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Properties of concrete using high C_3S cement with ground granulated blast-furnace slag

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HIGHLIGHTS

- Samples of cement clinker with high C_3S contents ranging from 59% to 71% were produced with a commercial plant.
- Effects of mineral composition of clinker on properties of blast-furnace slag cement concrete were investigated.
- Early-age compressive strength of concrete with blast-furnace slag cement was improved by increasing C_3S content up to 69%.

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ABSTRACT

Blast-furnace slag (BFS) cement has been often used for civil engineering structures, but it has rarely been used for reinforced concrete buildings because of slow strength development. The purpose of this study is to propose BFS cement which can be widely used for concrete structures including reinforced concrete buildings. Some clinkers with high C_3S contents were manufactured in a cement plant, and the effect of mineral composition of clinker on properties of BFS cement concrete was investigated. It was proved that early-age compressive strength of concrete with BFS cement was improved by increasing C_3S content, especially at low temperature.

1. Introduction

In Japan, Portland blast-furnace slag cement (BFS cements) is classified into three categories, Type A, B and C, which contain BFS from 5% to 30%, from 30% to 60% and from 60% to 70% respectively, according to Japan Industrial Standards (JIS R 5211) [1]. In general, conventional BFS cement is produced by blending BFS with ordinary Portland cement (OPC) which is made from clinker with C_3S content ranging from 55% to 60%. Conventional BFS cement Type B, in which BFS content generally ranges from 40% to 45%, has been extensively applied to civil engineering structures for ensuring concrete durability and reducing environmental impact. Therefore, the amount of BFS cement Type B used in Japan per year accounts for more than 20% of the total cement consumption, while OPC accounts for about 70%. On the other hand, BFS cement Type A and Type C have rarely been used for concrete structures, although there are some reports on properties of concrete with these types of cement and practical applications [2]. It should be also pointed out that the addition of BFS at concrete mixing plants is very rare in Japan because of the problems in delivery systems and facilities in concrete mixing plants.

In order to reduce CO_2 emission in process of cement production, it is very efficient to use BFS cement more widely for concrete structures. However, BFS cement has rarely been used for reinforced concrete buildings, to which OPC has generally been applied. It is because concrete with conventional BFS cement shows slower strength development at early ages and occasionally has lower resistances to shrinkage cracking and carbonation compared to OPC concrete.

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For the purpose of improving performance of BFS cement concrete, many researches have been conducted. It was reported that shrinkage cracking resistance of concrete with BFS cement Type A was improved by modifying gypsum content and by adding limestone powder [3]. However, it was pointed out that early-age strength development at low temperature has to be improved. In regard to chemical composition of cement clinker, it is well known that C_3S contributes strength at early ages and C_2S at later ages. It was revealed by experiments on laboratory clinkers that early-age strength of BFS cement was increased with increasing C_3S content of clinker up to 63% [4].

On the other hand, studies on the effects of chemical composition of clinker have rarely been conducted on the basis of clinkers produced in commercial plants. It was reported more than 40 years ago that super high early strength Portland cement with 1 day compressive strength more than 20 N/mm^2 was manufactured by increasing C_3S content of clinker. And this type of cement was used for urgent works such as repair of roads and bridges [5], but it has not recently been manufactured. It was also reported that compressive strength of BFS cement concrete at early ages could be improved by using high-early strength Portland cement clinker with C_3S content of 65% [6].

The purpose of this study is to propose BFS cement which can be widely used for concrete structures including reinforced concrete buildings. In order to investigate properties of concrete with BFS cement made from high C_3S clinker, several clinkers with C_3S contents up to 71% were produced with a commercial cement plant. And series of experiments were carried out to investigate the effects of C_3S content on strength development, drying shrinkage and carbonation rate of concrete with BFS cement.

2. Experiments

2.1. Materials

Table 1 provides chemical composition of the clinker samples and their mineral composition calculated with Bogue formula. The mineral composition of the clinkers was adjusted so that C_3S content ranged from 59% to 71%. Contents of C_3A and C_4AF were about the same among the clinkers prepared. The clinker samples were manufactured in a commercial cement plant. In the manufacture process of the clinker samples, the kinds of raw materials including large amount of waste

Table 1
Chemical composition of clinker.

Series	Type of clinker	Chemical composition (%)												Mineral composition (%)			
		Ig-loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	MnO	C_3S	C_2S	C_3A	C_4AF
I	A71	0.98	19.32	5.40	3.39	65.25	1.90	2.29	0.43	0.39	0.27	0.18	0.05	71.1	1.8	8.6	10.3
	A69	1.79	19.24	5.37	3.42	64.82	1.91	2.80	0.41	0.33	0.28	0.17	0.05	68.6	3.4	8.5	10.4
	A66	0.94	19.46	5.41	3.39	64.63	1.89	2.83	0.42	0.39	0.27	0.17	0.05	65.9	6.2	8.6	10.3
	A59	0.99	20.31	5.36	3.37	64.13	1.90	2.51	0.41	0.37	0.27	0.18	0.05	58.7	14.0	8.5	10.2
II	A69	–	18.76	5.18	2.85	64.16	1.88	3.97	0.42	0.38	0.26	0.21	0.04	68.4	2.3	8.9	8.7
	A59	–	–	–	–	–	–	–	–	–	–	–	–	59[a]	14[a]	8[a]	10[a]

[a] Calculated from quality control documents in the plant.

Table 2
Chemical composition and fineness of blast-furnace slag.

Series	Type	Fineness (cm^2/g)	Ig-loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
I	BS4	4530	0.04	33.64	14.33	0.16	42.96	6.38	0.20	0.34	0.62	0.01	0.36
II	BS3	3340	+0.05	33.72	14.41	0.26	42.47	6.66	0.19	0.29	0.66	0.01	0.31
	BS4	4520	0.02	33.72	14.34	0.36	42.89	6.22	0.21	0.32	0.59	0.01	0.34
	BS6	6110	+0.03	33.69	14.28	0.83	42.48	5.77	0.26	0.32	0.90	0.01	0.46
	BS8	8770	+0.06	34.15	14.52	0.28	42.23	6.34	0.18	0.31	0.64	0.01	0.33

Table 3
Physical properties of cement.

Series	Type of cement	BFS (%)	Blaine of BFS (cm^2/g)	Density (g/cm^3)	Blaine of cement (cm^2/g)	Setting time (h:m)		Compressive strength (N/mm^2)			
						Initial	Final	1 day	3 days	7 days	28 days
I	A71	–	–	3.16	4780	0:50	1:40	21.5	40.3	53.6	61.7
	A69	–	–	3.15	4780	1:20	2:00	25.3	44.4	56.1	64.5
	A66	–	–	3.13	4540	1:20	2:10	24.4	44.3	54.9	63.6
	A59	–	–	3.15	3460	1:40	3:05	14.2	31.2	46.9	58.3
	A71-BS4-20	20	4530	3.08	4840	1:50	2:50	–	37.5	49.7	66.5
	A69-BS4-15	15	4530	3.09	4820	2:05	3:05	–	40.4	52.5	68.0
	A69-BS4-20	20	4530	3.08	4850	1:55	3:10	–	37.6	51.1	69.3
	A69-BS4-25	25	4530	3.06	4830	2:10	3:15	–	35.5	49.2	67.0
	A66-BS4-20	20	4530	3.06	4670	2:20	3:20	–	39.0	51.1	67.6
	A59-BS4-20	20	4530	3.08	3860	2:20	3:30	–	30.0	43.4	62.1
II	A69	–	–	3.11	5480	1:25	2:25	–	47.9	52.9	64.2
	A59	–	–	3.16	3470	2:20	3:30	–	29.1	44.5	63.5
	A69-BS3-20	20	3340	3.05	5160	1:55	2:50	–	37.0	49.1	63.9
	A69-BS4-20	20	4520	3.05	5390	1:55	2:40	–	39.5	51.9	67.5
	A69-BS6-20	20	6110	3.05	5680	2:20	2:55	–	44.0	58.5	75.0
	A69-BS8-20	20	8770	3.05	6330	2:05	2:40	–	43.6	59.8	76.7
	A69-BS8-15	15	8770	3.06	6150	1:55	2:50	–	43.9	58.8	73.3
	A69-BS8-25	25	8770	3.04	6510	2:25	3:05	–	46.1	63.4	76.6