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Reduction of Autogenous Shrinkage of Ultra-High-Strength Concrete Containing Silica Fume-Premix Cement

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ABSTRACT

This paper investigates autogenous shrinkage behaviour of ultra-high-strength concrete containing silica fume-premix cement with a water-to-binder-ratio of 13% to 20%. The concrete mix was added with expansive additive (EX), shrinkage reducer (SR) or shrinkage-reducing type superplasticizer (SRSP) solely or in combination of EX and SR or EX and SRSP, and effects of these admixtures in reducing autogenous shrinkage were examined. The ultra-high-strength concrete specimens subjected to high temperature to simulate actual temperature conditions in massive columns exhibited distinct differences from those cured at a constant temperature of 20°C in autogenous shrinkage strain behaviour and resultant stress induced. Significant reduction in autogenous shrinkage was noted in all specimens, irrespective of the temperature conditions. Further investigation revealed that the effect of combined use of EX and SR, or of EX and SRSP, was equal to or greater than the sum of their individual effects.

Keywords. Ultra-high-strength concrete, Autogenous shrinkage, Silica fume-premix cement, Expansive additive, Shrinkage reducer

INTRODUCTION

High-strength concrete has been widely studied over the last decade and has been increasingly applied to enhance the structural performance and durability of concrete structures. Recently, ultra-high-strength concrete (UHSC) with design strength of 150N/mm^2 has been in practical use. However, such very low water-to-binder ratio (W/B) concretes are known to shrink significantly at early ages, which is likely to be caused by autogenous (self-desiccation) shrinkage, and possibly exhibit increased sensitivity to early-age cracking (Maruyama, 2008). Since UHSC is expected to yield more durable structural members, the establishment of a technique for minimizing autogenous shrinkage is an important task.

Experimental investigations on how to control autogenous shrinkage have been carried out comprehensively from a material point of view. These studies revealed that inorganic expansive additive and/or organic shrinkage reducer are effective in reducing autogenous shrinkage (Tazawa, 1992, Tanimura, 2002). However, few studies have been performed to evaluate the applicability of aforementioned admixtures on reducing autogenous shrinkage of UHSC with a lower W/B of 20% or less.

The present study, therefore, focused on investigating how much expansive additive and/or Shrinkage reducer contributes to reducing autogenous shrinkage in UHSC.

EXPERIMENTAL PROGRAMS

Table 1 and Table 2 list the constituent materials and mixture proportions of concretes, respectively. The expansive additive with a higher fineness (SSA: approximately 5000cm^2/g), compared to conventional one (SSA: approximately 3300cm^2/g), was used to reduce the risk of remarkable expansion at long-term ages (Tanimura, 2009). Targeted slump flow value and air content of concrete were 750±75mm for W/B=13% and 600±50mm for W/B=16.5-20%, and less than 2%, respectively.

Table 1. Constituent materials

Materials	Symbol	Type / Characteristics
Cement	C	Silica fume-premix cement / density: 3.07g/cm^3, SSA*: 6160cm^2/g
Expansive additive	EX	Lime-based / density: 3.19g/cm^3, SSA*: 4920cm^2/g
Fine aggregate	S	Pit sand / density**: 2.56g/cm^3(series 1,2), 2.58g/cm^3(series 3) absorption: 2.24%(series 1,2), 1.91%(series 3)
Coarse aggregate	G	Crushed sand stone / maximum size: 20mm, density**: 2.64g/cm^3, absorption: 0.5 %, solid content: 60%
Shrinkage reducer	SR	Lower-alcohol alkylene oxide adduct
Superplasticizer (SP)	SP1	High-range water reducer / Polycarboxylic acid based
	SP2	Air-entraining and high-range water reducer / Polycarboxylic acid based
	SP3	High-range water reducer (shrinkage reducing type) / Polycarboxylic acid and glycolic based

* Specific surface area measured by Braine's Method ** Saturated surface-dry condition

Table 2. Mixture proportions of concrete

Series	Symbol	W/B* (%)	s/a (vol.%)	Unit Content (kg/m^3)					
				W	C	EX	S	G**	SR
1	PL13	13.0	30.0	150	1154	-	349	840	-
	EX13				1124	30	349		-
	PL16.5	16.5	38.7	155	939	-	515		-
	EX16.5				909	30	516		-
	PL20	20.0	44.5	155	775	-	652		-
	EX20				745	30	653		-
2	PL	13.0	30.0	150	1154	-	349	840	-
	EX				1124	30	349		-
	SR			144	1154	-	349		6
	ES				1124	30	349		6
3	SP1	13.0	30.0	150	1154	-	351	840	-
	SP1-EX20				1134	20	352		-
	SP1-EX30				1124	30	352		-
	SP3				1154	-	351		-
	SP3-EX20				1134	20	352		-
	SP3-EX30				1124	30	352		-

* B=C+EX ** Bulk volume of coarse aggregate: 0.53 m^3/m^3

Prismatic specimens of 100 x 100 x 800 mm for series 1 and 100 x 100 x 400 mm for series 2 and 3 were prepared to measure the autogenous shrinkage strain of concrete. An embedded strain gauge with a reference length of 100 mm and low elastic modulus of 39 N/mm^2 to measure the free deformation, and a thermocouple were placed at the center of the specimens. The autogenous shrinkage strain of concrete was determined by subtracting the thermal strain from the measured strain, assuming the coefficient of thermal expansion of concrete to be 10 x 10^{-6}/°C. RC beam specimens of 100 x 100 x 800 mm with the embedded reinforcing bar was prepared to evaluate the autogenous shrinkage stress of concrete. Reinforcement ratio was 2.0%, 3.8% and 8.0% for series 1 and 3.5% for series 2. Self-temperature compensated wire strain gauges were attached to the upper and bottom sides of the reinforcement at mid-span to measure the reinforcement strain. To minimize the friction between the mould and the concrete specimen, a 1.0 mm thick Teflon sheet was placed at the bottom of the mould. Further, a 3 mm thick polystyrene board was placed on both ends of the mould. All the surfaces of the specimen mould were covered with a 0.1 mm thick polyester film. Cylindrical specimens of 100 x 200 mm were prepared to measure the compressive strength at the age of 7 and 28 days in accordance with JIS A 1108.

Figure 1 shows curing conditions of concrete specimens. High temperature hysteresis was considered to simulate actual temperature conditions in massive column members constructed by UHSC.

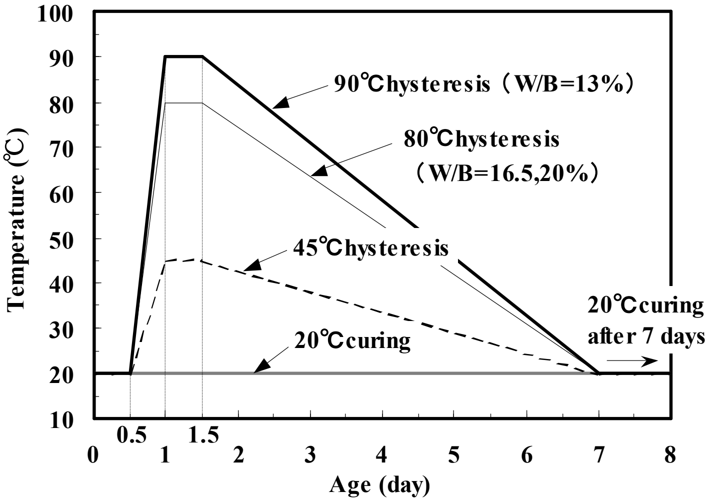

Figure 1. Curing conditions

Prismatic specimens of series 1 were demoulded at the age of 7days. Those of series 2 and 3 were demoulded at the age of 24 hours for 20°C curing and 7 days for temperature hysteresis curing. After demoulding, all the prismatic specimens were promptly sealed with a 0.1 mm thick aluminium adhesive tape to prevent water evaporation. Cylindrical specimens for testing compressive strength were cured under sealed condition except for 20°C water curing.

RESULTS AND DISCUSSION

Table 3 shows the fresh properties of concrete and time of setting of sieved out mortar. The slump flow values ranged within the targeted value, from 740 to 805mm for W/B=13% mixtures and from 570 to 615mm for W/B=16.5, 20% mixtures. The dosage of superplasticizer of concrete with expansive additive was somewhat larger than that of concrete without expansive additive regardless of addition or not of shrinkage reducer. Time of setting tended to be early in concrete with expansive additive, while be late in concrete with shrinkage reducer. However, the effect of containing expansive additive and/or shrinkage reducer on fresh properties of concrete is not significant from the viewpoint of practical use.

Table 3. Fresh properties of concrete and setting time

Series	Symbol	SP		Slump flow* (mm)	500mm-flow time (s)	Air content** (%)	Setting*** (h-m)	
		type	B×mass%				Initial	Final
1	PL13	SP1	1.2	740	11.2	1.2	11-45	13-50
	EX13	SP1	1.6	750	13.2	1.4	8-45	11-00
	PL16.5	SP1	0.8	570	18.4	1.5	9-00	10-55
	EX16.5	SP1	0.9	610	15.1	1.5	5-50	7-30
	PL20	SP2	1.35	615	9.8	1.5	13-35	15-45
	EX20	SP2	1.5	610	12.9	1.3	10-15	12-15
2	PL	SP1	1.20	805	10.2	1.2	12-05	14-05
	EX	SP1	1.45	790	12.1	1.0	8-20	10-10
	SR	SP1	1.20	785	9.1	1.1	14-40	17-00
	ES	SP1	1.45	785	9.3	1.2	10-25	12-45
3	SP1	SP1	1.05	750	15.1	1.4	11-05	14-05
	SP1-EX20	SP1	1.20	770	14.2	1.4	8-30	11-25
	SP1-EX30	SP1	1.30	780	15.2	1.2	8-20	11-10
	SP3	SP3	1.13	750	14.5	1.5	11-40	14-50
	SP3-EX20	SP3	1.28	780	13.4	1.4	8-50	12-10
	SP3-EX30	SP3	1.33	785	14.5	1.3	8-25	11-25

* JIS A 1150 ** JIS A 1128 *** JIS A 1147

Table 4 shows the results of compressive strength of the investigated mixtures. The compressive strength tended to be somewhat low in concrete with shrinkage reducer, while be negligible in concrete with expansive additive.

Table 4. Experimental results of compressive strength

Series	Symbol	Age (days)	20 °C curing	45 °C hysteresis	80 °C hysteresis	90 °C hysteresis
1	PL13	7	128	160	-	174
		28	157	167	-	183
	EX13	7	126	163	-	185
		28	162	171	-	182
	PL16.5	7	105	132	142	-
		28	139	144	145	-
	EX16.5	7	104	132	148	-
		28	129	138	148	-
	PL20	7	78.7	109	123	-
		28	118	118	125	-
	EX20	7	86.0	114	132	-
		28	119	125	132	-
2	PL	7	137	-	-	171
		28	165	-	-	172
	EX	7	132	-	-	176
		28	165	-	-	188
	SR	7	125	-	-	171
		28	161	-	-	164
	ES	7	120	-	-	181
		28	161	-	-	178
3	SP1	7	-	-	-	186
	SP1-EX20	7	-	-	-	191
	SP1-EX30	7	-	-	-	194
	SP3	7	-	-	-	175
	SP3-EX20	7	-	-	-	189
	SP3-EX30	7	-	-	-	182

Figure 2 shows the measurement results of autogenous shrinkage strain of series 1 concrete specimen. The data are plotted as a function of temperature adjusted age (CEB-FIP, 1990), after initial set. Autogenous shrinkage strain rapidly developed when subjected to high temperature hysteresis.

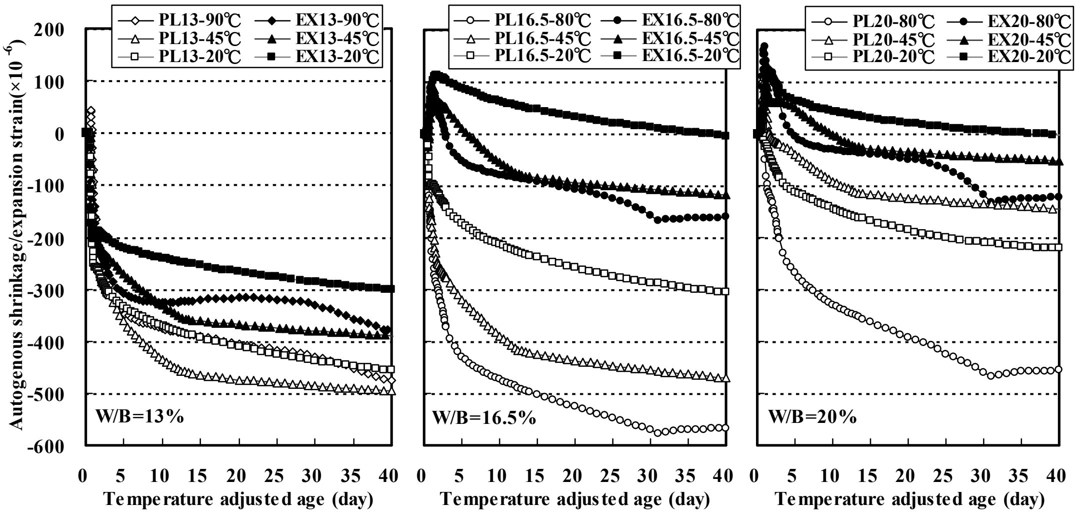

Figure 2. Autogenous shrinkage/expansion strain behaviour (series 1)

Figure 3 shows the rate of reduction in autogenous shrinkage strain at temperature adjusted age of 40 days, corresponding to the age of 7 days for 90 °C hysteresis and of 16 days for 80 °C hysteresis. The rate of reduction under temperature hysteresis curing of W/B=13%, 16.5% and 20% concrete was approximately 20%, 70% and 70%, respectively, regardless of maximum temperature. On the other hand, that under 20 °C curing was approximately 35%, 98% and 98%, respectively; therefore, the rate of reduction under temperature hysteresis curing was smaller than that under 20 °C curing.

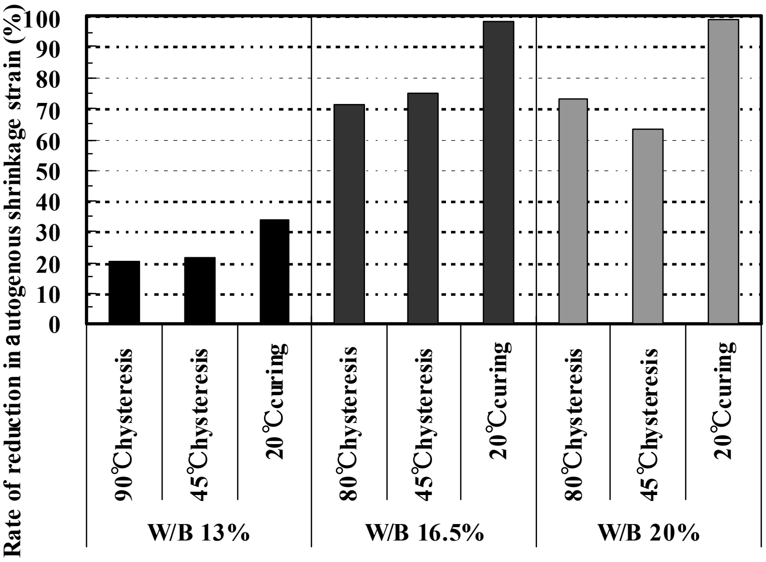

Figure 3. Rate of reduction in autogenous shrinkage strain (series 1)

Figure 4 shows the rate of reduction in autogenous shrinkage stress at temperature adjusted age of 40 days. The restrained stresses are calculated based on the following equation, derived from the equilibrium of the force among concrete and reinforcement, in which the stress is positive in tension and negative in compression.

$$\sigma_c = -\frac{P_s}{A_c}, \quad P_s = E_s \varepsilon_s A_s \tag{1}$$

where, σ_c : restrained stress of concrete, P_s : axial force in reinforcement, E_s: Young's modulus of reinforcement, ε_s : measured strain in reinforcement, A_s: cross-sectional area of reinforcement, A_c: cross-sectional area of concrete.

The rate of reduction in autogenous shrinkage stress under temperature hysteresis curing of W/B=13%, 16.5% and 20% concrete was approximately 30-45%, 55-70% and 50-75%, respectively.

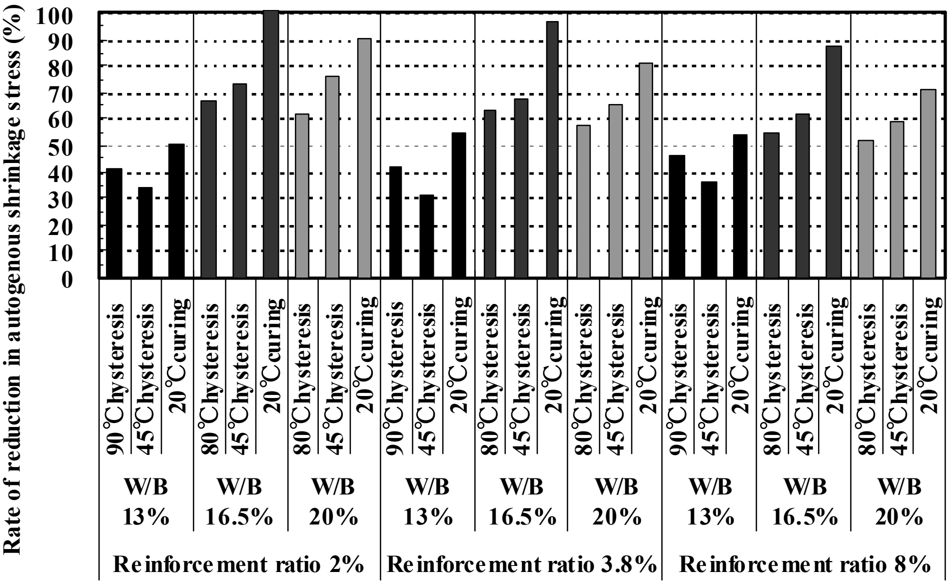

Figure 4. Rate of reduction in autogenous shrinkage stress (series 1)

Figure 5 shows the comparison between the rates of reduction in autogenous shrinkage stress and strain, in order to investigate the influence of restraint or not. The case of W/B=16.5% and 20% revealed the 0-20% higher rate of reduction in autogenous shrinkage strain, however, that of W/B=13% revealed 10-30% higher rate of reduction in autogenous shrinkage stress, therefore rate of reduction differ between strain and stress. The investigation results suggested that the effectiveness of material countermeasure against autogenous shrinkage at early ages should be evaluated based on not only strain behaviour but also stress behaviour.

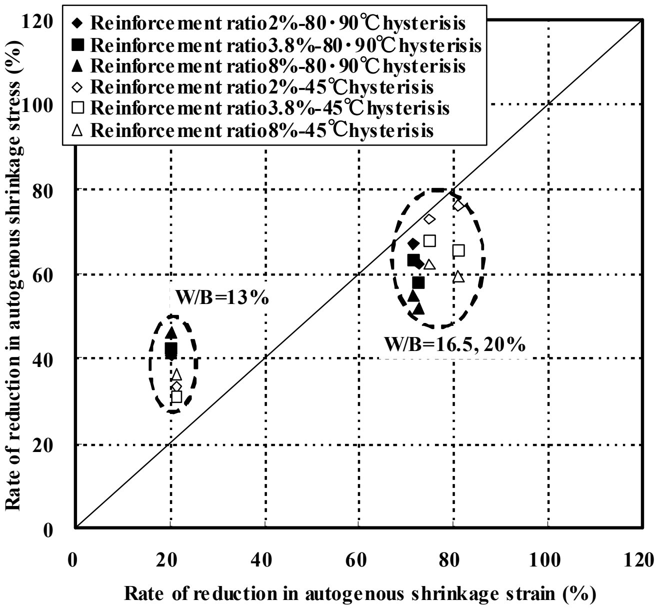

Figure 5. Comparison with the rate of reduction in autogenous shrinkage stress and strain

Figure 6 and Figure 7 shows the amount of reduction in autogenous shrinkage strain and autogenous shrinkage stress of series 2 concrete specimen, respectively. A synergistic effect of using both expansive additive and shrinkage reducer was observed for autogenous shrinkage strain regardless of curing conditions; i.e., the reduction amount of ES was greater than the sum of those of EX and SR, shown in Figure as the calculated values. On the other hand, the reduction amount in autogenous shrinkage stress of ES was almost same as the sum of their individual effects.

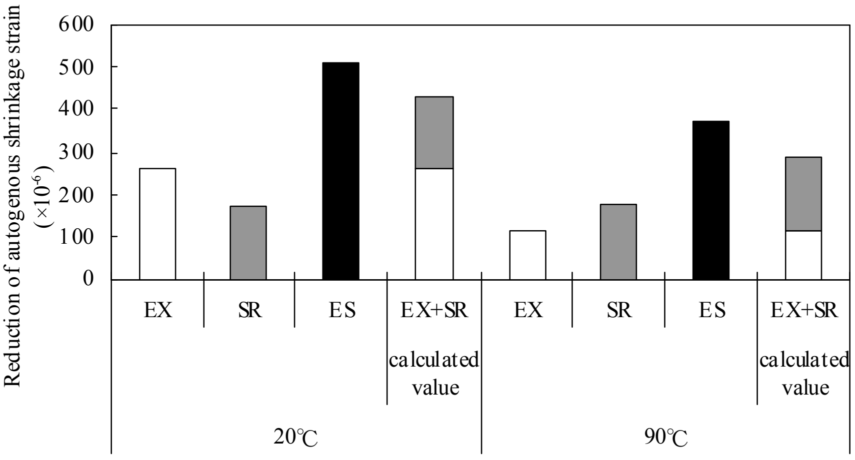

Figure 6. Amount of reduction in autogenous shrinkage strain (series 2)

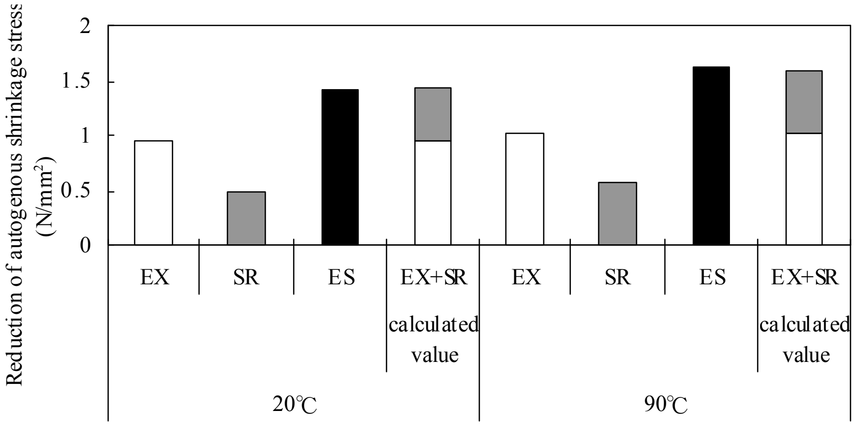

Figure 7. Amount of reduction in autogenous shrinkage stress (series 2)

Figure 8 shows the rates of reduction in autogenous shrinkage strain of series 3 to evaluate the effectiveness of shrinkage reducing type superplasticizer (SP3), compared to the effect of shrinkage reducer (SR) of series 2. The results revealed that work of SP3 was comparable to that of SR.

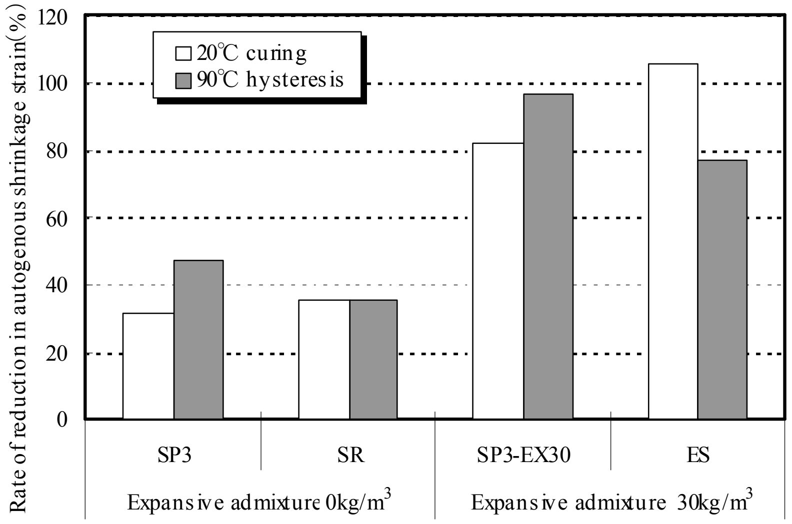

Figure 8. Rate of reduction in autogenous shrinkage strain (series 3)

Thus, significant reduction in autogenous shrinkage strain/stress was noted in all specimens, irrespective of the temperature conditions, demonstrated that expansive additive (EX), shrinkage reducer (SR) or shrinkage-reducing type superplasticizer (SRSP) solely or in combination of EX and SR or EX and SRSP were obviously effective in reducing autogenous shrinkage strain/stress.

CONCLUSIONS

The following conclusions can be drawn from the present study.

(1) The expansive additive (EX), shrinkage reducer (SR) or shrinkage-reducing type superplasticizer (SRSP) solely or in combination of EX and SR or EX and SRSP were obviously effective in reducing autogenous shrinkage not only strain but also stress induced.

(2) Aforementioned effectiveness was displayed even when subjected to high temperature hysteresis, simulating the actual temperature conditions in massive column members.

(3) The effect of combined use of EX and SR, or of EX and SRSP, was equal to or greater than the sum of their individual effects.

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