FUNDAMENTAL PROPERTIES OF AMBIENT-TEMPERATURE-CURED ULTRA-HIGH-STRENGTH FIBER-REINFORCED CONCRETE

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Abstract

This paper is about fundamental properties of ultra-high-strength fiber-reinforced concrete (UFC) that does not need steam curing. The compressive strength of ordinary UFC is over than 150 N/mm^2, and it has high toughness and durability. Most UFC needs steam curing at high temperature and for long time to achieve stable performance, and the energy required for steam curing results in high cost of manufacturing. UFC is usually manufactured in concrete products factories and transported to construction sites. This leads to improved product quality and concrete stability, but increases constructing costs. In this study, new type of UFC that can be produced by curing at ambient temperature has developed. The main materials used are ordinary Portland cement, fine blast-furnace slag powder, silica fume and so on. In this paper, it is examined the effects of cement types, blending ratio of powders, and Blaine specific surface area of blast-furnace slag powder on fresh and hardened characteristics of UFC. Based on the results, it is found that UFC using ordinary Portland cement as the main powder shows superior fluidity, lowering requirements for air entraining and high-range water reducing agents. And without steam curing, the developed UFC achieves compressive strength exceeding 150 N/mm^2 and bending strength exceeding 40 N/mm^2 by curing at ambient temperature (20 °C). The developed UFC can be produced in constructing site, therefor it can reduce construction costs comparing to ordinary UFC.

Keywords: *Ultra-High –Strength Fiber-Reinforced Concrete, Ambient-temperature-cured, ordinary Portland cement*

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1. INTRODUCTION

Ultra-high-strength fiber-reinforced concrete (UFC) has ultra-high compressive strengths exceeding 150 N/mm^2 and bending strength exceeding 40 N/mm^2. And it also has high toughness by containing fibers, and high durability against chloride ion penetration, freezing and thawing cycles and so on. It is expected that use of UFC can reduce constructing costs by making cross sections of concrete members smaller and by improving durability significantly.

Ordinary UFC must be steam-cured at high temperatures and for long times to achieve high strength and high durability stably, so UFC members are generally produced in concrete products factories. Therefore in order to apply UFC members to construction, it is necessary to transport them. And these increase construction costs. Therefore, to come into common use of UFC, it is required to achieve its performance by on-site casting and ambient temperature curing[1)].

This research investigates candidate materials and mix proportions for new UFC that can achieve high performance by curing at ambient temperatures. In this paper, it was examined the effects of cement types, blending ratio of powders, and Blaine specific surface area of blast-furnace slag powder on fresh and hardened characteristics of UFC

2. FUNDAMENTAL PROPERTIES OF AMBIENT-TEMPERATURE-CURED UFC CONTAINING FINE BLAST-FURNACE SLAG POWDER

2.1 Outline of Experiment

In this chapter, it is investigated the effects of differences in content and the specific surface area of the blast-furnace slag powder, and the type of cement used on the properties of fresh and hardened UFC.

2.2 Material Used

Table 1 shows the materials used, Table 2 shows the properties of the fibers, and Table 3 shows the cement mineral components and Blaine specific surface area. A prototype high-alite cement (HAC) was used as candidate main material for new UFC. It is expected to improve strength at early age. Ordinary Portland cement (OPC) was also used for comparison. And an admixture for high strength concrete was used. It is comprised of silica fume mainly.

2. 3 Testing Conditions

Table 4 shows the mixing conditions in the tests, and Table 5 shows the powder compositions.

In these tests, for all mixes the water-to-powder ratio (W/P) was 15%, the sand-to-powder ratio (S/P) was 30%, and the fiber content was 2% of the total volume. The content of blast-furnace slag powder (Blaine specific surface area 8000 cm^2/g class) was 10%, 15%, and 25%. To investigate the effect of differences in the Blaine specific surface area, other 2 types of blast-furnace slag powder with 4000 cm^2/g class and 12000 cm^2/g class of Blaine specific surface area were used at 15% content. Powder of No.6 is containing 4000 cm^2/g class and 1200 cm^2/g class at 20% and 5% content respectively. The content of admixture for high strength concrete was 15% in all compositions. OPC as the base cement was used for comparison.

Table 1: Materials used

Materials	Type	Symbol	Density(g/cm^3)
Binder	High-alitel cement	HAC	3.16
	Ordinary Portland cement	OPC	3.15
	Blaine specific surface area 4000cm^2/g class	BS4	2.90
	Blaine specific surface area 8000cm^2/g class	BS8	2.91
	Blaine specific surface area 12000cm^2/g class	BS12	2.91
	High-strength concrete admixture comprising mainly silica fume	SFP	2.43
Fine aggregate	silica sand	S	2.61
Water	Tap water	W	1.00
Water reducing agent	Polycarboxylic acids ether-based high range water reducing and air entraining agent	SP	1.10
Defoaming agent	Polyalkylene derivative	DF	1.00
Reinforcing agent	Steel fiber	F	7.80

Table 2: Properties of the fibers used

	length (mm)	diameter (mm)	Tensile strength (MPa)	shape
Steel fiber	13.0	0.16	2000over	straight

Table 3: Cement mineral components and Blaine specific surface area

material name	cement mineral components(%)				Blaine specific surface area(cm^2/g)
	C_3S	C_2S	C_3A	C_4AF	
HAC	68.6	3.4	8.5	10.4	4780
OPC	56.0	18.0	9.0	9.0	3340

Table 4: Mixing conditions

W/P (%)	S/P (%)	Fiber-containing ratio(vol%)	Target value	
			Air content (%)	mortar flow value(mm)
15	30	2	Under3	250±25

Table 5: Powder compositions

No.	Symbol	Mass ratio(%)					
		HAC	OPC	BS4	BS8	BS12	SFP
1	25BS8	60	-	-	25	-	15
2	15BS8	70	-	-	15	-	
3	10BS8	75	-	-	10	-	
4	15BS4	70	-	15	-	-	
5	15BS12	70	-	-	-	15	
6	20(5)BS4BS12	60	-	20	-	5	
7	OPC15BS8	-	70	-	15	-	

2.4 Mixing Method

An omni type mixer with 10 litter capacity was used. First, only the powder and fine aggregate were mixed for 30 s, then water and high range water reducing and air entraining agent (SP) were added and mixed for 9 min. Steel fiber was then added while the mixing and defoaming agent was then added after it.

2.5 Testing Items and Methods

2.5.1 Fresh Properties Tests

(1) Mortar flow test: Mortar flow test was carried out in accordance with "JIS R 5201 Physical Testing Methods for Cement." The spread of the test specimen when the test cone was removed is taken to be the mortar flow value.

(2) Air content test: The air content test was carried out in accordance with "JIS A 1116 Test Method for Unit Mass and Air Content of Fresh Concrete."

(3) Mortar flow time to reach 200 mm of mortar flow value: When carrying out the mortar flow test, to evaluate the viscosity, the time for the mortar flow to reach 200 mm of mortar flow value was measured.

(4) Temperature of mortar: A thermometer was used to measure the temperature of the mortar when mixing was completed.

2.5.2 Hardened Properties Tests

(1) Compressive strength test: Compressive strength test was carried out in accordance with "JSCE-G 505-1999 Test Method for Compressive Strength of Mortar and Cement Paste Using Cylindrical Specimens (φ50×100mm)." Measurement was carried out at 1 day after casting, and at 7 and 28 days after curing in water (20℃).

(2) Bending strength test of thin plate (100×20×400mm) Bending strength test was carried out in accordance with "JIS A 1106:2006 Test Method for Flexural strength of Concrete Using Center Point Loading." Measurement was carried out at 1 day after casting, and at 7 and 28 days after curing in water (20℃).

2.6 Test Results

(1) Test results of fresh properties: Table 6 shows the test results. In all the mixes that satisfied the target values, segregation of materials and any fiber balls were not confirmed. Photo 1 shows example of mortar flow.

Reducing BS8 content tended to increase the dosage of SP. As for it, it is thought that the specific surface area of HAC is large at 4780 cm^2/g (Table 3) and HAC contains much C_3S, and reducing BS8 content, or in other words increasing HAC content, increased the quantity of water bound in the powder particles and increased SP adsorption.

Comparing 15BS8 and OPC15BS8, BS8 content was the same but the kind of base cement was different. Dosage of SP in OPC15BS8 to obtain the target workability was less than that in 15BS8. So the effect of HAC and OPC on the fresh properties is clear.

Increasing HAC content trended to increase mortar flow time to reach 200 mm, and it indicates that HAC makes mortar more viscous. In the case of 10BS8, the flow time was 16min 13s, and it was found that the viscosity was very high and handling was extremely difficult. Therefore, it is necessary to investigate the appropriate viscosity.

In the cases that fine blast-furnace slag powder with specific surface area 4000 cm^2/g and 1200 cm^2/g was used (15BS4 and 15BS12), SP was added more than 5.0%, but it was not possible to achieve the target mortar flow value. It is thought that much dosage of SP delays setting time, so other tests of these 2 mixes were terminated. The target mortar flow value could not be obtained because BS4 has a specific surface area close to that of HAC, and BS12 has much finer particles. It is considered that the particle size distribution of the powder as a whole was not ideal for densely packing. For 20(5)BS4BS12, which contains 20% of BS4 and 5% of BS12, it was possible to achieve the target mortar flow value with an SP content of 2.3%, so it seemed the particle size distribution of the powder as a whole has a large effect on fresh properties.

(2) Test results of compressive strength: Figure 1 shows the test results of compressive strength. In this study, HAC was used to improve strength at early age. At the age of 1 day, mixes using HAC showed higher compressive strength that that using OPC. However, the effect using HAC was not clear.

Comparing 25BS8, 15BS8, and 10BS8 at 7 days, 25BS8 and 15BS8 showed compressive strength over than 150 N/mm^2, but the compressive strength of 10BS8, which contains much HAC, was 133.5 N/mm^2. This is considered that the dosage of SP content was very high (3.5%), so the SP adhered excessively to the cement particles and delayed hydration. However, it is necessary to investigate further.

(3) Test results of bending strength: Figure 2 shows the test results of bending strength. OPC15BS8 which used OPC showed the highest bending strength. At 7 days and 28 days, it is confirmed a trend of increasing bending strength with increasing HAC content. However, it is not clear the effect of difference of specific surface area of fine blast-furnace slag on the test results.

In these tests, the UFC using OPC showed higher compressive and bending strength. And fresh properties of it was better than that using HAC. Therefore, in the next experiment, OPC was used as the base cement.

Table 6: Test results of fresh properties

No.	Symbol	SP (%)	DF (%)	Mortar flow value(mm)	Mortar flow time to reach 200 mm (s)	Air content (%)	Temperature (℃)
1	25BS8	2.3	0.4	250	4″ 57	0.1	30
2	15BS8	2.5	0.4	238	6″ 86	2.0	28
3	10BS8	3.5	0.3	225	16″ 13	0.3	28
4	15BS4	3.0	0.4	185	–	1.4	21
5	15BS12	6.0	0.4	173	–	0.9	21
6	20(5)BS4BS12	2.3	0.4	240	6″ 94	0.3	19
7	OPC15BS8	1.8	0.4	263	5″ 86	0.3	20

Photo 1: Example of mortar flow (20(5)BS4BS12)

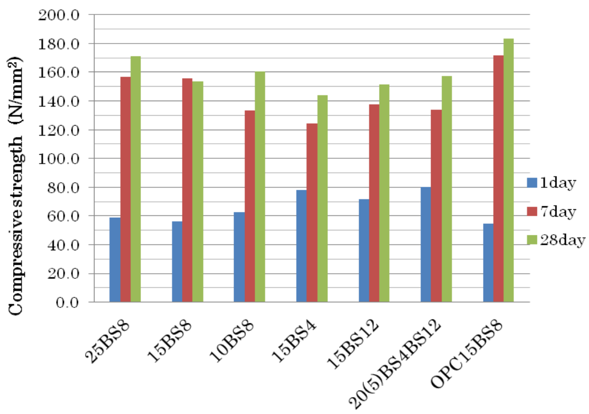

Fig 1: Test results of compressive strength

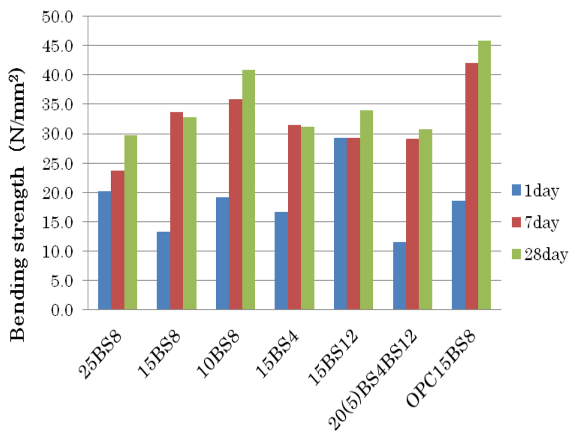

Fig 2: Test results of bending strength

3. FUNDAMENTAL PROPERTIES OF AMBIENT-TEMPERATURE-CURED UFC USING ORDINARY PORTLAND CEMENT

3.1 Outline of Experiment

In this chapter, it is investigate the effect of differences in the content of fine blast-furnace slag powder and specific surface area on the fresh and hardened properties of UFC using OPC as the base cement, for which excellent results were obtained in the previous experiment.

3.2 Materials Used and Mixing Conditions

Table 1 shows the materials used. Table 7 shows the mixing conditions, and Table 8 shows the powder composition. In all mixes, SP was added 1.8% to mass of powder and antifoaming agent was added 0.4% to it.

Table 7: Mixing condition

W/P (%)	S/P (%)	Fiber-containing ratio(vol%)	SP/P (%)	DF/P (%)
15	30	2	1.8	0.4

Table 8: Powder compositions

No.	Symbol	Mass ratio(%)				
		OPC	BS4	BS8	BS12	SFP
1	OPC25BS8	60	–	25	–	15
2	OPC15BS8	70	–	15	–	
3	OPC10BS8	75	–	10	–	
4	OPC15BS4	70	15	–	–	
5	OPC15BS12	70	–	–	15	

3.3 Mixing Method

Same as Section 2.4

3.4 Testing Items and Methods

Same as Section 2.5

3.5 Test Results

(1) Test results of fresh properties: Table 9 shows the test results. As the BS8 content increases, the mortar flow value increased greatly. The particles of fine blast-furnace slag powder have glassy smooth surfaces, and it is thought that these smooth surface improved fluidity of them. And the mortar flow value increased greatly as the specific surface area of the fine blast-furnace slag powder increases, unlike the case where HAC was used as described in Section 2.5. This is because when OPC is used as the base cement, the greater the specific surface area of BS, the better the particle size distribution of the powder as a whole from the point of view of densely packing. And it increased the quantity of free water contributing to improve its fluidity.

(2) Test results of compressive strength: Figure 3 shows the test results of compressive strength. Compressive strength of OPC15BS12 at the age of 28 days was close to 200 N/mm^2.

At the ages of 7 days and 28 days, the compressive strength increased as the BS8 content increases. The strength also increases with increasing specific surface area. It is considered that increasing specific surface area improve densely packing of particles and reactivity, which greatly contributes to densification of the internal matrix micro structures.

(3) Test results of bending strength: Figure 4 shows the test results of bending strength. The bending strength of OPC15BS12 showed over than 45 N/mm^2. Bending strength increased with increasing of BS8 content. At the age of 7 days, the bending strength increases with increasing of specific surface area of the BS. It is thought that the increased specific surface area improve the matrix micro structures, and this increased adhesion to the fibers.

Table 9: Test results of fresh properties

No.	Symbol	SP (%)	DF (%)	Mortar flow value(mm)	Mortar flow time to reach 200 mm (s)	Air content (%)	Temperature (℃)
1	OPC25BS8	1.8	0.4	295.0	4″ 09	0.8	22
2	OPC15BS8			262.5	5″ 86	0.3	20
3	OPC10BS8			242.5	8″ 63	0.8	23
4	OPC15BS4			245.0	10″ 50	0.6	20
5	OPC15BS12			270.0	5″ 11	0.4	21

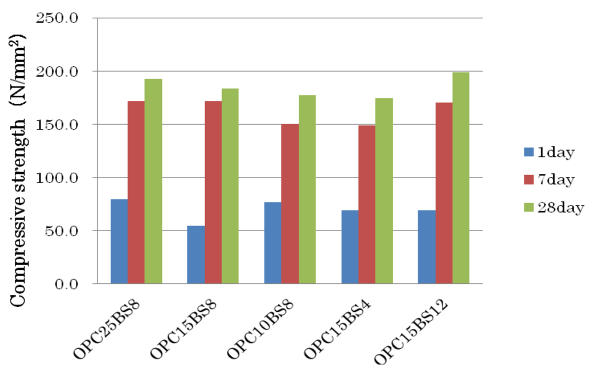

Fig 3: Test results of compressive strength

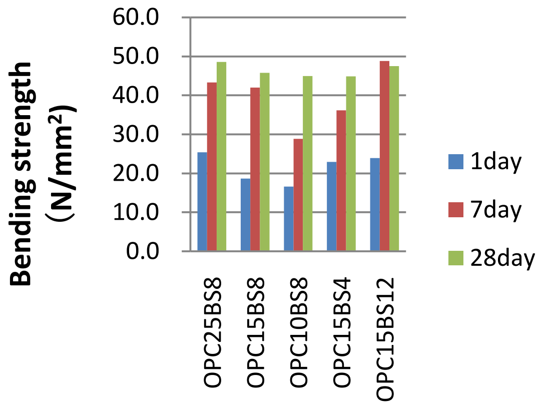

Fig 4: Test results of bending strength

4. CONCLUSIONS

(1) Fresh properties

- UFC using OPC exhibits superior fluidity compared with that using HAC.
- Fluidity increases with increasing of BS8 content.
- Fluidity of UFC using OPC increases with increasing of specific surface area of BS.

(2) Hardened properties

- UFC containing OPC, blast furnace slag and admixture for high strength concrete comprised of silica fume mainly shows very high compressive strength close to 200 N/mm^2 and high bending strength over than 45 N/mm^2 by curing at ambient temperature.
- The compressive and bending strength of UFC using OPC increase with increasing of BS8 content.
- The compressive and bending strength of UFC using OPC increase with increasing of BS specific surface area.

The above results indicate that the same strength can be obtained by ambient temperature curing as with steam curing. However, further investigation is necessary in order to improve the workability of it.

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