- Technical Paper -

EXPERIMENTAL STUDY ON SHRINKAGE PROPERTIES OF ULTRA-HIGH STRENGTH STEEL FIBER REINFORCED CONCRETE

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ABSTRACT

This study investigates the shrinkage properties of ultra-high strength steel fiber reinforced concrete developing compressive strength larger than 180MPa. The effects of expansive additive and shrinkage reducing agent on the reduction of shrinkage are also examined. Results reveal that ultra-high strength SFRC is experiencing very small drying shrinkage while extremely high autogenous shrinkage. In addition, the composition with 5% of expansive additive and 1% of shrinkage reducing agent is seen to reduce significantly the autogenous shrinkage.

Keywords: ultra-high strength steel fiber reinforced concrete, autogenous shrinkage, drying shrinkage, expansive additive, shrinkage reducing agent

1. INTRODUCTION

The recent development of various ultra-high strength fiber reinforced concretes is attracting attention worldwide [1, 2]. In Korea, the authors are also developing an ultra-high strength steel fiber reinforced concrete (SFRC) with compressive strength larger than 180MPa [3]. Apart from its compressive strength, this ultra-high strength SFRC also exhibits extremely high flexural strength exceeding 20MPa and remarkable durability compared to previous concretes. Besides, the fabrication of ultra-high strength SFRC requires very low W/B ratio reaching merely 0.2, the use of large quantities of fine binder without coarse aggregates, and curing at high temperatures rising up to 90°C at early age. Such process is likely to accelerate significantly the propagation of hydration at early age, which forecasts very large development of autogenous shrinkage. However, poor attention has been paid on this subject to date.

Accordingly, this study investigates the properties of the drying and autogenous shrinkages of ultra-high strength SFRC and examines the effects of expansive additive and shrinkage reducing agent on the reduction of shrinkage.

2. TEST PROGRAMS

2.1 Test Variables

Table 1 summarizes the test variables. The effects of the steel fibers on ultra-high strength SFRC are examined by comparing a cementitious composite (Plain) without addition of steel fibers and a reference mix (F2) mixed with 2% of steel fibers in volume. Examination is also performed for F2 mixed with 5% expansive additive (F2E5), F2 mixed with 1% shrinkage reducing agent (F2S1), and F2 mixed simultaneously with 5% expansive additive and 1% shrinkage reducing agent (F2E5S1) in order to evaluate the reduction of shrinkage. The effect of high-temperature curing is analyzed through tests conducted on F2 at 90°C and 20°C (F2-W).

Table 1 Test variables

Type	Curing temperature	Mix proportions
Plain	90°C	Cementitious composite
F2		Reference mix (steel fiber 2%)
F2E5		Fiber 2%+EA 5%
F2S1		Fiber 2%+SRA 1%
F2E5S1		Fiber2%+EA5%+SRA1%
F2-W	20°C	Reference mix

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Table 2 Properties of cement and silica fume

Items / Types	Fineness (cm^2/g)	Density (g/cm^3)	Chemical composition (%)					
			SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
Cement	3,413	3.15	21.01	6.40	3.12	61.33	3.02	2.14
Silica fume	240,000	2.10	96.00	0.25	0.12	0.38	0.1	-

Table 3 Properties of filling powder

Items / Types	Mean diameter (μm)	Density (g/cm^3)	Chemical composition (%)					
			SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
Filling powder	10	2.62	99.3	0.15	0.01	0.03	0.04	-

Table 4 Properties of expansive additive

Items / Types	Fineness (cm^2/g)	Density (g/cm^3)	Chemical composition (%)					
			SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
Expansive additive	3,117	2.98	3.80	28.66	13.55	51.35	0.56	16.02

Table 5 Mix proportion of ultra-high strength SFRC(by weight)

Types	W/B	Cement	Silica fume	Sand	Filling powder	Superplasticizer	Steel fiber(V_f)
F2	0.21	1	0.25	1.1	0.3	0.016	2%

2.2 Materials

The cement adopted in the tests is an ordinary Portland cement and silica fume is used as admixture. Their physical and chemical properties are listed in Table 2. The aggregates are a mixing of aggregates A (density 2.62g/cm^3, average grain diameter 0.3~0.5mm, SiO_2 93%) and aggregates B (density 2.62g/cm^3, average grain diameter 0.17~0.3mm, SiO_2 93%) with ratio of 7:3. Filling powder of which physical and chemical properties are listed in Table 3 is added in order to prevent fracture at the cement-aggregate interface. The expansive additive is of CSA (calcium sulfate aluminate) type with properties summarized in Table 4. The shrinkage reducing agent is a powdered glycol type agent (density 3.18g/cm^3) and the superplasticizer is of polycarbonate ether (density 1.01g/cm^3) in a dark brown liquid state with 30% of solid contents. The steel fibers are 13mm long with diameter of 0.2mm and tensile strength of 2,500MPa to improve the toughness. The fibers are mixed with a volumetric proportion of 2% in the cementitious composite.

2.3 Mix Proportions and Mixing Method

Table 5 indicates the mix proportions of the reference mix (F2) as the relative ratio to the quantity of cement. Using a forced mixer (capacity 200ℓ) with controllable speed up to 150rpm, the mixing of ultra-high strength SFRC began with the dry mixing of the cement, silica fume, filling powder and aggregates at 50rpm during 5 minutes. Then, the superplasticizer admixed to the water was introduced and mixing continued at 100~ 120rpm during 5 minutes. Finally, the introduction of the steel fibers ended the mixing at 30rpm during 5 minutes.

2.4 Test Method

(1) Compressive strength

Using a cylindrical specimen of ø100×200 mm, the compressive strength was measured by means of a 500tonf UTM. The resulting value of the compressive strength corresponds to the average of 5 concrete specimens.

(2) Autogenous shrinkage

The autogenous shrinkage tests of the ultra-high strength SFRC were performed in conformity with the prescriptions of JCI(2002)[7] on 100×100×400mm specimens cured at high temperature (90°C) and standard conditions (20°C). However, considering that the high-temperature curing was carried out at 90°C, the measurement of the variations in length of the specimen was conducted dial gauges as well as embedded gauges. Free deformations of the specimens were allowed by disposing 1mm thick Teflon sheet at the bottom of the mold and at both extremities. After casting of concrete, a polyester film was placed to avoid contact with the air and prevent evaporation and absorption at the surface.

The high-temperature curing proceeded by curing at 20±1°C during 1 day before stripping followed by steam curing at

90±2°C during 3 days and, finally under constant temperature of 20±1°C and constant humidity of 60±5%. The standard curing was carried out under constant temperature and humidity conditions. After stripping, the specimens were wrapped 2~3 times with a polyester film and silver foil to prevent evaporation and absorption.

(3) Drying shrinkage

The drying shrinkage was measured by means of the variations in length using dial gauges on 100×100×400mm specimens. The high-temperature curing of the specimen proceeded by 1 day of wet curing at 20±1°C followed by 3 days of steam curing at 90±2°C. Measurement of the length variations were finally conducted on the specimens at defined ages exposed to air dry conditions (temperature 20±1°C, humidity 60±5%). The standard curing was carried out by means of water curing during 7 days and the variations of length were measured on the specimens at defined ages exposed to air dry conditions.

3. TEST RESULTS AND DISCUSSION

3.1 Properties of Fresh Concrete

Table 6 summarizes the properties of the non-hardened ultra-high strength SFRC. The admixing of steel fibers is seen to have quasi no effect on the fluidity and air content. The slump flow being about 600mm reveals that self-compacting may be achieved without tamping. For F2S1 and F2E5S1 corresponding to the mix proportions with shrinkage reducing agent, it is seen that the slump flow increases and the air content reduces and, that the setting time is retarded by 3 hours compared to Plain and F2.

Table 6 Properties of fresh concrete

Type	Slump flow (mm)	Air content (%)	Setting times(hrs)	
			Initial	Final
Plain	595	4.1	13.2	15.6
F2	590	3.9	13.3	15.8
F2E5	570	3.7	12.8	15.6
F2S1	685	2.8	16.2	18.6
F2E5S1	630	2.9	16.9	19.1

3.2 Properties of Compressive Strength

Fig. 1 plots the results of the compressive strength tests. Expect for Plain, the cases for which steam curing was performed at 90°C exhibited compressive strength of about 200MPa at 7 days. Even if F2S1 and F2E5S1 developed slightly reduced strength at 1 day due to the effect of the shrinkage reducing agent, the difference became insignificant since 7 days. Until 7 days, F2-W for which water curing was performed at 20°C presented strength reaching approximately 60% of that of F2, which experienced high-temperature curing. However, the strength increased with time to become similar at 91 days. Besides, the strength of F2-S, which was air cured, could not develop with time and remained merely at 80% of that of F2.

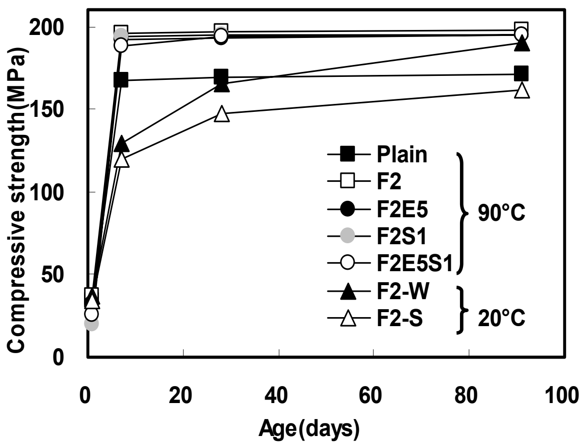

Fig. 1 Compressive strength

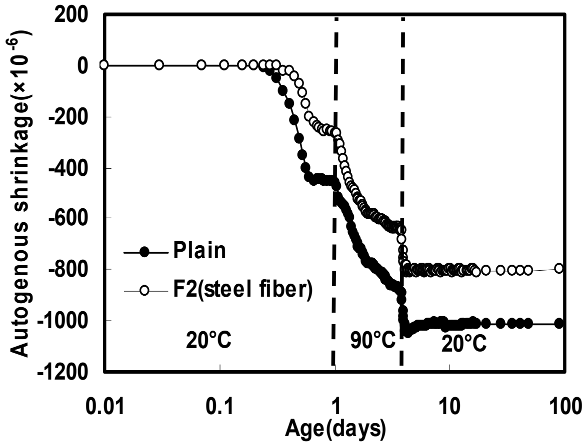

Fig. 2 Effect of the mixing of steel fibers on the autogenous shrinkage

3.3 Properties of Autogenous Shrinkage

(1) Effect of the mixing of steel fibers

Fig. 2 plots the resulting autogenous shrinkage of ultra-high strength SFRC according to the eventual mixing of steel fibers. In the case of Plain, the specimen without steel fiber, extremely large autogenous shrinkage strain was observed with values exceeding $1,000\times10^{-6}$. In addition, the shrinkage strain of F2 mixed with 2% steel fibers reached 800×10^{-6} corresponding to a reduction of shrinkage by about 20% compared to Plain.

(2) Effect of curing temperature

Fig. 3 illustrates the effect of the curing temperature on the autogenous shrinkage of ultra-high strength SFRC. When high-temperature curing is performed at 90°C, the autogenous shrinkage is seen to develop suddenly due to the acceleration of hydration during the curing period. But the final autogenous shrinkage appears to be similar to that resulting from curing performed at 20°C. Accordingly, even if high-temperature curing carried out to accelerate the pozzolan reaction during the fabrication process of ultra-high strength SFRC is also accelerating the progression of the autogenous shrinkage through the hydration, the curing temperature is verified to have no influence on the final strain.

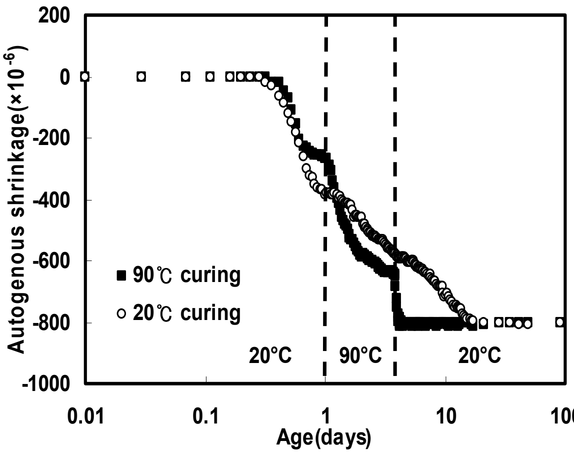

Fig. 3 Effect of curing temperature on the autogenous shrinkage

(3) Effect of expansive additive and shrinkage reducing agent

Fig. 4 shows the autogenous shrinkage resulting for ultra-high strength SFRC combined with 5% expansive additive and 1% shrinkage reducing agent. The admixing of the expansive additive and shrinkage reducing agent is seen to reduce the autogenous shrinkage of ultra-high strength SFRC. That is a reduction by about 22% for F2E5 mixed with 5% expansive additive compared to F2, and approximately 11% for F2S1 mixed with 1% shrinkage reducing agent. The reduction of the autogenous shrinkage according to the addition of such expansive additive and shrinkage reducing agent can be explained respectively by the shrinkage compensation effect brought by the ettringite and the diminution of the surface tension[4,5,6]. Moreover, F2E5S1 mixed with 5% expansive additive and 1% shrinkage reducing agent resulted in a decrease of the autogenous shrinkage by about 43% compared to F2, and an increase of such effect by approximately 10% regard to the individual use of expansive additive and shrinkage reducing agent.

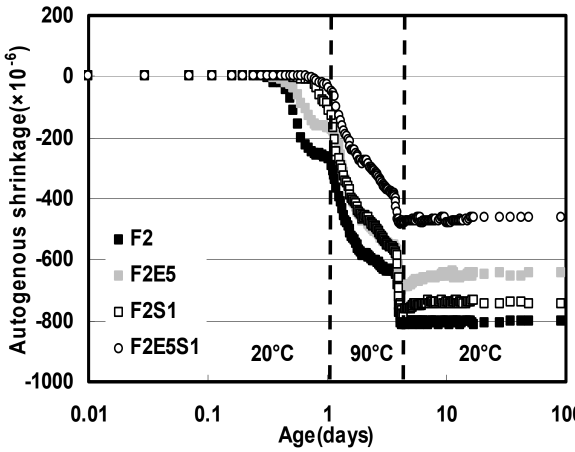

Fig. 4 Effect of the expansive additive and shrinkage reducing agent on the autogenous shrinkage

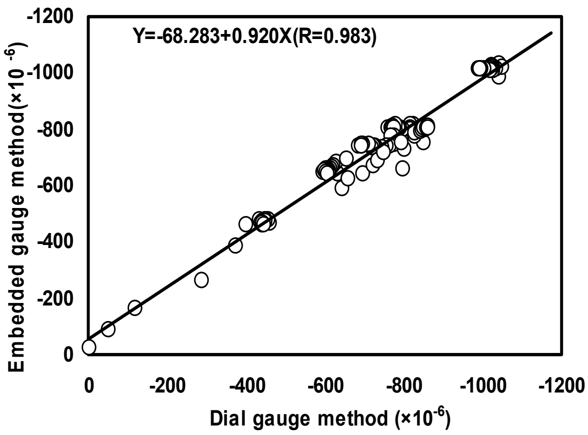

Fig. 5 Effect of the measurement method on the autogenous shrinkage

(4) Effect of measurement method

Fig. 5 plots the correlation between the autogenous shrinkage strains measured by embedded gauges and dial gauges. The autogenous shrinkages resulting from both methods exhibited similar trend without significant difference. Regardless of the temperature and test variables, the correlation factor appeared to be very satisfactory with value of about 0.98, which advocates poor difference in the practicability of both methods. Especially, when shrinkage is assessed under particular conditions such as high-temperature like in this study, it appears that embedded gauges are effective.

(5) Mass Changes

Fig. 6 plots the mass change of the specimens during the autogenous shrinkage tests using dial gauges. The criterion of 0.05% specified by JCI(2002)[7] was satisfied for all the specimens during the 90 days of the tests. The high-temperature curing is also seen to have no particular effect on the mass change.

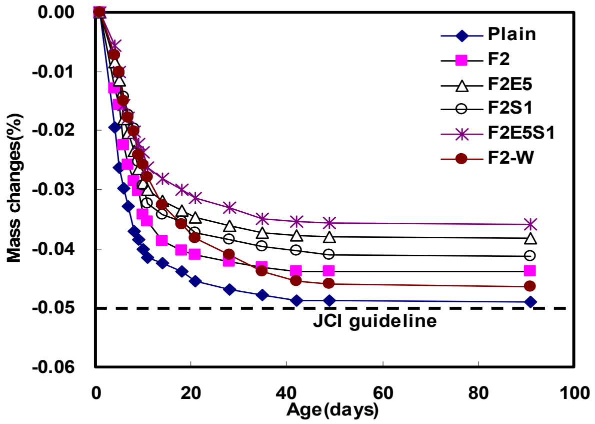

Fig. 6 Mass changes of the specimens during autogenous shrinkage tests

3.4 Properties of Drying Shrinkage

Fig. 7 plots the drying shrinkage test results. The drying shrinkage of Plain at 91 days reached approximately 150×10^{-6}, while the other specimens reinforced with steel fibers exhibited values smaller than 100×10^{-6} revealing that ultra-high strength SFRC is developing extremely small drying shrinkage. This can be explained by the dense organization of the cement composite, which obstructs the evaporation, as well as the very small quantity of evaporated water content.

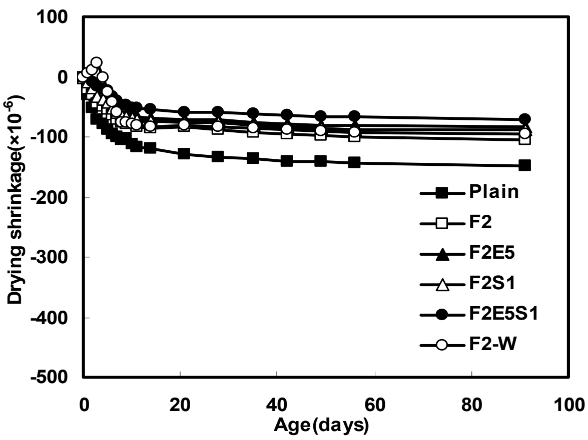

Fig. 7 Results of drying shrinkage test

Fig. 8 plots the mass changes of the specimens during drying shrinkage test. F2-W exhibited slight increase of its mass due to the absorption of moisture during the water curing. However, the mass decreased while drying. The specimens for which high-temperature curing was performed did not present clear change of their masses.

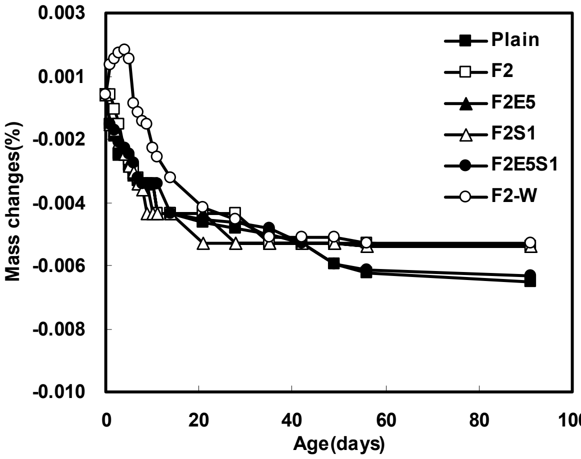

Fig. 8 Mass changes of the specimens during drying shrinkage tests

3.5 Comparison of Autogenous and Drying Shrinkages

Fig. 9 compares the autogenous and drying shrinkages of ultra-high strength SFRC at 91 days. The contribution of the autogenous shrinkage to the whole shrinkage averaged around 88% regardless of the type of specimen, which reveals the importance of the autogenous shrinkage in the shrinkage of ultra-high strength SFRC. Therefore, the effects of the autogenous shrinkage should be imperatively considered during the design and construction of structures using ultra-high strength SFRC.

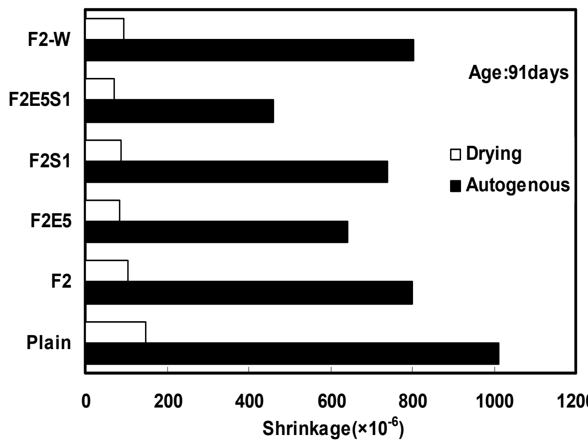

Fig. 9 Comparison of autogenous and drying shrinkages of ultra-high strength SFRC

3.6 Comparison of the Shrinkage Properties of High-Strength Concretes

Fig. 10 compares the shrinkage

properties of high-strength concrete (HSC) and ultra-high strength SFRC. The considered HSC is a composite with W/B of 30% and unit water content of 175kg/m3, using ordinary Portland cement, 10% fly ash and 5% silica fume[4]. The indicated total shrinkage is the sum of the drying shrinkage and autogenous shrinkage. It can be seen that the autogenous shrinkage of ultra-high strength SFRC increased compared to that HSC regardless of the mix proportions, while the drying shrinkage diminished. Particularly, the autogenous shrinkage of F2E5S1 mixed with 5% expansive additive and 1% shrinkage reducing agent presented an increase of about 30% compared to HSC, but the total shrinkage including the drying shrinkage reduced by 50%, which gives promising possibilities to control the development of cracks induced by shrinkage.

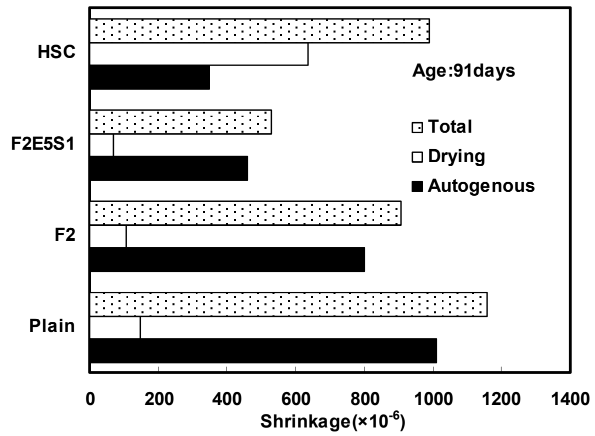

Fig. 10 Comparison of the shrinkage properties of ultra-high strength SFRC and HSC

5. CONCLUSIONS

(1) Plain, the specimen without steel fiber, and the ultra-high strength SFRC mixed with 2% steel fibers exhibited very large autogenous shrinkage strains with respective values larger than $1{,}000\times10^{-6}$ for Plain and approaching 800×10^{-6} for the latter. In addition, even if the high-temperature curing executed to hasten the pozzolan reaction of ultra-high strength SFRC resulted in accelerated autogenous shrinkage due to the hydration, the temperature was seen to be without influence on the final strain.

(2) The autogenous shrinkage of ultra-high strength SFRC reduced with the addition of expansive additive and shrinkage reducing agent. Especially, the admixing of a composition of 5% expansive additive and 1% shrinkage reducing agent revealed to produce increased effect of approximately 10% compared to the individual use of each admixture and to control the autogenous shrinkage to about 450×10^{-6}.

(3) The contribution of the autogenous shrinkage in the whole shrinkage averaged approximately 88% for ultra-high strength SFRC, which revealed the importance of the autogenous shrinkage in the whole shrinkage process.

(4) The autogenous shrinkage of ultra-high strength SFRC using 5% expansive additive and 1% shrinkage reducing agent increased by 30% compared to high-strength concrete while the total shrinkage including the drying shrinkage reduced by 50%, which gives promising possibilities to control effectively the development of shrinkage-induced cracks.

(5) The drying shrinkage of ultra-high strength SFRC was seen to be extremely small with value below 100×10^{-6}.

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