EFFECT OF OPTIMIZING CURING CONDITION AND CONSTITUTIVE MATERIALS ON IMPROVING SHRINKAGE CRACKING RESISTANCE OF BFS BLENDED CEMENT CONCRETE EXPOSED TO HOT ENVIRONMENT

T. KANDA[1*†], H. MOMOSE[1], K. ISHIZEKI[1], K. IMAMOTO[2] and C. KIYOHARA[2]

[1]*Kajima Technical Research Institute, Japan*

[2] *Department of Architecture, Tokyo University of Science, Japan*

ABSTRACT

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.

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 simulating construction work under hot weather. 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. In the experiments, effects of initial curing condition before drying on cracking resistance were also investigated. Modified BFS concretes were mixed by optimizing SO_3 contents in blended cement and course aggregate type. As a result of the experiment, BFS concretes' low shrinkage cracking resistance under hot environment can be substantially improved by using modified BSF concrete with high SO_3 content BFS and limestone coarse aggregate. Furthermore, water curing before drying at 7 day age shows visible cracking age enhancing effects compared with sealed curing. As a result of this study, we found practical cracking resistance strengthening measure for BFS concrete under hot environment, which appears to extend the concrete's application.

Keywords: Blast-furnace slag, cracking, shrinkage, temperature, curing conditon

* Corresponding author: Email: kandat@kajima.com

† Presenter: Email: kandat@kajima.com

1. 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.

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 a few restrained cracking test data were published under limited testing conditions in literatures (Pane and Hansen 2008a and 2008b, 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 ^{o}C unlike at 10 and 20 ^{o}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 and different initial curing conditions 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.

2. EXPERIMENTAL DESIGN

2.1. Experiments Overview

Restrained shrinkage cracking experiment was performed. Experimental parameters and their variations are shown in Table 1. The experiment consists of three series, temperature series, material series, and curing series where the first 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 from 10 to 30°C. The material series are planned to investigate to compensates shrinkage crack resistance degradation for BFS concrete mainly in hot environment by involving low shrinkage BFS and limestone coarse aggregate. In the curing series, effects of initial curing condition before drying on cracking resistance were also investigated.

Table 1 Test parameters and variation

Exp. series	Exp. parameters	Variations
Temp. series (Kanda et al. 2012)	BFS addition	Normal BFS, none
	Ambient temperature	10 ^{o}C 20 ^{o}C 30 ^{o}C
Material series	BFS addition	Low shrinkage BFS, none
	Coarse aggregate type	Sand stone, Lime stone
Pre-curing condition	Ambient temperature	20 ^{o}C 30 ^{o}C
	pre-curing condition	water curing, sealed curing

Table 2 Test parameter combination

Exp. series	Specimen	Experimental parameters				
		Concrete type	*Ambient temperature	BFS type	Coarse aggregate	Pre-drying curing
Temp. series (Kanda et al. 2012)	N10	Normal concrete	10 ^{o}C (RH40%)	None	Sand stone	Sealed
	N20		20 ^{o}C (RH60%)			
	N30		30 ^{o}C (RH60%)			
	B10	BFS concrete	10 ^{o}C (RH40%)	Normal		
	B20		20 ^{o}C (RH60%)			
	B30		30 ^{o}C (RH60%)			
Material series	N30-Lime	Normal concrete	30 ^{o}C (RH60%)	None	Lime stone	Sealed
	BLS30	Modified BFS concrete	30 ^{o}C (RH60%)	Low shrinkage	Sand stone	Sealed
	B30-Lime		30 ^{o}C (RH60%)	Normal	Lime stone	Sealed
Curing series	BLS20-W	Modified BFS concrete	20 ^{o}C (RH60%)	Low shrinkage	Sand stone	Water
	BLS30-W		30 ^{o}C (RH60%)	Low shrinkage	Sand stone	Water
	BLS30-Lime-W		30 ^{o}C (RH60%)	Low shrinkage	Lime stone	Water

* Numbers in parenthesizes show ambient relative humidity.

2.2. Materials, Mix Design, Mixing and Placing Method

Materials used and their mix proportions are shown in Table 3and Table 4. In the temperature series, Portland cement was the only binder for normal concrete while for BFS concrete, BFS fine powder substituting 42% 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, low shrinkage BFS and limestone coarse aggregate are used for modified 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, BFS concrete is modified adopting the above constitutive materials. Low shrinkage BFS contains over 5% of SO_3 amount, which is beyond upper limit, 4%, specified in JIS A 6206. Higher SO_3 amount leads to active ettringite formation at early stage of hydration, which causes expansive strain and compensating shrinkage strain thereafter. Limestone aggregate is also adopted to reduce shrinkage strain.

In the curing series, effects of water curing before drying are investigated, which appears to significantly affect shrinkage behavior of BFS concrete (Saric-Coric and Aïtcin 2003). Water curing is well known strongly enhancing hydration of BFS blended cement much more effective than that of Portland cement. Initial water curing for BFS concrete is expected to lead higher cracking strength, lower shrinkage and resulting better shrinkage cracking resistance.

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
Cement	OPC	Density 3.16g/cm^3	JIS R 5210
BFS powder	Normal BFS	Specific surface area by Blaine 4170 cm^2/g Density 2.89g/cm^3	JIS A 6206
	Low shrinkage BFS	Specific surface area by Blaine 4880 cm^2/g Density 2.89g/cm^3	–
Fine aggregate	Blended sand: crashed sand and land sand	Density in saturated surface-dry condition: 2.64g/cm^3 Percentage of water absorption: 1.34% Fineness modulus: 2.61	JIS A 5005
Coarse aggregate	Crashed gravel: Sand stone	Density in saturated surface-dry condition: 2.65g/cm^3 Percentage of water absorption: 0.6%	JIS A 5005
	Crashed gravel: Lime stone	Density in saturated surface-dry condition: 2.70g/cm^3 Percentage of water absorption: 0.41%	JIS A 5005
Plasticizer	Combined: polycarboxylic and lignin sulphonic acid	Density 1.08g/cm^3	JIS A 6204

Table 4 Mix proportion

Exp. Series	Concrete type	Water to binder ratio (%)	Sand-aggregate ratio (%)	BFS adding ratio in binder	Unit weight (kg/m^3)			
					*Water	Cement	Normal BFS	Low shrinkage BFS
Temp. series	BFS concrete	50	46.3	0.42	175	203	147	-
	Normal concrete	50	46.7	-	175	350	-	-
Material series	N30-Lime	50	46.0	-	175	350	-	-
	BLS30	50	46.0	0.47	175	186	-	165
	B30-Lime	50	46.0	0.47	175	186	-	165
Curing series	BLS20-W BLS30-W	50	46.0	0.47	175	186	-	165
	BLS30-Lime-W	50	46.0	0.47	175	186	-	165

Table 5 Characteristics of BFS powders

Characterisitcs		Characteristics of normal BFS	Characteristics of low shrinkage BFS	Requirement in JIS A 6206
Density	(g/cm^3)	2.89	2.89	≧ 2.8
Specific surface area	(cm^2/g)	4139	4880	≧ 3000 < 5000
Reactivity index	(%)	83 at 7day age 103 at 28 day age 114 at 91 day age	74 at 7day age 88 at 28 day age 97 at 91 day age	≧ 55 at 7 day age ≧ 75at 28 day age ≧ 95 at 91 day age
Relative flow value	(%)	100	103	≧ 95
Content of magnesium oxide	(%)	6.16	4.98	≦ 10.0
Content of sulfur trioxide	(%)	1.87	5.1	≦ 4.0
Ignition loss	(%)	1.26	1.75	≦ 3.0
Content of chloride ion	(%)	0.004	0.004	≦ 0.02
Basicity		1.84	1.95	≧ 1.6

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	

2.3. 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 in the temperature and material series 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. In the curing series, specimens were stored as same as in the other series till 7days, but only difference was 2cm depth of water pooled on the top surface in specimens. 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 or water curing till the age of 7 days and subsequent air curing with ambient condition shown in Table 2.

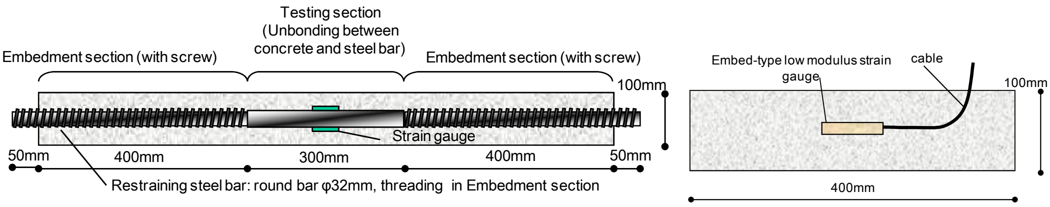


Figure 1 Specimen for the shrinkage cracking experiment, left: restrained cracking test specimen, right: free shrinkage test specimen

3. EXPERIMENTAL RESULTS AND DISCUSSION

Table 7 Mechanical properties

Specimen	Identical curing condition to restraint shrinkage test specimen (sealed or water cured until 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
N30-Lime	30.3	38.2	42.8	31.7	34.0	32.8	-	3.36	3.45
BLS30	25.6	34.4	42.9	26	28.8	31.0	-	3.37	3.74
B30-Lime	28.9	38.4	45.1	30.1	33.2	31.8	-	2.75	3.64
BLS20-W	18.8	27.5	44.7	23.5	27.2	30.6	-	2.57	3.58
BLS30-W	25.2	35.1	48.2	25.3	30.6	31.4	-	3.32	3.97
BLS30-Lime-W	27.5	36.5	47.5	28.9	31.8	34.2	-	3.14	3.48

3.1. Results of Restrained Cracking Experiment

Results of the mechanical tests are compiled in Table 7. It is seen in the table that compressive strength and split tensile strength of BFS concrete cured initially in water appear higher than that of cured in sealed condition.

Changes in free shrinkage strain of all mixes are shown in Figure 2. A left Figure 2a 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 in Figure 2b 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. Figure 2c demonstrates modified BFS concretes with low shrinkage BFS or lime stone coarse aggregate showing much smaller free shrinkage than BFS concrete, where this reduction at 80 days reaches 200μ at 30°C. Water curing further restricts free shrinkage of modified BFS concrete. Figure 2d shows free shrinkage results of curing series, where BLS30-W demonstrates 250μ smaller free shrinkage at 80 days than B30 in Figure 2b. Furthermore, BLS30-Lime-W has another 100μ smaller free shrinkage than BLS30-W.

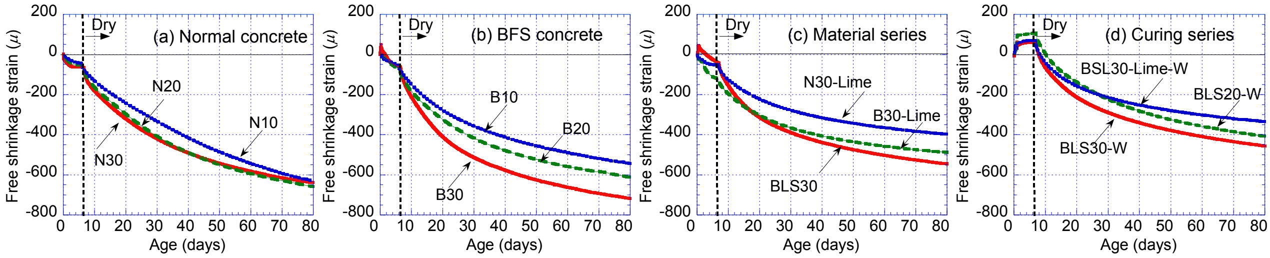


Figure 2 Free shrinkage test result examples

Results of the restrained shrinkage cracking tests are exampled in Figure 3 and Figure 4, where the developments of restrained shrinkage stresses are shown. As shown in Figure 3, development of the restrained shrinkage stress in BFS concrete was largely depending on temperature (left diagram) while the normal concrete was less sensitive to temperature (right). In Figure 3, 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 4 also depicts the effects of BFS concrete modification and water curing on restrained cracking behavior. Visible improvement in terms of cracking age was found in modified BFS concrete using low shrinkage BFS at 30°C (BLS30) and lime stone coarse aggregate (B30-Lime) in Figure 4a. Figure 4b indicates water curing further improve crack resistance of modified BFS concrete. Notable change in restraint stress profiles in Figure 4b is in compressive stress development in initial curing stage contrast to tensile stress in Figure 3a and Figure 4a.

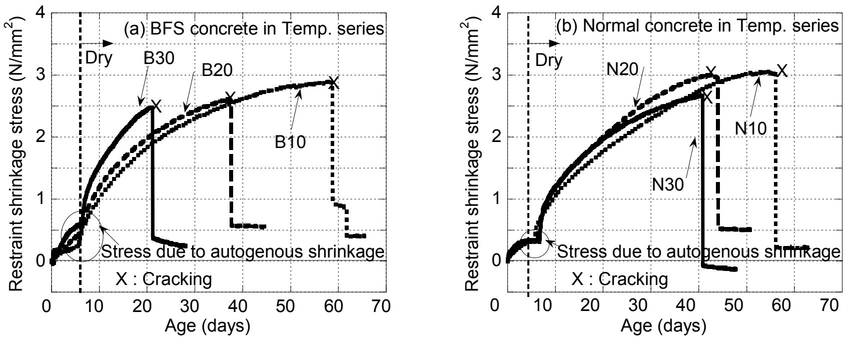


Figure 3 Restrained cracking test result examples, in temperature series

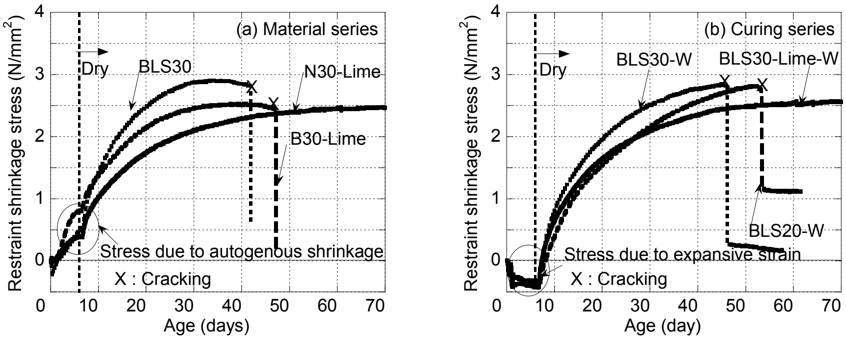
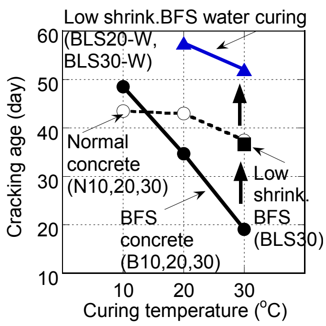


Figure 4 Effects of BFS concrete modification and water curing on restrained cracking behaviour

3.2. Discussion

Cracking resistance represented by cracking age is illustrated in Figure 5, where cracking age of BFS concrete was earlier than that of the normal concrete. The cracking resistance of BFS concrete is lower than that of the normal concrete when ambient temperature is higher than 20 ^{o}C in Figure 5. Primary reason for BFS concretes' low crack resistance at higher temperature appears due to larger free shrinkage as shown in Figure 2a and b. This is likely due to considerable autogenous shrinkage which drives larger restrained shrinkage stress developing than that of the normal concrete. This is particularly prominent in B30 specimen that was subjected to 30^{o}C.

However, Modified BFS concretes with low shrinkage BFS have impressively improved crack resistance, comparable to Normal concrete at 30 ^{o}C. Further improvement is achieved beyond the Normal concrete with water curing as shown Figure 5. This appears to arise due to shrinkage reduction demonstrated in Figure 2c and d. Figure 6 depicts crack resistance improvement at 30 ^{o}C due to the effects of experimental parameters. In Figure 6, adopting low shrinkage BFS (BLS30) or limestone aggregate (B30-Lime) strengthen crack resistance of BFS concrete in hot environment comparable to normal concrete. Using low shrinkage BFS and initial curing condition before drying leads to better crack resistance, and additional usage of limestone aggregate shows remarkable improvement.



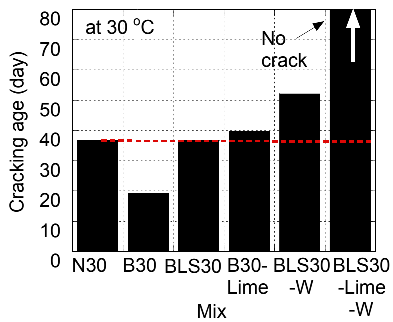


Figure 5: Effects of concrete type, material modification and ambient temperature on the cracking age

Figure 6: Crack resistance improving for BFS concrete

4. CONCLUSIONS

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 concretes were modified using low shrinkage BFS and limestone coarse aggregate. Initial water curing before drying is also tried to strengthen crack resistance. 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^{o}C, can be effectively restricted using low shrinkage BFS and limestone coarse aggregate.

2) BFS concrete's short cracking age in 30^{o}C can be effectively extended using the low shrinkage BFS and limestone coarse aggregate better than normal concrete.

3) Adding to the above material modification, initial in-water curing condition demonstrates powerful option to improve BFS concretes' shrinkage cracking resistance in hot environment.

AKNOWLEDGEMENT

This study was supported by Japan Society for the Promotion of Science, through research grant 5301-23360252-0002 to Kajima Technical Research Institute and Tokyo University of Science.

REFERENCES

Aly, T, Sanjayan, J,G. (2008) "Factors contributing to early age shrinkage cracking of slag concrete.", *Materials and Structures*, 41, 633-642.

Japan Concrete Institute (2010) "*JCI-TC083A Technical Committee on Reduction of Shrinkage Cracks and Durability Enhancement from Viewpoints of Mineral Admixtures, Technical Committee Reports*." (http://www.jci-net.or.jp/j/publish/etc/guide_0069.html)

Kanda, T., Shintani, A., Momose, H., Imamoto, K., and Ogawa, A. (2012) "An Experimental Study of Shrinkage Cracking Resistance of BFS Blended Cement Concrete Subjected to Different Ambient Temperature.", *Proceedings of the International Conference, Concrete in the Low Carbon Era*, University of Dundee, UK, 1106-1118.

Pane, I, Hansen, W. (2008a) "Predictions and verifications of early-age stress development in hydrating blended cement concrete.", *Cement and Concrete Research*, 38, 11, 1315-1324.

Pane, I, Hansen, W. (2008b) "Investigation on key properties controlling early-age stress development of blended cement concrete," *Cement and Concrete Research*, 38, 11, 2008, 1325-1335.

Saric-Coric, M., Aïtcin, P-C. (2003) "Influence of curing conditions on shrinkage of blended cements containing various amounts of slag," *ACI Materials Journal*, 100, 6, 477-483.