- Technical Paper -

EFFECT OF THE CURING METHOD ON THE COMPRESSIVE STRENGTH OF UHSCC

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ABSTRACT

This paper intends to investigate the effects of the curing method on the compressive strength of the developed UHSCC. In view of the results, wet curing during one day followed by 2 to 3 days of steam curing at 90°C seems to be advisable and leads to the possibility to obtain a compressive strength of approximately 200MPa at age 7 days. We carried out XRD and NMR analysis to explain the signification improvement of strength at high temperature. The extreme densification of the structure of the hardened cement paste accelerated by the pozzolanic reaction caused the increase of strength.

Keywords: ultra-high strength steel fiber reinforced cementitious composites (UHSCC), compressive strength, curing method, high temperature curing

1. INTRODUCTION

Recently, attention has been paid on newly developed and diversified ultra-high strength steel fiber reinforced cementitious composites (UHSCC) exhibiting compressive strength larger than 100MPa[1, 2]. The authors also performed studies on the mix proportions[3] and shrinkage characteristics[4, 8] of UHSCC that can secure compressive strength exceeding 180MPa. Besides, the performance of concrete depends sensitively on the adopted method of curing. Especially, it seems natural that concretes like UHSCC exhibiting large amount of pozzolanic binders and very small water to binder ratio will show large differences in their performances with respect to the applied curing method. Accordingly, even if high temperature curing is performed at early age in order to improve the performances like the strength for UHSCC[4, 6], one has to deplore the lack of systematic researches related to the effects of the curing method on the physical properties of UHSCC. UHSCC in this study is a type of UHPFRC(Ultra-High Performance Fiber Reinforced Concrete) such as RPC(Reactive Powder Concrete)[5] and CRC(Compact Reinforced Composites)[9].

Therefore, this study intends to examine the influence of the curing method on the physical properties of UHSCC by investigating the effects of the curing conditions and duration prior to performing high temperature curing at 90°C as well as of the conditions and duration of high temperature curing on the compressive strength of UHSCC.

2. TEST PROGRAMS

2.1 Materials and Mix Proportion

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 1. The aggregates are a mixture 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 2 is added in order to prevent fracture at the cement-aggregate interface[3, 4]. The superplasticizer is a 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 of UHSCC. The fibers are mixed with a volumetric proportion of 2% in the cementitious composite. Table 3 summarizes the mix proportions of UHSCC.

2.2 Curing Method

Table 4 lists the curing method adopted in the tests. The effects of high temperature curing, the curing conditions and wet curing duration prior to demoulding and, the conditions and duration of high temperature curing was estimated in order to evaluate the influence of the curing method on the compressive strength of UHSCC. For the high temperature curing, temperature was increased at a rate of 15°C/hr until the target temperature of 90°C, and this temperature was maintained during a definite period before being reduced at a rate of 20°C/hr. Thereafter, air dry curing was conducted in constant temperature and humidity chamber at temperature 20±1°C and humidity of 60±5%.

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Table 1 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 2 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 3 Mix proportion of UHSCC (by weight)

W/B	Cement	Silica fume	Sand	Filling powder	Superplasticizer	Steel fiber(Vf)
0.20	1	0.25	1.1	0.3	0.016	2%

Table 4 Curing method of UHSCC

Investigated item	Specimen designation	Curing method before stripping		Curing method after stripping		Remarks
		Conditions	Duration	Conditions	Duration	
Effect of high temperature curing	90SC	20°C wet	1 day	90°C steam	3 days	20°C air dry curing after 90°C high temperature curing
	20WC	20°C wet		20°C water	91 days	
	20AC	20°C air dry		20°C air dry	91 days	
Effect of curing conditions before stripping	MC	20°C wet	1 day	90°C steam	3 days	
	WC	20°C water				
	AC	20°C air dry				
Effect of curing duration before stripping	De6	20°C wet	6 hours	90°C steam	3 days	
	De12		12 hours			
	De24		24 hours			
	De36		48 hours			
Effect of high temperature curing conditions	HC-S	20°C wet	1 day	90°C steam		
	HC-W			90°C water		
	HC-A			90°C air dry		
Effect of high temperature curing conditions	HC-1	20°C wet	1 day	90°C steam	1 day	
	HC-2				2 days	
	HC-3				3 days	
	HC-5				5 days	

Finally, wet curing was executed by supplying sufficient humidity to the curing blanket so as to maintain humidity larger than 90%.

2.3 Test Method

The compressive strength was measured on cylindrical specimens of ø100×200mm using a 5,000kN Universal Testing Machine. The value of the compressive strength corresponds to the mean of 5 concrete specimens. Moreover, XRD(X-ray diffraction) and NMR (Nuclear Magnetic Resonance) were analyzed before and after high temperature curing in order to evaluate the effects of high temperature curing. The adopted samples are powders that passed through sieves No. 200 and No. 100, respectively.

3. TEST RESULTS AND DISCUSSION

3.1 Properties of Fresh Concrete

Table 5 presents the properties of the fresh UHSCC. The slump flow being approximately 600mm, UHSCC can develop sufficient self-compacting that does not need compaction. Apart from that, the air content and setting times appeared to be relatively similar to those of ordinary concrete.

Table 5 Properties of fresh UHSCC

Items		Results
Flow (mm)*		205
Slump flow (mm)**		595
Air content (%)		3.9
Setting time (hrs)	Initial	13.3
	Final	15.8

* JIS R 5201, no dropping
** JIS A 1150

3.2 Effect of high temperature curing

Fig. 1 compares the effects of high temperature curing and normal curing on the compressive strength of UHSCC. The white marks in Fig. 1 stand for the values of the strength of each specimen with respect to the age, and the black marks correspond to the mean values of the strength for the 5 specimens. The standard deviation of the compressive strength ranges from 1.08 to 7.88MPa according to the age.

It can be seen that UHSCC already developed significantly large compressive strength at age 1 day, which reached a value of about 35MPa.

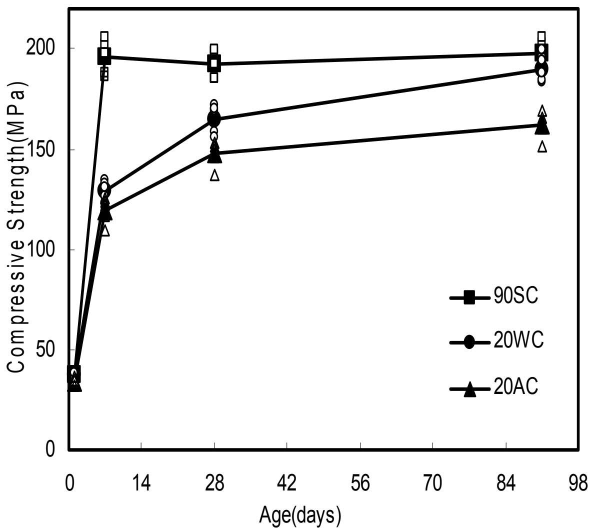


Fig. 1 Effect of high temperature curing

Even if specimen 90SC, which experienced high temperature curing, exhibited compressive strength of 200MPa at age 7 days, the developed compressive strength appeared to stagnate without increase thereafter. Besides, the strength at age 7 days developed by specimens subjected to curing at 20°C reached 60% of the one of 90SC, but continued to increase with age to attain a value nearly equivalent to 90SC at age 91 days as can be seen for specimen 20WC for which water curing was performed. However, specimen 20AC, which experienced air dry curing, could not develop strength with age and exhibited a compressive strength reaching merely 80% of the one produced by 90SC at age 90 days.

Accordingly, when UHSCC has to be exploited in environment where the execution of high temperature curing is troublesome, sufficient humidity has to be supplied all along the curing period so as to help strength to develop.

3.3 Effect of curing method before stripping

Fig. 2 illustrates the effects of the pre-stripping curing conditions on the compressive strength of UHSCC. The standard deviation of the compressive strength ranges from 2.97 to 4.32MPa according to curing condition.

The strength of specimens WC subjected to water curing appears to be the highest, followed successively by wet cured specimens, MC, and air dry cured specimens, AC. However, no remarkable difference could be observed between WC and MC.

Such difference in the strength occurring with respect to the curing method prior to stripping can be explained by the large consumption of water corresponding to the acceleration of hydration since early age due to the very small water to binder ratio and large amount of binders.

Accordingly, the activation of the hydration of UHSCC requires to supply sufficient humidity since early age or to provide hermetical sealing so as to prevent evaporation.

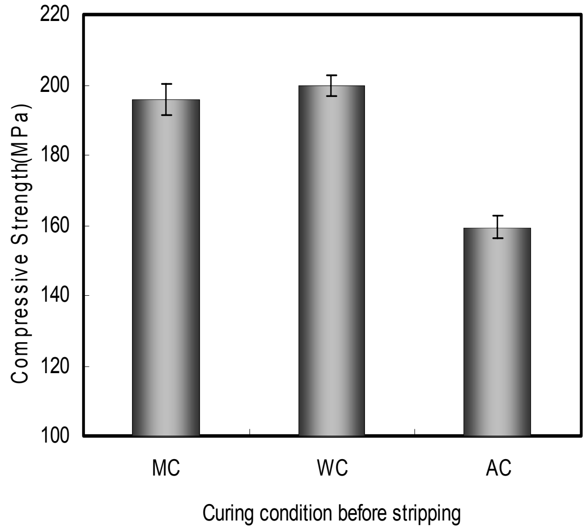


Fig. 2 Effect of curing conditions before stripping

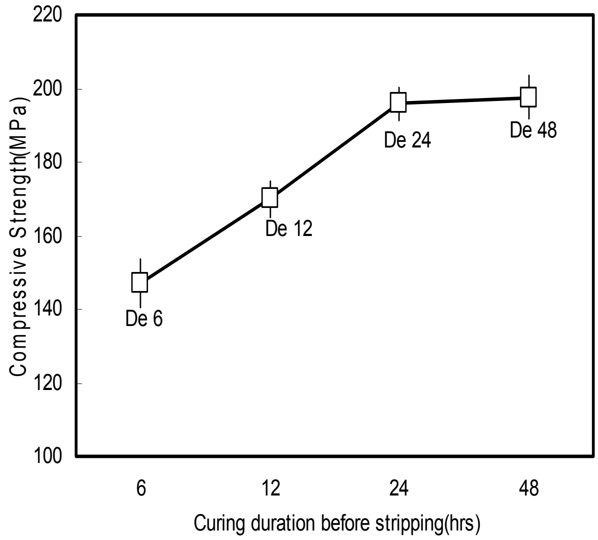


Fig. 3 Effect of curing duration before stripping

Fig. 3 shows the effects of the duration of wet curing before stripping on the compressive strength. The standard deviation of the compressive strength ranges from 4.32 to 6.60MPa according to wet curing duration.

Larger compressive strength seems to develop with longer duration of wet curing prior to demoulding. Even if specimen De6 develops compressive strength of about 150MPa, this compressive strength increases significantly up to approximately 200MPa in the cases of De24 and De48. This seems to be the result of the degradation of strength provoked by the occurrence of micro-cracks during or after the period of high temperature curing caused by the poor confinement of the structure of the hardened paste when high temperature curing is performed prematurely[5].

In view of the experimental results, a wet curing period of at least 24 hours after stripping seems advisable prior to the execution of high temperature curing for UHSCC to reach a compressive strength of about 200MPa.

3.4 Effect of high temperature curing method

Fig. 4 illustrates the effects of the conditions of high temperature curing on the compressive strength of UHSCC. The standard deviation of the compressive strength ranges from 4.32 to 6.60MPa according to high temperature curing condition.

During high temperature curing, specimen HC-W corresponding to high temperature water curing exhibited the largest strength followed successively by the high temperature steam cured specimen HC-S and the high temperature air dry cured specimen HC-A, without significant difference between HC-W and HC-S. Accordingly, preventing drying and supplying sufficiently moisture appear to be required during high temperature curing of UHSCC.

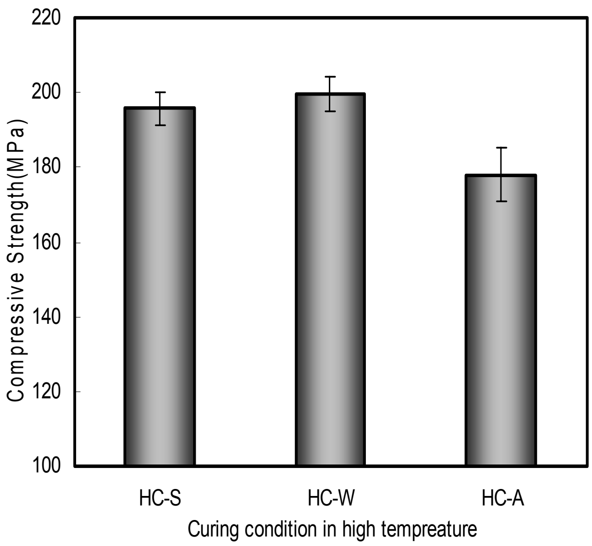


Fig. 4 Effect of high temperature curing conditions

Fig. 5 depicts the effects of the duration of high temperature steam curing on the compressive strength of UHSCC. The standard deviation of the compressive strength ranges from 4.32 to 7.11MPa according to high temperature duration.

The compressive strength of HC-1 on which high temperature steam curing was performed during 1 day reaches approximately 155MPa, while values of about 200MPa were obtained for HC-2 and HC-3 subjected to 2 and 3 days of high temperature steam curing. The improvement of the strength with longer duration of high temperature curing within the 3 days of high temperature steam curing can be attributed to the activation of the hydration of cement and pozzolanic reaction of silica fume by the high temperature curing, which lead to the densification of the structure of the hardened cement paste[6].

On the other hand, the compressive strength of HC-5 subjected to 5 days of high temperature steam curing decreased compared to the strength developed by HC-3 with a value reaching approximately 180MPa. This highlights the problems of excessively long periods of high temperature steam curing, which may cause not only loss of economical efficiency but also may provoke micro-cracks to develop due to drying following the consumption of moisture inside the cementitious composite.

Accordingly, performing high temperature steam curing during 2 to 3 days appears to be adequate to accelerate the hydration of UHSCC, even if this duration may differ according to the experimental scale of the cementitious composite.

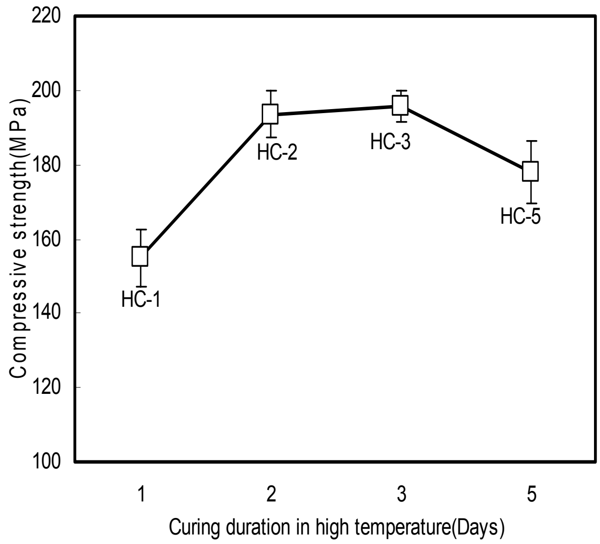


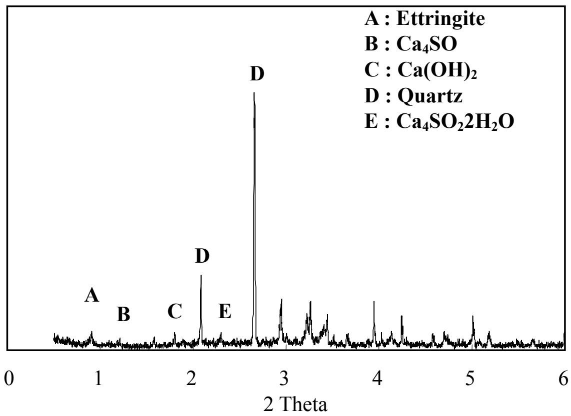
Fig. 5 Effect of high temperature curing duration

3.5 XRD Analysis Results

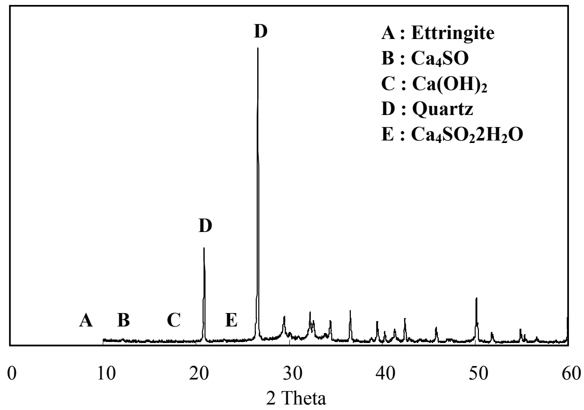
Fig. 6 compares the XRD measurement results obtained before and after high temperature curing in order to examine the effects of high temperature curing. The peak of $Ca(OH)_2$ was observed even though it was relatively quite small before performing high temperature curing but disappeared after its execution. This phenomenon can be explained by the non-consumption of $Ca(OH)_2$ due to poor occurrence of pozzolanic reactions prior to high temperature curing, and the consumption of almost all the $Ca(OH)_2$ following the activation of the pozzolanic reaction through the execution of high temperature curing at 90°C.

3.6 NMR Analysis Results

Fig. 7 compares the NMR before and after high temperature curing to evaluate the effects of high temperature curing on the strength of UHSCC. In Q^n, Q stands for the SiO_4^{-4} unit, n for the oxygen-binding factor, Q^0 represents C_3S, Q^1 and Q^2 correspond to the

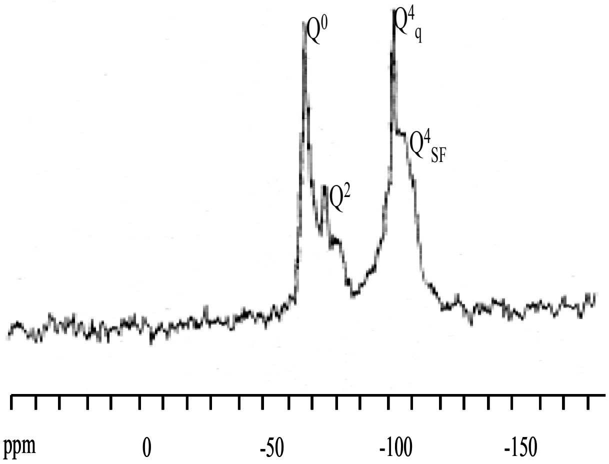


(a) Before high temperature curing

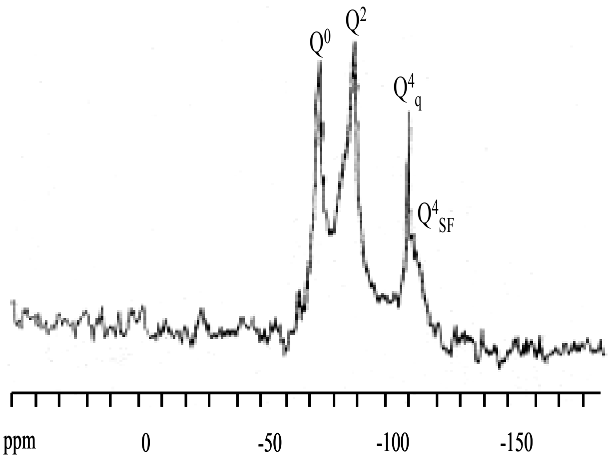


(b) After high temperature curing

Fig. 6 XRD analysis results



(a) Before high temperature curing



(b) After high temperature curing

Fig. 7 NMR analysis results

C-S-H generated by the hydration and pozzolanic reactions of cement, Q^4_q represents quartz or sand, and Q^4_{SF} represents the silica fume[7]. Comparison of the results before and after the execution of high temperature curing reveals that peak Q^2 became higher after steam curing, which is due to the generation of large amounts of hydrated C-H-S following the activation of the pozzolanic reaction according to the execution of steam curing. Moreover, Q^4_{SF} representing the silica fume exhibited reduced peak following the performing of steam curing. This reduction can be attributed to the consumption of silica fume through the occurrence of pozzolanic reaction following the steam curing.

5. CONCLUSIONS

This study investigated the effects of the curing method such as the curing conditions and duration before high temperature curing at 90°C and the conditions and duration of high temperature curing on the compressive strength of UHSCC. The corresponding conclusions can be arranged as follows.

(1) UHSCC required high temperature curing at 90°C during a definite period for the activation and activation of hydration of the pozzolanic materials. In the case where high temperature curing was performed, a compressive strength of approximately 200MPa could be developed at age 7 days.

(2) UHSCC subjected to wet curing at 20°C developed larger strength with age, which became nearly equivalent at age 91 days to that obtained when performing high temperature curing. However, the strength degraded with the age when air dry curing was performed to reach merely 80% of that obtained when performing high temperature curing. Accordingly, it appeared that supplying sufficient humidity during the curing period was crucial in cases where performing high temperature curing is difficult.

(3) When high temperature curing is implemented for UHSCC, it appeared advisable to perform steam curing at 90°C during 2 to 3 days after early curing through sufficient supply of moisture during about 1 day immediately after

casting prior to implementing high temperature curing at 90°C in order to obtain sufficient strength.

(4) Regard to the XRD and NMR analyses, the remarkable improvement of the compressive strength achieved through high temperature curing was the result of the extreme densification of the structure of the cement composite due to the acceleration and activation of the pozzolanic reaction.

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