K_2O (%)**	**Cl^- (%)**
C	2360	13300	71.2	23.3	0.27	0.27	0.029
S	*2240*	*16900*	*94.0*	*0.26*	*0.21*	*0.28*	*0.014*

2.2 Materials

The materials are summarized in Table 2. Ordinary Portland cement defined in a Japanese Industrial Standard (JIS R 5210) was used. Fine and coarse aggregates are general aggregate in western Japan. Chemical admixtures given in Table 2 were used for suitable fresh properties.

Table 2. Materials used in the study.

Material	**Type**	**Property**
Water	Tap-water (W)	Density 1.00 g/cm^3
Cement	Ordinary Portland cement (OPC)	Density 3.16 g/cm^3, Blaine fineness 3280 cm^2/g
Admixture	Limestone powder (L)	Density 2.71 g/cm^3, Blaine fineness 3640 cm^2/g
	Fly-ash (F)	Class II (JIS A 6201), Density 2.22 g/cm^3, Blaine fineness 3530 cm^2/g
	Blast furnace slag powder (B)	Density 2.90 g/cm^3, Blaine fineness 4840 cm^2/g
	Silica-fume (S)	Density 2.21 g/cm^3
	Chloride resistance admixture (C)	Density 2.36 g/cm^3, BET fineness 13.3 m^2/g
Fine aggregate	Sea sand (S1)	Density 2.60 g/cm^3, FM 2.91, Size 5-0 mm
	Crashed stone sand (S2)	Density 2.60 g/cm^3, FM 2.90, Size 5-0 mm
Coarse aggregate	Crashed stone (G1)	Density 2.71 g/cm^3, Size 20-15 mm
	Crashed stone (G2)	Density 2.70 g/cm^3, Size 15-5 mm
Chemical admixture	Air-entraining and water reducing agent (WRA)	Lignin sulfonate, oxy-carboxylate, and poly-carboxylic acid-based compound
	Air-entraining and high-range water-reducing agent (HRWRA)	Poly-carboxylic acids-based compound
	Antifoaming agent (AFA)	Nonionic surfactant

2.3 Mixture Proportions of Concrete

Mixture proportions of tested concrete are summarized in Table 3. The water-cementitious material ratios (*w/cm*) were designed as 0.45, 0.55 and 0.65 for control mixtures and concrete containing the chloride resistance admixture (C). All admixtures tested herein were used as an alternative cementitious material for Portland cement. The cement-replacement ratios were 0.1, 0.2 and 0.4 by mass of cement. In the mixture I.D. of admixture concrete, the first number shows the water-cementitious material ratios (*w/cm*), the following letter presents the admixture and the last number shows the cement-replacement ratios. The mixed volume ratios of aggregate were S1: S2 = 0.4 : 0.6, and G1 :G2 = 0.5 : 0.5, respectively.

Table 3. Mixture proportions and fresh properties.

Mixture I.D.	Unit weight (kg/m^3)							Chemical admixture (***cm***×%)		Slump -cm-	Air -%-
	W	OPC	Admixture	S1	S2	G1	G2				
Control-45	162	360	0	581	249	488	486	1.00 [a]	0.0015 [c]	14.0	3.4
Control-55	162	295	0	618	265	488	486	0.40 [a]	0.0020 [c]	14.0	4.5
Control-65	162	250	0	644	276	488	486	0.80 [a]	0.0018 [c]	15.0	4.5
45-C10	162	324	36	574	246	488	486	1.00 [b]	0.0026 [c]	11.0	4.7
45-C20	162	288	72	567	243	488	486	1.05 [b]	0.0009 [c]	9.0	5.0
45-C40	162	216	144	552	237	488	486	1.70 [b]	0.0090 [d]	14.0	4.7
55-C10	162	266	30	312	262	488	486	1.10 [a]	0.0014 [c]	12.0	4.2
55-C20	162	236	59	607	260	488	486	1.40 [a]	0.0023 [c]	12.5	5.8
55-C40	162	177	118	595	255	488	486	1.75 [b]	0.0002 [c]	11.0	5.7
65-C10	162	225	25	639	274	488	486	1.00 [a]	0.0	13.5	5.4
65-C20	162	200	50	634	272	488	486	1.60 [a]	0.0	11.0	4.7
65-C40	162	150	100	624	268	488	486	1.30 [b]	0.0125 [d]	9.0	5.5
55-F10	162	266	30	610	261	488	486	0.70 [a]	0.0112 [c]	14.0	4.5
55-F20	162	236	59	604	259	488	486	0.40 [a]	0.0090 [c]	19.0	5.9
55-F40	162	177	118	589	253	488	486	0.40 [a]	0.0210 [c]	16.5	4.2
55-B10	162	266	30	616	264	488	486	0.55 [a]	0.0019 [c]	14.0	4.9
55-B20	162	236	59	615	264	488	486	0.50 [a]	0.0021 [c]	16.0	4.7
55-B40	162	177	118	612	262	488	486	0.45 [a]	0.0012 [c]	12.0	4.6
55-L10	162	266	30	615	263	488	486	0.50 [a]	0.0027 [c]	12.5	4.3
55-L20	162	236	59	612	262	488	486	0.40 [a]	0.0018 [c]	17.5	5.2
55-L40	162	177	118	607	260	488	486	0.40 [a]	0.0018 [c]	11.0	4.0
55-S10	162	266	30	610	261	488	486	1.40 [a]	0.0	13.5	5.0
55-S20	162	236	59	603	259	488	486	1.50 [a]	0.0125 [d]	9.5	4.7
55-S40	162	177	118	589	252	488	486	1.80 [b]	0.0275 [d]	9.0	5.0

[a] WRA, [b] HRWRA, [c] AEA, [d] AFA

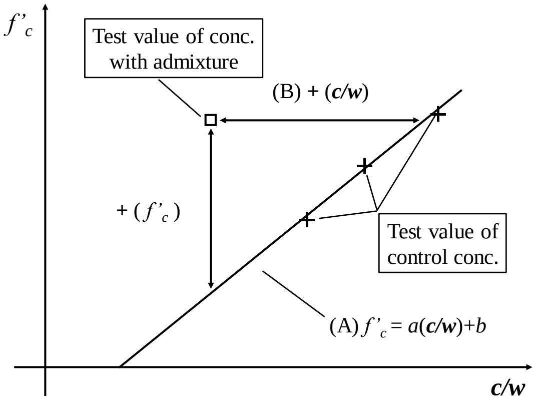
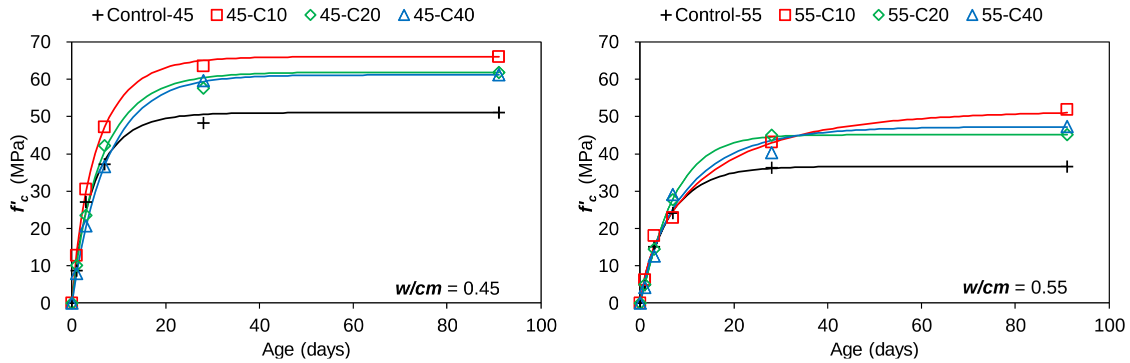


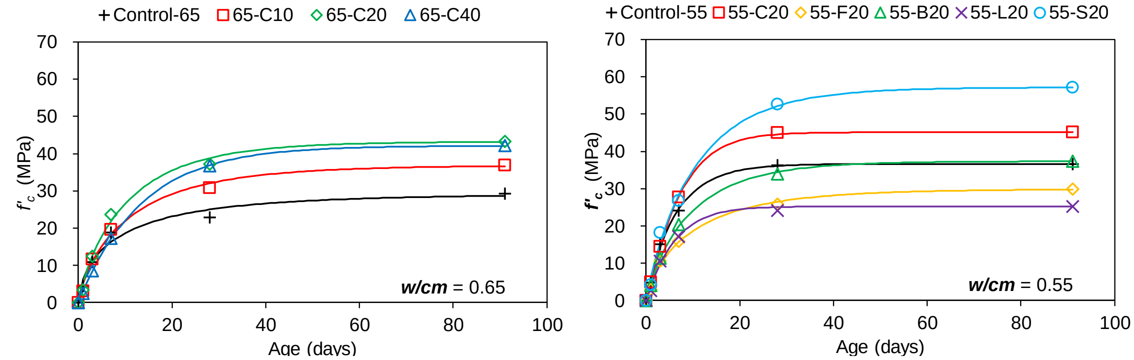
Figure 3. Alternative cement efficiency factor (k) based on $f'_c - c/w$.

2.4 Alternative Cement Efficiency Factor (*k*) Based on Compressive Strength

To determine the effectiveness of each alternative cementitious material for Portland cement, the study evaluated the cement efficiency factor based on the compressive strength test. The factor can be calculated by applying the compressive strength of admixture concrete into a compressive strength (f'_c) – cement-water ratio (c/w) relation of the reference concrete (control mixtures). Figure 3 illustrates the estimation method for the cement efficiency factor (k).



(a) *w/cm* = 0.45.
(b) *w/cm* = 0.55.



(c) *w/cm* = 0.65.
(d) cement-replacement of 20 %.

Figure 4. Compressive strength.

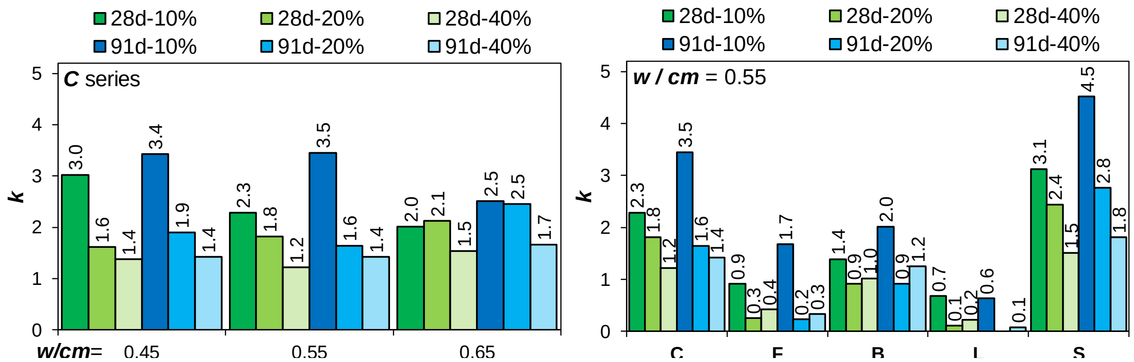
3 RESULTS AND DISCUSSION

3.1 Compressive Strength

Compressive strength test was conducted in accordance with the Japanese standard (JIS A 1108). Three cylindrical specimens, 100 x 200 mm, were used at each test age. Figure 4 (a) (b) (c) presents compressive strengths of the chloride resistance admixture (C) concrete of *w/cm* = 0.45, 0.55, 0.65, respectively. These test results confirm that the chloride resistance admixture (C) concrete achieved higher strength than the control concrete at all test ages. It is noteworthy that the concrete has higher early-age strength through the admixture is a kind of pozzolanic powder material. In addition, Figure 4 (d) shows compressive strengths of various admixture concrete made with the cement-replacement ratio of 20 %. The result shows that the chloride resistance admixture (C) concrete indicated always higher strength than fly-ash (F), blast-furnace slag powder (B), limestone powder (L) concretes. The concrete indicated high early-age strength as well as silica fume (S) concrete. The strength property assures that chloride resistance admixture (C) is a useful material to improve concrete quality in addition to excellent durability.

3.2 Alternative Cement Efficiency Factor (*k*)

Figure 5 (a) (b) summarizes the alternative cement efficiency factors (*k*) of the chloride resistance admixture and other admixtures, respectively. Regardless of the water-cementitious ratios and the cement-replacement ratio, the factor (*k*) of the chloride resistance admixture (C) achieved 1.0 or higher as well as silica fume (S). The result implies that strength contribution of these admixtures (C, S) was higher than Portland cement.



(a) Chloride resistance admixture.

(b) Various admixture (*w/cm* = 0.55).

Figure 5. Alternative cement efficiency factor (***k***).

4 SUMMARY

This paper reported the effect of various admixtures on strength properties in addition to durability of concrete based on the previous investigations. It can be concluded that the chloride resistance admixture (C) is an effective material to improve strength and durability of concrete.

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