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Experimental Study on Effects of Type and Replacement Ratio of Fly Ash on Strength and Durability of Concrete

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Abstract: This paper presents the test results of a series of experimental studies on the effects of type and replacement ratio of fly ash on strength and durability of concrete. 3 types of fly ashes are used in this research, the specific surface area of which are 5070 cm^2/g, 3760 cm^2/g and 1970 cm^2/g, respectively. They satisfy the requirement of Type-1, Type-2 and Type-4 fly ashes in Japanese Industrial Standard. Ordinary Portland cement, river sand, crushed sandstone, water reducer and air entraining agent are used as well. The results indicate that drying shrinkage of concrete is reduced when cement is partially replaced by fly ash. Comparatively, Type-2 fly ash's addition leads to a more effective drying shrinkage reduction, and those with replacement ratios result in larger dry shrinkage reduction. Carbonation increases with the increase of replacement ratio of fly ash, and concrete with Type-1 fly ash has higher carbonation than those with Type-2 and Type-4 fly ashes. The carbonation rate is found to be linear with water cement ratio regardless of replacement ratio of fly ash. Durability factor decreases with the replacement ratio of fly ash after 300 freezing and thawing cycles. Also, durability factor of concrete containing Type-1 and Type-2 fly ashes with replacement ratio of 25% to 55% is higher than 80%. However, those with Type-4 fly ash show lower durability factor after 300 cycles. Concretes with 70% replacement of fly ash are not durable in spite of the type of fly ash or specific surface area.

Keywords: Carbonation, Compressive strength, Drying shrinkage, Fly ash, Freezing and thawing, Replacement ratio.

1. INTRODUCTION

Fly ash in Japan has been rapidly increasing with the increase of coal-fired power stations. The annual production of fly ash is 10 million tons [1]. Though approximately 80% of fly ashes are utilized mainly in cement industries, only 2.4% of fly ash is used as admixture material for concrete, including composite cement and concrete. In addition, more and more ground granulated blast-furnace slag is used in concrete partially replacing cement for the purpose of reducing material costs and avoiding cracks in mass concrete. Furthermore, the addition of such kinds of supplementary cementitious materials can reduce the risk of alkali-aggregate reaction, and reduces CO_2 emission. The obstacles preventing fly ash utilization in Japan are that the permissible replacement ratio of fly ash is limited to 30% for structural concrete, and that only Type-1 and Type-2 fly ashes are usually specified, while JIS A 6201 *Japanese Industrial Standard for Fly Ash Used in Conrete* specifies Type-1, Type-2, Type-3, and Type-4 fly ashes. For instance, JIS R 5213 *Japanese Industrial Standard for Fly Ash Cements* requires that the portion of fly ash in the cementitious material is limited to 30% by mass. *Japanese Architectural Standard Specification JASS 5 for Reinforced Concrete Work* requires the permissible Portland cement replacement with Type-1 and Type-2 fly ash is limited to 30% by mass, and *JASS 5N for Reinforced Concrete Work at Nuclear Power Plants* requires that the cement replacement should not more than 20% by mass. Therefore, it is necessary to clarify the influence of type and replacement ratio of fly ash on the strength and durability of concrete in which cement is replaced by higher volume of fly ash, so as to expand the application field of fly ash.

At present, the utilization of fly ash in Japan is defined in Type-1 and Type-2 fly ashes, and the replacement ratio is limited to 30% for structural concrete. In order to expand the application range of fly ash in structural concrete, the Type-1, Type-2, and Type-4 fly ashes are taken as research object in this study, and the replacement ratio increases to 70%. Meanwhile, the effects of type and replacement ratio of fly ash on mixture proportions, fresh concrete properties, strength development, drying shrinkage, carbonation and freezing-thawing resistance of concrete are widely discussed.

2. SCOPE OF EXPERIMENT

5 mixtures of ordinary Portland cement (OPC) concrete, of which the water cement ratio is from 38% to 75%, are designed as reference specimen. 28 mixtures of fly ash concrete with the water binder ratio from 38% to 60% are used to test the compressive strength, drying shrinkage, carbonation and freezing and thawing resistance, where Portland

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cement is replaced by 3 types of fly ashes by ratios from 25% to 70%.

3. MATERIALS

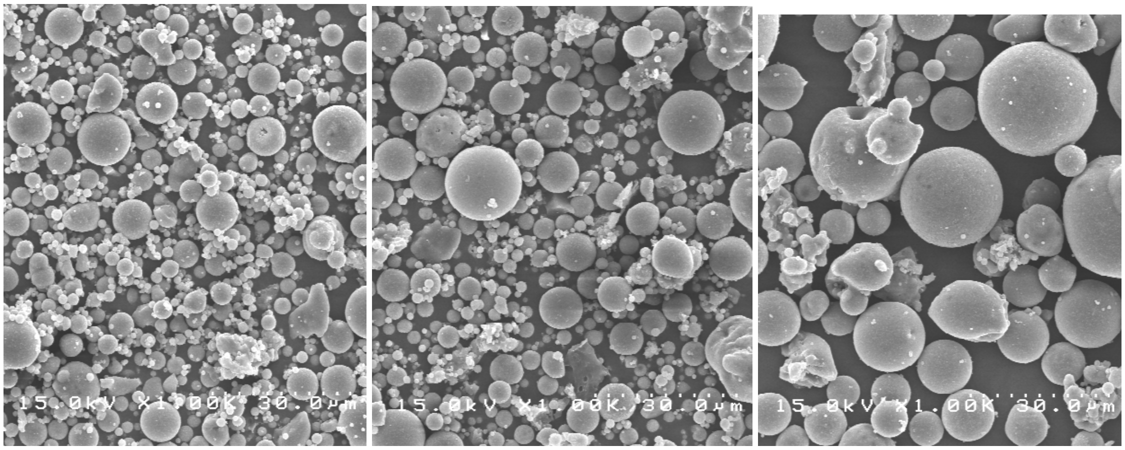
Type-1 fly ash (FA1), Type-2 fly ash (FA2) and Type-4 fly ash (FA4), from a coal-fired power plant are used. All the indexes satisfy the requirements of JIS A 6201 *Japanese Industrial Standard for Fly Ash Used in Conrete*. Chemical analysis and physical characteristics of fly ashes are shown in Table **1**. Scanning electron micrographs of fly ashes are shown in Fig. (**1**). The differences among 3 fly ashes are mainly in particle size. The specific surface area of FA1, FA2 and FA4 are 5070 cm^2/g, 3760 cm^2/g and 1970 cm^2/g, respectively.

Ordinary Portland cement with density of 3.16 g/cm^3, specific surface area of 3280 cm^2/g and 28 days compressive strength of 62.0 N/mm^2 is used. The coarse aggregate is a kind of crushed sandstone from Oume, and the fine aggregate is a kind of river sand from Oui-River. The physical properties of aggregates are shown in Table **2**. The water reducer used in this research is of lignosulphonic acid type, and the air-entraining agent of anionic surfactant is used in this research.

4. MIXTURE PROPORTIONS AND DOSAGE OF AE AGENT

Mixture proportions of concretes are shown in Table **3**. The target slump is 18.0 cm, and the target air content is 4.5%.

Water content of concrete containing FA1 and FA2 decreases with the increase of fly ash dosage, while water content of concrete increases with the addition of FA4. Air-



FA 1 FA 2 FA 4

Fig. (1). Scanning electron micrographs of fly ashes (1,500 times).

Table 1. Chemical Analysis and Physical Characteristics of Fly Ashes

	Chemical analysis							**Physical characteristics**			**Percent flow of mortar (%)**	**Strength activity of mortar (%)**	
	SiO_2 (%)	**SO_3 (%)**	**CaO (%)**	**MgO (%)**	**Ka_2O (%)**	**Na_2O (%)**	**Loss on Ignition (%)**	**Density (g/cm^3)**	**Fineness**			**28 days**	**91 days**
									Retained on 45µm sieve (%)	**Specific surface area (cm^2/g)**			
FA 1	60.0	0.2	1.2	1.8	0.7	0.0	0.9	2.39	0.1	5070	114	93	111
FA 2	59.9	0.2	1.3	0.6	0.7	0.0	0.9	2.29	7.1	3760	107	84	103
FA 4	57.4	0.2	1.6	0.5	0.7	0.0	1.7	2.15	12.5	1970	104	74	86

Table 2. Physical Properties of Aggregates

	Type of Aggregate	**Maximum Size (mm)**	**Density in Oven-Dry Condition (kg/m^3)**	**Absorption (%)**	**Bulk Density (kg/m^3)**	**Fineness Modulus**
Coase aggregate	Crushed Sandstone	20	2.70	0.51	1.58	6.69
Fine aggregate	River sand	2.5	2.61	1.08	1.81	2.87

Table 3. Mixture Proportion and Properties of Fresh and Hardened Concrete

	FA/ (C+FA) (%)	W/ (C+FA) (%)	W/C (%)	Mixture Proportion (kg/m^3)					Fresh Concrete		Compressive Strength (N/mm^2) (Moist cured)			
				W	C	FA	S	G	Slump (cm)	Air (%)	7	28	91	182d
OPC	0	-	43	178	414	-	762	971	17.5	5.0	39.9	48.8	56.3	57.9
		-	50	174	348	-	827		18.5	4.9	35.1	38.9	49.0	52.0
		-	60	170	283	-	892		17.5	4.6	25.6	30.5	38.6	38.5
		-	75	175	233	-	936	955	18.5	4.7	16.1	21.9	27.4	27.2
FA 1	25	43	57	176	307	102	743	971	17.5	4.7	28.8	43.1	56.6	62.8
		50	67	165	248	82	844		18.0	3.2	22.6	34.8	46.3	51.4
	40	43	72	174	239	159	751		17.0	4.4	21.0	33.5	45.0	49.8
		50	83	163	196	130	840		16.5	4.3	16.9	28.9	38.9	44.4
	55	43	96	167	175	214	770	955	18.0	4.0	11.3	19.3	26.2	32.3
		50	111	166	149	183	828		16.5	5.4	9.6	17.8	23.6	32.2
	70	43	143	168	115	269	765		19.0	5.0	4.7	9.5	14.4	22.5
		50	167	164	98	230	824		16.5	4.6	3.5	6.9	11.6	16.8
FA 2	25	43	57	165	288	96	791	971	18.0	4.3	31.2	37.9	54.8	60.8
		50	67	165	248	82	840		18.5	4.5	23.0	32.8	44.5	49.9
		60	80	161	201	67	907		17.0	4.8	15.9	24.6	34.7	39.6
	40	38	63	170	268	179	698		19.0	4.7	28.0	39.2	53.9	58.2
		43	72	163	227	152	782		18.0	4.4	21.3	31.7	44.3	50.9
		50	83	165	198	132	824		18.0	4.4	15.4	26.0	36.4	41.0
	55	38	84	167	198	242	708	955	19.0	4.9	17.3	27.2	38.4	43.3
		43	96	163	171	208	780		19.0	5.1	12.6	21.3	31.6	42.8
		50	111	167	150	184	815		18.0	4.8	9.3	16.4	25.5	31.5
	70	38	127	177	140	326	633		19.0	4.7	9.2	15.0	22.7	31.8
		43	143	160	112	260	777		18.5	5.4	6.0	9.6	17.3	26.6
		50	167	158	95	221	842		19.0	4.9	3.2	5.6	13.0	20.8
FA 4	25	43	57	176	307	102	731	971	18.5	4.4	31.1	41.0	53.6	57.6
		50	67	172	258	86	802		18.0	3.9	21.9	31.0	40.1	44.2
	40	43	72	180	251	167	687		18.5	5.0	20.8	29.9	40.0	46.0
		50	83	174	209	139	773		18.0	4.6	15.1	22.6	32.6	39.0
	55	43	96	184	195	238	647	955	19.0	5.1	11.2	16.4	26.1	31.8
		50	111	175	158	193	763		18.0	5.3	8.7	14.0	21.3	27.0
	70	43	143	198	138	322	559		18.5	4.7	5.2	9.4	16.4	22.7
		50	167	176	106	246	738		16.5	5.3	3.0	5.4	10.9	18.4

entraining agent dosage increases linearly with the fly ash replacement ratio, and that of FA1 is higher than that of FA2 and FA4, which is due to adsorption of air-entraining agent to particles of fly ash.

5. EXPERMENTAL PROCEDURES

5.1. Fabrication and Curing of Test Specimens

Cylinders, 100 mm in diameter and 200 mm in height, for compression tests are cast in metal moulds in 3 layers by

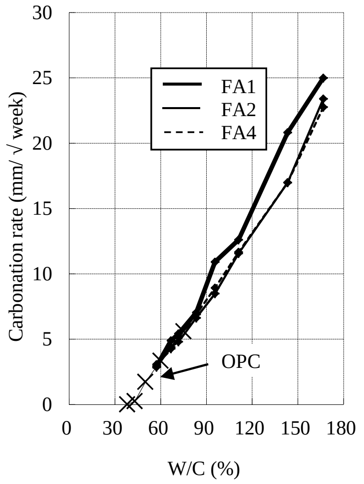


Fig. (11). Relationship between water cement ratio and carbonation rate

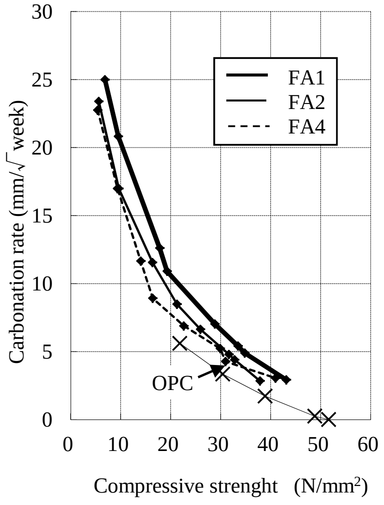


Fig. (12). Relationship between compressive strength at 4 weeks and carbonation rate

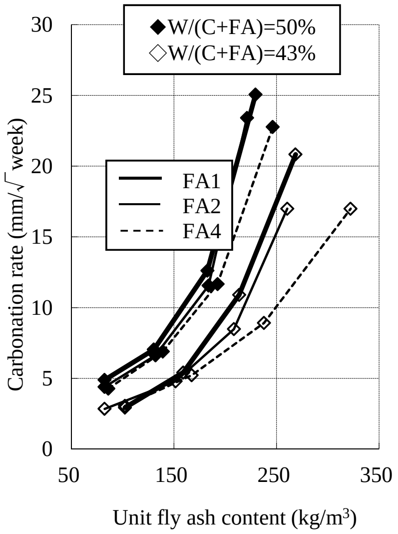


Fig. (13). Relationship between fly ash contentt and carbonation rate

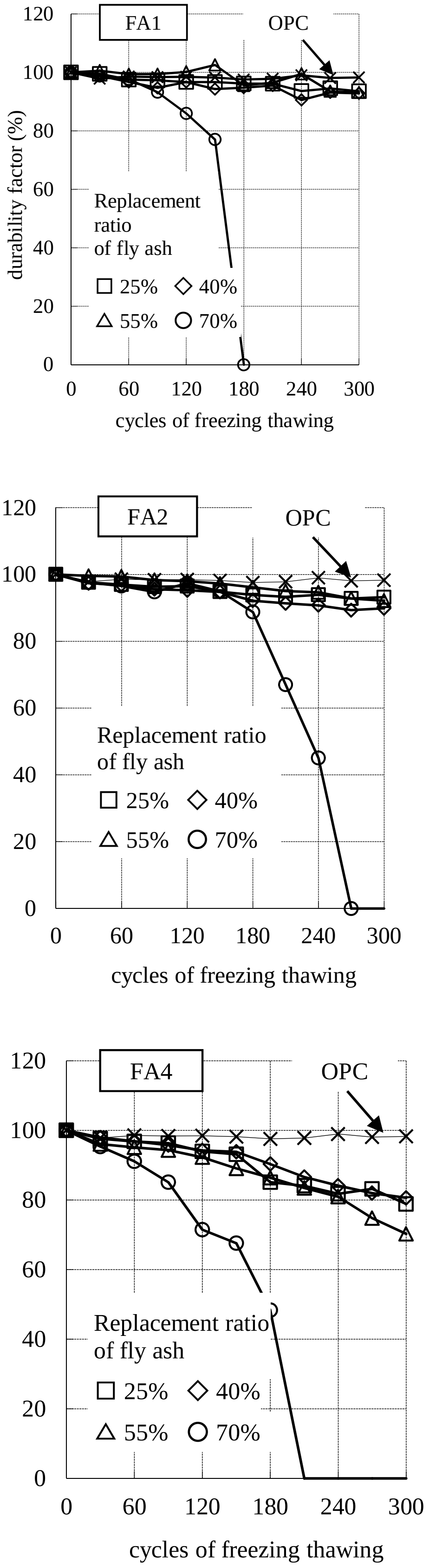


Fig. (14). Durability factor of concrete containing OPC, FA1, FA2 and FA4

(2) Drying shrinkage of concrete with FA1 and FA2 is smaller than OPC concrete and concrete with FA4, and a higher replacement ratio of fly ash lead to lower drying shrinkage.

(3) Concrete containing fly ash is more prone to be carbonated. A higher replacement ratio or higher content of fly ash in concrete leads to a higher carbonation rate. The increase in carbonation rate with the fly ash replacement may be attribute to the reduction of $Ca(OH)_2$ formation caused by reduction of Portland cement and consumption of $Ca(OH)_2$ in pozzolanic reaction of fly ash.

(4) Air-entraining concrete containing FA1 and FA2 fly ash replacing cement from 25% to 55% has better freezing and thawing resistance. Concrete with Fly ash replacing 70% cement is much less durable.

CONFLICT OF INTEREST

The author(s) confirm that this article content has no conflicts of interest.

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