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Experimental Investigation for Improving Shrinkage Cracking Resistance of BFS Blended Cement Concrete Exposed to Hot Environment

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ABSTRACT

It was reported that shrinkage cracking resistance of BFS cement concrete tended to be significantly lower than that of the normal concrete at hot environment due to higher autogenous shrinkage and smaller creep. This study investigates effects of concrete constituents on improving shrinkage cracking resistance via restraint shrinkage cracking experiments. Experimental parameters are: fineness in BFS powder, anti-shrinkage admixtures like expansive agents and shrinkage reducing agents. As a result, a shrinkage reducing agent, which has been newly developed as improving water retaining ability, most significantly affect to strengthen shrinkage cracking resistance in BFS concrete in hot environment.

Keywords. blast-furnace slag, cracking, shrinkage, temperature, shrinkage reducing agent

INTRODUCTION

Application of blast-furnace slag fine powder blended cement is an important option to achieve low carbon emission from concrete materials in construction. However, concrete using such blended cement (BFS concrete, hereafter) has been believed to be vulnerable to shrinkage cracking and traditionally avoided for use in building construction except for underground structural elements in Japan. To extend the use of BFS concrete in building construction, it is necessary to quantitatively evaluate the shrinkage cracking resistance of BFS concrete.

BFS concrete with relatively low water to binder ratio (w/b) has been broadly investigated in terms of autogenous shrinkage in the literatures. It is generally known that higher BFS content leads to a larger autogenous shrinkage (e.g., Pane and Hansen, 2008b). Furthermore, temperature increase due to hydration heat at early age causes an increase in larger autogenous shrinkage (Saric-Coric and Aïtin, 2003, dos Santos et al., 2012). Hence massive concrete elements with BFS concrete or even thin element with low w/b BFS concrete are prone to early age cracking.

However, relatively long term restraint shrinkage cracking behavior due to autogenous plus drying shrinkage has not been sufficiently clarified for BFS concrete with normal strength level when applied to thin building element such as floor slabs and walls. While few restrained cracking test data were published under limited testing conditions in literatures (Pane and Hansen, 2008a, Aly and Sanjayan, 2008), accumulated technical knowledge for this problem is insufficient to accomplish the shrinkage controlling design in the construction practice. A part of authors quite recently demonstrated that BFS concrete's shrinkage cracking resistance deteriorates with rising ambient temperature (Kanda et al., 2012). The shrinkage cracking resistance of BFS concrete is much lower than normal concrete at 30 °C unlike at 10 and 20 °C. This tendency appears due to increasing autogenous shrinkage and decreasing creep strain with rising temperature. Hence anti-cracking measures should be considered for BFS concrete at higher ambient temperature.

Based on the above background, the ultimate goal of this research is to establish shrinkage cracking controlling design for BFS concrete building construction. Toward this goal, the scope of this study is to experimentally improve shrinkage cracking resistance of BFS concrete with particular attention to effects of high ambient temperature. In experiments, restraint shrinkage cracking experiments were conducted with modified BFS concrete mainly subjected to 30°C in comparison with normal concrete, where we adopted cracking age in the restraint tests as a performance index representing cracking resistance. Modified BFS concretes were mixed by combining a new type shrinkage reducing agent (SRA), coarse BFS powder, and expansive agent. As a result, we aim at demonstrating effective BFS concrete modification approach to increase the shrinkage cracking resistance.

EXPERIMENTAL DESIGN

Experiments Overview. Restrained shrinkage cracking experiment was performed. Experimental parameters and their variations are shown in Table 1. The experiment consists of two series, temperature series and material series, where former series was reported in detail in literature (Kanda et al., 2012). Combinations of the parameters are shown in Table 2. In the temperature series, BFS concrete and concrete with the ordinary Portland cement (hereafter referred to as the normal concrete) were used for the restrained shrinkage cracking experiment. To imitate the shrinkage cracking of slabs or walls under construction conditions in different seasons, the curing temperatures were varied in 10°C, 20°C and 30°C. The material series are planned to investigate to compensates shrinkage crack resistance degradation for BFS concrete mainly in hot environment by involving additives with shrinkage reducing effects such as SRA.

Table 1. Test parameters and variation Table 2. Test parameter combination

Exp. series	Exp. parameters	Variations
Temp. series (Kanda et al. 2012)	Concrete type	Normal concrete BFS concrete
	Ambient temperature	10 °C 20 °C 30 °C
Material series	Ambient temperature	20 °C 30 °C
	Additive	SRA, BFS fineness, Expansive agent

Exp. series	Specimen	Experimental parameters: Concrete type	*Ambient temperature	BFS type	Expansive agent	SRA
Temp. series (Kanda et al. 2012)	N10	Normal concrete	10 °C (RH40%)	None	None	None
	N20		20 °C (RH60%)	None	None	None
	N30		30 °C (RH60%)	None	None	None
	B10	BFS concrete	10 °C (RH40%)	Normal	None	None
	B20		20 °C (RH60%)	Normal	None	None
	B30		30 °C (RH60%)	Normal	None	None
Material series	B20-SRA	Modified BFS concrete	20 °C (RH60%)	Normal	None	Added
	B30-SRA		30 °C (RH60%)	Normal	None	Added
	B30-C-SRA		30 °C (RH60%)	Coarse	None	Added
	B30-C-Ex		30 °C (RH60%)	Coarse	Added	None

* Numbers in parenthesizes show ambient relative humidity.

Materials, Mix Design, Mixing and Placing Method. Materials used and their mix proportions are shown in Table 3and Table 4. In temperature series, Portland cement was the only binder for the normal concrete while for BFS concrete, BFS fine powder substituting 42 percent of Portland cement content was used as an alternative to the blast-furnace slag mix cement type B specified in JIS R 5201, which is very popular in Japanese construction market. In Table 4, water to binder ratio and unit water content is fixed in 50% and 175kg/m^3, which are within typical range for normal concrete and BFS concrete. Quality of the BFS powder is shown in Table 5. In the material series, a new type SRA, coarse BFS, and expansive agent are used for BFS concrete. The temperature series results showed that hot environmental temperature, 30^{o}C, dramatically deteriorates shrinkage cracking resistance of BFS concrete much less than normal concrete. To improve this low resistance, BFS concrete is modified adopting the above constitutive materials (modified BFS concrete, hereafter).

This study adopts a water retaining type SRA for modified BFS concrete (Table 3), which is newly developed to buster practical difficulties in using existing SRA products based on a new anti-shrinkage concepts. The water retaining SRA consists of water holding polymer consisting of Ethylene oxide and absorbs and retains water in micro-microstructure of cement hydration products. This SRA was designed to effectively reduce shrinkage strain while its water retaining capability is not significant in terms of mass, which leads to 0.5-1% higher mass water content for concrete than that of concrete without the SRA. This design concept is very different from existing SRA products which are generally know to reduce surface tension in pore solution (Nawa et al., 2011). This concept results in remarkably improving freeze and thaw resistance of concrete involving SRA, which is the most serious shortcoming of existing products. It is reported that the water retaining type SRA replacing unit water content by 10 kg/m^3 contributes to 10 to 20% less drying shrinkage strain for normal strength concretes in literature (Kuroiwa et al., 2011). The water retaining type SRA is expected effective on reducing shrinkage of BFS concrete in hot environment. As shown in Table 3, 10kg/m^3 of the water retaining SRA replace unit water content for B20-SRA B30-SRA and B30-C-SRA mixes.

The material series also investigates the effects of coarse BFS powder and expansive agent (Table 3and Table 4). Aforementioned cracking resistance degradation in hot environment appears responsible by higher autogenous shrinkage and smaller tensile creep strain (Kanda et al., 2012). The former phenomena may be restricted or compensated with the both additives. Coarse BFS powder has lower specific surface area than normal BFS powder used in temperature series, where the former has 3450 g/cm^3 of Blaine value and the latter has 4170 g/cm^3. The coarse BFS powder gradually hydrates in BFS concrete even in hot environment, thus causing moderate autogenous shrinkage strain revelation. However, the coarse BFS powder alone may not be sufficient in reducing autogenous shrinkage, the water retaining SRA is simultaneously used in B30-C-SRA mix. Furthermore, expansive agent is coupled with the coarse BFS powder as a typical shrinkage compensating option in B30-C-Ex.

In Table 4, the targeted slump and air content were 18±2.5cm and 4.5±1.5% respectively common to all mixes. Mixing was performed with a biaxial forced mixer. Coarse aggregate, sand and cement was mixed without water for the first 15 seconds and, after introducing water and admixture, all the constituents were mixed for 120 seconds at a room temperature of 20°C, and placed in the molds set in chambers with different temperatures.

Table 3. Materials of concrete

Material	Type	Characteristics	Satisfying standard in quality
Cement	Normal Portland cement (OPC)	Density 3.16g/cm^3	JIS R 5210
BFS powder	Normal	Specific surface area by Blaine 4170 cm^2/g Density 2.89g/cm^3	JIS A 6206
	Coarse	Specific surface area by Blaine 3450 cm^2/g Density 2.87g/cm^3	
Expansive agent	Ettringite and free-CaO combined type	Density 3.12g/cm^3	JIS A 6202
Fine aggregate	Crashed sand	Density in saturated surface-dry condition: 2.64g/cm^3 Percentage of water absorption: 1.10% Fineness modulus: 2.74	JIS A 5005
Coarse aggregate	Crashed gravel 1	Density in saturated surface-dry condition: 2.66g/cm^3 Percentage of water absorption: 0.55% Fineness modulus: 7.0	JIS A 5005
	Crashed gravel 2	Density in saturated surface-dry condition: 2.66g/cm^3 Percentage of water absorption: 0.62% Fineness modulus: 6.14	JIS A 5005
Super plasticizer	Polycarboxylic acid type	Density 1.04g/cm^3	JIS A 6204
Shrinkage reducing agent	Water retaining type (Ethylene oxide type)	Density 1.05g/cm^3	JASS 5-M402

Table 4. Mix proportion

Exp. Series	Concrete type	Water to binder ratio (%)	Sand-aggregate ratio (%)	Unit weight (kg/m^3)				
				*Water	Cement	Normal BFS	Coarse BFS	Expansive agent
Temp. series	BFS concrete	50	46.3	175	203	147	-	-
	Normal concrete	50	46.7	175	350	0	-	-
Material series	B20-SRA B30-SRA	50	48.4	175	203	147	-	-
	B30-C-SRA	50	48.4	175	203	-	147	-
	B30-C-Ex	50	48.4	175	191	-	139	20

*For B20-SRA, B30-SRA, and B30-C-SRA, 10kg/m^3 of SRA is added by substituting water.

Table 5. Characteristics of BFS powders

Characterisitcs		Characteristics of normal BFS	Characteristics of corse BFS	Requirement in JIS A 6206
Density	(g/cm^3)	2.89	2.87	≧ 2.8
Specific surface area	(cm^2/g)	4170	3450	≧ 3000
Reactivity index	(%)	70 at 7day age 93 at 28 day age 115 at 91 day age	56 at 7day age 83 at 28 day age 101 at 91 day age	≧ 55 at 7 day age ≧ 75at 28 day age ≧ 95 at 91 day age
Relative flow value	(%)	99	101	≧ 95
Content of magnesium oxide	(%)	5.66	6.1	≦ 10.0
Content of sulfur trioxide	(%)	2.03	3	≦ 4.0
Ignition loss	(%)	0.93	1.2	≦ 3.0
Content of chloride ion	(%)	0.004	0.002	≦ 0.02
Basicity		1.84	1.95	≧ 1.6

Testing Items and Methods. Testing items and methods of the restrained shrinkage cracking experiments are shown in Table 6. The restrained shrinkage cracking test and free shrinkage test were performed on the basis of the literature (JCI, 2010). Specimen for the restrained cracking experiment is shown in Figure 1. The restrained shrinkage stress over the concrete section due to autogenous and drying shrinkage was measured with a strain gauge adhered at the center of the restraining steel bar and calculated with the equation (1).

$$\sigma_i^r = -\frac{\varepsilon_i^s \cdot E_s \cdot A_{rs}}{A_{rc}} \tag{1}$$

where σ_i^r is restrained shrinkage stress at a time i (N/mm^2), ε_i^s is the strain of steel bar at a time i, E_s is elastic modulus of restraining steel bar (N/mm^2), A_{rs} is cross-sectional area of the restraining steel bar (mm^2) and A_{rc} is the cross-sectional area of concrete specimen at the center of the test area (mm^2).

The restraining steel bar with a diameter of 32mm was screw-threaded over the embedment length of 400mm in each end in Figure 1. Specimen for the free shrinkage test was 100x100x400mm in size and an embed-type strain gauge was set at the center. To measure autogenous shrinkage, low modulus gauge capable of measuring deformation at very early stage of hydration, autogenous shrinkage, was selected. All the specimens were subjected to sealed curing without unmolding in a chamber with a temperature of 20°C and a relative humidity of 60% till the age of 7 days. After unmolding, specimen was sealed with aluminum foil leaving only two sides of the specimen opened for drying. For restrained shrinkage cracking test and free shrinkage test, 2 specimens are respectively prepared in each testing condition.

Mechanical properties such as compressive strength, elastic modulus and split tensile strength were tested at material ages of 3, 7 and 28 days. Curing condition of the specimens subjected to the mechanical tests were the same as that of the restrained cracking test; sealed curing till the age of 7 days and subsequent air curing.

Table 6. Items of experiments

Testing items	Specimen size (mm)	Testing method
Fresh tests (slump, air content, concrete temperature, unit weight)	-	Japanese Industrial Standard
Compressive and splitting tensile tests	ϕ100x200	
Restrained shrinkage cracking test	100x100x1100	JCI method
Free shrinkage test	100x100x400	

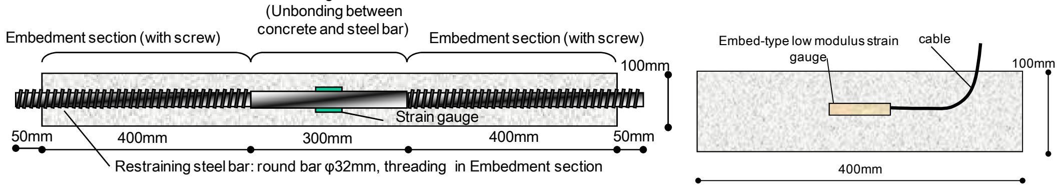

Figure 1. Specimen for the restrained shrinkage cracking experiment, left: restrained cracking test specimen, right: free shrinkage test specimen

EXPERIMENTAL RESULTS AND DISCUSSION

Results of Restrained Cracking Experiment. Properties of concrete at fresh state are shown in Table 7. Workability of all the mixes after mixing was generally favorable and specimen was placed and formed without problems.

Results of the mechanical tests are compiled in Table 8 and the developments of mechanical properties are shown in Figure 2, Figure 3 and Figure 4. It is seen in these figures and table that compressive strength and split tensile strength of BFS concrete are at maximum 20% smaller than that of the normal concrete when compared at the same material age, while the reduction in elastic modulus was slight compared to that of the strengths in 30^{o}C as depicted in right diagram of Figure 4. For the BFS concrete, low tensile strength and comparable elastic modulus compared with normal concrete appear to lead to low cracking resistance.

Changes in free shrinkage strain of all mixes are shown in Figure 5. A central figure shows the free shrinkage strains of the normal concrete at the age of 80 days were nearly equal regardless of the ambient temperatures while that of B30 of BFS concrete showed more than 100μ larger strain than that of others as a result of an significant increase in shrinkage strain at early stages up to material age of 30 days in a left figure. A right figure demonstrates BFS concretes with the SRA show smaller free shrinkage than BFS concrete, where this reduction at 80 days reaches 200μ smaller at 30^{o}C.

Table 7. Fresh properties

Specimen	Fresh property			
	Slump (cm)	Air content (%)	Concrete temperature (^{o}C)	Unit weight (kg/L)
B30	19.0	4.6	20.3	2.30
B20	19.0	4.7	20.2	2.29
B10	19.0	4.3	20.5	2.30
N30	19.5	4.9	20.6	2.29
N20	19.5	5.1	20.8	2.28
N10	18.0	4.9	20.9	2.29
B30-SRA	20.0	4.9	19.5	2.29
B20-SRA	20.0	4.8	19.5	2.29
B30-C-SRA	19.5	4.5	19.3	2.29
B30-C-Ex	20.0	4.9	19.5	2.29

Table 8. Mechanical properties

Specimen	Identical curing condition to restraint shrinkage test specimen (sealing 7day, and drying thereafter)								
	Compressive strength (N/mm^2)			Elastic modulus ($\times 10^3$N/mm^2)			Splitting tensile strength (N/mm^2)		
	3 day	7 day	28 day	3 day	7 day	28 day	3 day	7 day	28 day
B30	21.4	34.1	41.9	22.1	27.8	28.5	2.09	2.92	3.70
B20	15.4	26.4	40.4	20.5	23.7	28.2	1.64	2.31	3.51
B10	8.7	20.3	37.5	15.6	22.6	28.4	0.98	1.93	3.53
N30	29.0	38.1	48.6	26.0	29.6	30.6	2.83	2.99	4.39
N20	24.8	36.1	47.8	22.9	30.4	29.7	2.62	3.04	4.32
N10	17.3	33.9	44.8	21.0	26.0	29.6	1.80	2.67	3.66
B30-SRA	22.1	33.9	47.5	23.0	26.7	29.1	1.36	1.72	3.78
B20-SRA	16.0	26.0	41.6	21.0	23.5	29.5	1.31	1.41	3.40
B30-C-SRA	20.2	31.3	44.4	20.1	25.6	29.5	1.26	1.48	3.55
B30-C-Ex	22.6	33.2	44.8	24.9	27.6	29.8	2.20	3.00	3.39

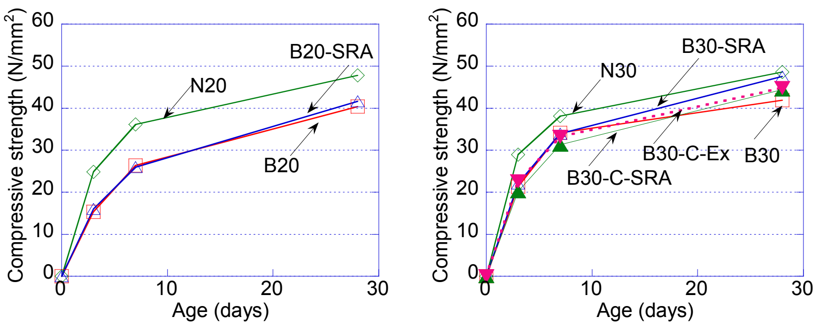

Figure 2. Compressive strength results, left: in 20^{o}C, right: in 30^{o}C

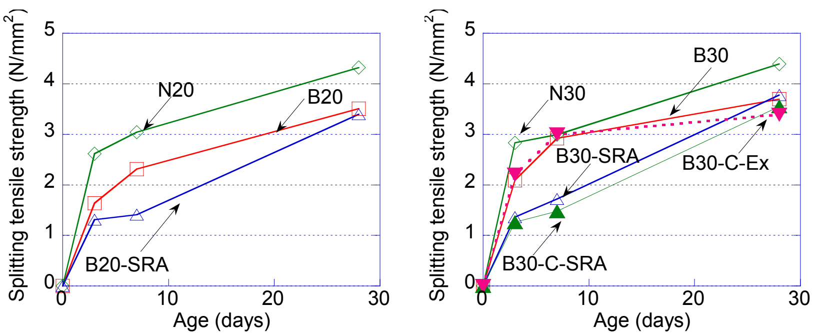

Figure 3. Split tensile strength results, left: in 20^{o}C, right: in 30^{o}C

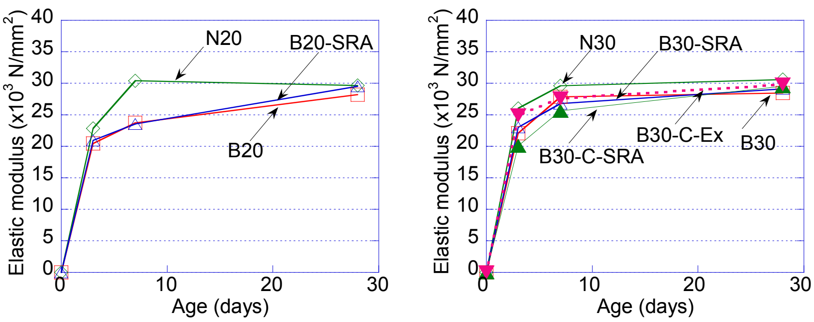

Figure 4. Elastic modulus test results, left: in 20^{o}C, right: in 30^{o}C

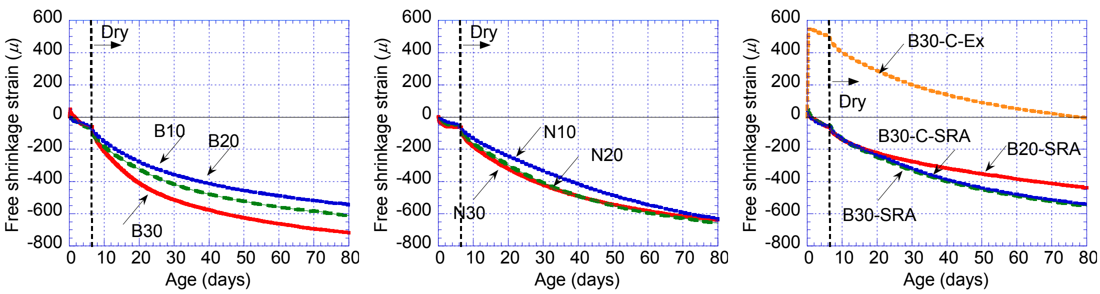

Figure 5. Free shrinkage test result examples, left: BFS concrete, centre: Normal concrete, right: modified BFS concrete

Results of the restrained shrinkage cracking tests are compiled in Table 9 and the developments of restrained shrinkage stresses are shown in Figure 6 and Figure 7. As shown in Figure 6, development of the restrained shrinkage stress in BFS concrete was largely depending on temperature (left daiagram) while the normal concrete was less sensitive to temperature (right). In Table 9, i) retrained shrinkage stress at drying initiation is larger, and ii) cracking age is earlier in BFS concrete at 20 and 30°C than in normal concrete. Figure 7 also depicts the effects of BFS concrete modification on restrained cracking behaviour. Remarkable improvement in terms of cracking age was found in modified BFS concrete using SRA both at 20^{o}C and 30^{o}C (B20-SRA and B30-SRA) while mixes combining coarse BFS powder and shrinkage reducing additives show limited improving effects (B30-C-SRA and B30-C-Ex).

Table 9. Results of restrained shrinkage cracking experiment

Specimen	Restrained shrinkage tensile stress at dying initiation (N/mm^2)		Cracking age (days)		Cracking strength (N/mm^2)	
B30	0.59	0.60	21.2	19.2	2.46	2.34
	0.60		17.2		2.22	
B20	0.45	0.45	37.6	34.7	2.80	2.83
	0.45		31.9		2.87	
B10	0.27	0.25	57.9	48.0	2.90	2.73
	0.23		38.2		2.56	
N30	0.32	0.36	40.8	36.8	2.66	2.58
	0.39		32.8		2.51	
N20	0.34	0.35	42.8	42.0	3.00	3.00
	0.37		41.2		2.99	
N10	0.32	0.33	56.1	43.5	3.06	2.69
	0.33		30.9		2.32	
B30-SRA	0.41	0.39	71.7	58.9	2.72	2.44
	0.36		46.1		2.16	
B20-SRA	0.51	0.45	86.1	80.0	2.58	2.33
	0.39		73.8		2.07	
B30-C-SRA	0.37	0.36	27.3	28.0	1.63	1.67
	0.36		28.7		1.70	
B30-C-Ex	-0.22	-0.22	36.4	34.7	1.60	1.49
	-0.23		32.9		1.37	

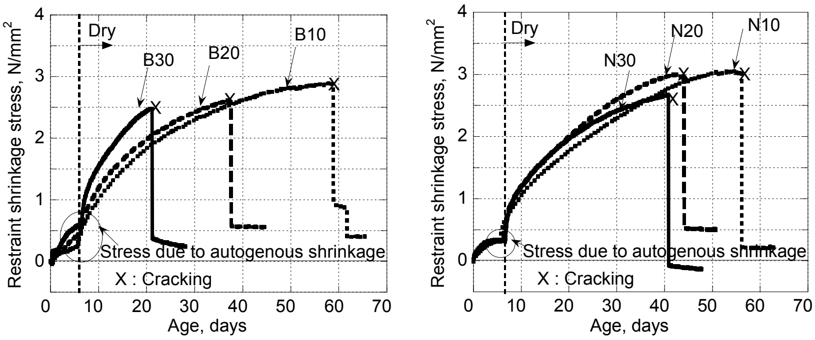

Figure 6. Restrained cracking test result examples, left: BFS concrete, right: Normal concrete

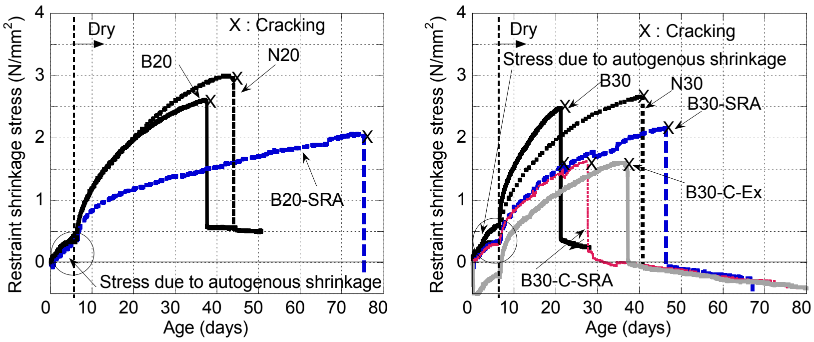

Figure 7. Effects of BFS concrete modification on restrained cracking behaviour, left: at 20^{o}C, right: 30^{o}C

Discussion. Cracking resistance represented by cracking age is illustrated in Figure 8. As shown in Figure 8, cracking age of BFS concrete was earlier than that of the normal concrete and hence the cracking resistance of BFS concrete is lower than that of the normal concrete when ambient temperature is higher than 20 °C. Primary reason for BFS concretes' low crack resistance at higher temperature appears larger free shrinkage as shown left and central diagrams in Figure 5. This is likely due to considerable autogenous shrinkage which drives the development of restrained shrinkage stress than that of the normal concrete. This is particularly prominent in B30 specimen that was subjected to 30°C.

However, Modified BFS concretes with SRA have impressively improved crack resistance. This improvement is significant at 20 °C but outstanding even at 30 °C. This appears to arise due to shrinkage reduction demonstrated in right diagram in Figure 5. Contrary to this effect, coarse BFS powder combined with SRA and expansive agent provides limited improvements on cracking age, whose cracking resistances do not reach to that of normal concrete. This insufficient improvement can be explained by low cracking strength shown in Figure 7, where cracking strength of B30-C-Ex and B30-C-SAR is much lower than the others. Reasons for this low strength are not known at this stage but further investigation should be necessary.

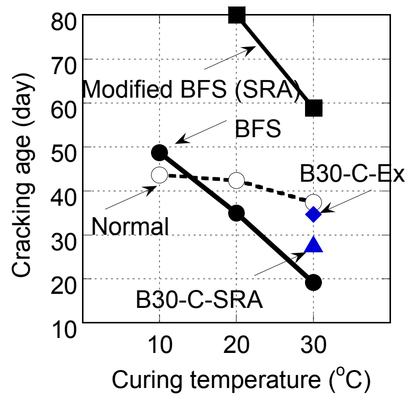

Figure 8. Effects of concrete type and ambient temperature on the cracking age

CONCLUSION

Cracking resistance of BFS concrete in hot environment was focused and aimed at being improved by investigating with restrained cracking experiments in this study. BFS concrete were modified using a new water retaining type SRA, coarse BFS powder, and expansive agent. As a result of the experiment, next findings were revealed.

1) Larger Shrinkage developed in BFS concrete than in normal concrete, particularly eminent in ambient temperature 30°C, can be effectively restricted using the water retaining type SRA.

2) BFS concrete's early cracking age in 30°C can be effectively extended using the water retaining type SRA better than normal concrete, which appears a powerful option to improve its shrinkage cracking resistance in hot environment.

3) The water retaining type SRA significantly strengthen crack resistance of BFS concrete in 20°C as well as in 30 °C.

4) Effects of coarse BFS powder combined with either the water retaining type SRA or the expansive agent on shrinkage resistance improvement are not significant in 30°C.

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