Effects of curing types on the strength of high Strength self-compacting concrete

Sinan A. yaseen\textsuperscript{1}, Mohammad A. Ihsan\textsuperscript{2}, Dillshad K.H. Amen\textsuperscript{1}, Nawal M. Abdulrazzaq\textsuperscript{1}

1- Civil Engineering Department, College of Engineering, Salahaddin University, Erbil, Kurdistan Region, Iraq.

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\textbf{*Corresponding Author:}  
Dillshad K.H. Amen  
dkhamen12@gmail.com

\section*{Abstract}
Curing strongly influences the strength and durability of hardened concrete through its remarkable effect on the hydration of cement. The present study conducted experiments to show the effects of different curing processes on the compressive strength of high-strength self-compacting concrete (HSSCC). Three mixes of HSSCC were prepared with w/cm ratio of 0.265, 0.345, and 0.375. Silica fume, which is 9\% by weight of the cementitious material, was used. Standard cubic specimens were cast to test the compressive strength at 3, 7, and 28 days. Specimens were cured using different curing systems, namely, immersion in water, covering the surface with wet burlap, coating by a bituminous membrane, and open-air curing. Furthermore, different moistening conditions were studied by totally curing specimens in dry air and curing in water for different periods (1, 3, 7, and 28 days) and using the remaining time to store them in dry air before testing the compressive strength at the age of 28 days. Test results indicated that covering concrete with a wet burlap is the most economic and effective method to cure HSSCC and that curing in water for 3 to 7 days is necessary for HSSCC to obtain reasonable and good results.

\section*{1. INTRODUCTION}
Curing is defined as the process of maintaining satisfactory moisture content and a favorable temperature in concrete during the hydration of the cementitious materials to develop desirable properties of concrete (\textit{ACI COMMITTEE 308}).

Two categories of curing were applied to concrete based on the conditions on-site and the size, shape, and position of the concrete member. The methods were called, “wet curing” and “membrane curing (\textit{NEVILLE, A.M. 1995}). Wet curing involves providing water to the concrete, wherein the surface of concrete remains in contact with water for a specific period of time. This type of curing can be achieved by spraying, ponding (immersion), covering the concrete with wet sand or earth, or covering by wet burlap or cotton mats.
The second method of curing is called the water-barrier method, which aims to prevent moisture loss from the concrete surface. This method is applied through different techniques, one of which is by spraying curing compounds to form a membrane. Common membranes used are solutions of synthetic hydrocarbon resins and other resins such as acrylic, vinyl or styrene butadiene, and chlorinated rubber. Both types of curing should start immediately after concrete placing and finishing. Curing is known to strongly influence the properties of hardened concrete: proper curing will increase its durability, strength, volume stability, abrasion resistance, impermeability, and resistance to freezing and thawing (UNIVERSITY OF MEMPHIS).

The American Concrete Institute (ACI) Committee 301 recommends a minimum curing period corresponding to concrete to attain 70% of the specified compressive strength (ACI COMMITTEE 301). James O, et al. showed that continuous curing in water is the most effective method of curing. This method produces the highest level of compressive strength of concrete made with a water-to-cement ratio of 0.5. The second best method is the sprinkling method, which produces concrete with a compressive strength higher than plastic sheeting. Raghavendra and Aswath conducted a comparative study on different curing methods and reported that the efficiency of the membrane curing compound is 90% that of conventional standard water curing. The hydration of cement is a long-term process that requires water and the proper temperature. Therefore, curing allows for continued hydration and, consequently, continued gains in concrete strength (MAMLOUK, M. S. and ZANIEWSKI, J.P, 1999). The hydration of the cement virtually ceases when the relative humidity within the capillaries drop below 80% (POWERS, T.C. 1947).

BENTZ, D.P., STUTZMAN, P.E., 2006. showed that hydration products fill the pores of hydrated cement paste, reduce the porosity, and increase the density of the microstructure of concrete. The hydration products from the surface of cement grains.

Many types of concrete exist: the normal type, high-strength concrete, high-performance concrete, and self-compacting concrete (SCC), and many others. The mixture proportions and strength development of these types of concrete vary. Therefore, identifying the most suitable curing system for each respective type of concrete is necessary. For instance, in a number of situations, wet curing is unnecessary; only the loss of water from the concrete needs to be prevented. In other situations, wet curing is necessary depending on the water-to-cement ratio. For concrete with a water-to-cement ratio less than 0.5, filling the pores using external sources of water is necessary to prevent self-desiccation and to promote the hydration of cement. On the other hand, concrete with a water-to-cement ratio greater than 0.5 requires water-prevention curing methods. Furthermore, the effect of inadequate curing on strength is greater in concrete with a high water-to-cement ratio, those with a low rate of strength development, and those containing fly ash or GGBFS. Curing compounds are reported to produce a compressive strength that is 10 % less than normally cured SCC specimens (AKANKSHA, A.P., VYAWAHARE, M.R., 2014). SAFUDDIN, M.D. et, al. 2007 studied the effect of air-dry curing on the properties of micro silica concrete. Their results indicated that dry curing is ineffective because insufficient water hinders hydration, making the concrete weak and permeable. (FAUZI, M., 1995) showed that drying concrete could
develop micro-cracks or shrinkage cracks on the surface of the concrete.

YAZICIOGLU, S., et al. 2006. Investigated the effects of curing conditions on the properties of SCC. Results indicated that SCC made using silica fume as a cement component had higher compressive and tensile strength values than SCC including fly ash. For all concrete, the water-cured specimens had the highest compressive strength values, followed by the sealed and air cured specimens.

2. SIGNIFICANT OF THE STUDY

This study presents the effects of different curing conditions, namely, immersion in water, covering by wet burlap, and curing by a protective layer, on the compressive strength of high-strength SCC (HSSCC). This study also identifies the most effective curing process. Furthermore, this study shows the effect of different moistening conditions, which can be described as follows; The effect of continuously moist, cured in air after 1, 3, and 7 days of moist curing, and continuous exposure to dry air on the compressive strength of SCC mixtures tested at 28 days.

3. MATERIALS AND METHODS

Ordinary Portland cement (OPC) was obtained from a mass cement factory in Iraq. We confirmed that the requirements of ASTM type I grade were met. The cement had a specific gravity of 3.16 and used silica fume as the cement component type (Sika Fume-HR). The size of particles was 0.1 μ, and 9% by weight of total cementitious materials were used.

A polycarboxylates based polymer type Sika ViscoCrete-PC 15 with a specific gravity of 1.09 was used in all the mixtures to obtain the required flowability. The stone powder was obtained by grinding limestone rocks, particles passing a sieve of 150 μ were used as inert filler to enhance the particle size distribution of the OPC. Clean natural river sand from Erbil city, with a specific gravity of 2.67 and fineness modulus of 2.85; and Natural river gravel, with a maximum size of 12.5 mm and with gradation in accordance to ASTM C-33, were used. Three mixes of SCC were selected: HSSCC-I, HSSCC-2- and HSSCC-3. Their w/cm ratios were 0.265, 0.345, and 0.375, respectively. Cementitious material contents ranged from 422 kg/m³ to 543 kg/m³. Several trials were conducted to obtain the proper mixture proportions. The quantities of materials required for 1 cubic meter are shown in Table-1.

The following tests were conducted for fresh SCC mixtures: the slump flow, T₅₀, V funnel, and L-Box were used as described by ACI 237. Test results indicated that the selected mixes of SCC had good filling and passing abilities.

SCC specimens were cast without any compaction. Standard 150-mm cube specimens were produced. The specimens were de-moulded after one day of casting and subjected to different curing conditions. The following methods were conducted: standard curing in water (immersion method), curing by bituminous coating membrane and covering concrete surface with jute burlap for 1, 3, 7 and 28 days, and curing in air for the remaining time before testing at the Age specified. At the end of each curing period, and for all curing systems, a total of three cubic specimens were tested for compressive strength.
Table-1 Quantities of materials required for 1 m³ of HSSCC mixtures.

| Mix No. | Cement kg/m³ | Gravel kg/m³ | Sand kg/m³ | S.F kg/m³ | Stone Powder kg/m³ | %Pc-15 By weight of cement | Free water kg/m³ |
|---------|---------------|--------------|------------|-----------|---------------------|-----------------------------|------------------|
| HSCC-1  | 384           | 859          | 910        | 38        | 58                  | 1.33                        | 157              |
| HSCC-2  | 437           | 794          | 893        | 44        | 66                  | 2.13                        | 164              |
| HSCC-3  | 494           | 926          | 741        | 49        | 74                  | 2.13                        | 143              |

4. RESULTS AND DISCUSSION

4.1. Fresh Properties

SCC is characterized by filling, passing ability, and segregation resistance. Different method has been developed to characterize the properties of fresh SCC.

In the present research, each mix was tested by more than one test method for the different workability parameters. The results with their recommended values are given by the codes are shown in Table-2. Results demonstrated the flowability and passing ability of SCC mixtures.

Notably, the highest performance of HSSCC was obtained by HSCC-2. This indicated that HSCC-2, with total powder content of 547 kg/m³, a water-to-powder ratio of 0.30, and a dosage of superplasticizer 2.13 % by weight of cement, provided the lowest viscosity, as represented by the highest slump flow, lowest T50, lowest V-Funnel values, and the highest blocking resistance.

The slump flow test was used to assess the horizontal free flow of SCC in the absence of obstruction. This is a measure for the filling ability of fresh SCC. This test is influenced primarily by the yield value of the concrete. The lower the yield value, the larger the extended circle of the concrete. The yield value depends, in turn, on the degree of agglomeration of the fine constituents in the concrete, which is reduced as the dosage of the superplasticizer increases. The diameter of the circle of the slump flow test extended from 645 mm for HSCC-1 to 675 mm for HSCC-2 due to the increase in superplasticizer content from 1.13 % to 2.13% by weight of cement. The diameter of the circle decreased to 565 mm for HSCC-3 because of the decrease in water-to-powder ratio without the increase in superplasticizer content. All mixes remained homogeneous; no tendency to segregation was observed. The flow time T50 is a measured variable that describes the viscosity of SCC. This is the time required by the SCC to flow to a diameter of 500 mm after the slump cone has been withdrawn in slump flow test. The shorter the flow time, the lower the viscosity of the SCC. Therefore, mix HSCC-2 showed the lowest viscosity, as shown by the slump flow result. Another way to assess the viscosity of fresh SCC is by determining the V-funnel flow time (T).

The method of determining V-funnel flow time is described by the European guidelines regarding SCC (EFCA, 2005). The viscosity of a suspension depends on numerous factors, such as the water/powder ratio and the overall grading curve. This means that SCC with lower water content flows more slowly out of the funnel and has a higher viscosity than SCC with higher water content. Our results
show that the V-funnel time decreased from 9.65 sec for HSCC-1 to 8 sec for HSCC-2 and increased to 12.3 sec for HSCC-3. The L-box test was conducted to demonstrate the placeability of SCC. All the mixes of SCC showed high resistance to blocking. Results showed that HSCC-2 was most resistant blocking.

Table 2. Rheological parameters of HSSCC mixtures with the recommended values.

| Mix No. | Slump (mm) | T500 (Sec) | V-Funnel time (Sec) | L-Box ratio H2/H1 |
|---------|------------|------------|---------------------|-------------------|
| HSSCC-1 | 645        | 4.45       | 9.65                | 0.88              |
| HSSCC-2 | 675        | 3.12       | 8.4                 | 0.91              |
| HSSCC-3 | 565        | 5.85       | 12.32               | 0.8               |

Recommended Values: 450 – 750, 3 – 7, 0 – 10, 0.8 – 1.0

4.2 Compressive Strength

4.2.1. Effect of curing methods
The results of compressive strength at different curing times for different curing systems and three mixtures of HSSCC are shown in Fig. (1). Notably, the compressive strength increased with time for all the systems of curing and mixtures. A slight difference in strength can be seen between the two curing systems, namely, by immersion in water for 28 days and covering by a wet burlap. This result occurred because both systems saturated the specimens with water, which was necessary to continue the hydration of cement. On the other hand, curing by bituminous coating then curing in open air resulted in the lowest compressive strength for all the curing times and mixtures. This result occurred because bituminous coatings incompletely hinder the evaporation of water from the pores. Several micro-cracks may have been produced as a consequence, thereby decreasing the strength of the concrete.

Figures (1-a, b, c) Strength of concrete versus time cured by different methods for of HSSCC mixtures

4.2. 2. Effect of type of mix
The rates of strength development for different curing systems and for three mixtures of HSSCC are shown in figure (2), that at 28 days. HSSCC-1 had the highest rate of strength development, and HSCC-2 showed the lowest results for all curing systems except the system of coating membrane. The rate of HSSCC-2 was higher than HSSCC-3.

Considering the strength development equation predicted by ACI 209 for normal type and normally cured concrete, the rate of strength at ages of 3 and 7 days with reference to 28 days are about 0.46 and 0.70, which are lower than the lowest rate of strength development, which is about 0.5 and 0.7 for HSSCC-2 at age of 3 and 7 days, respectively, for specimens continuously cured in water. On the other hand, the rate for other curing systems was higher. Therefore, HSSCC mixtures had higher rates of strength development than normal types of concrete because silica fume improved pore size distribution and reduced the porosity of concrete significantly, thereby increasing compressive strength at an early stage.

4.2.3. Effect of moisture condition.

The effect of the water-to-cementitious material ratio (w/cm) on the compressive strength at 28 days for specimens cured in water with different curing conditions or different moisture conditions are shown in figure (3). The results show that the compressive strength decreased as the w/cm ratio increased, which can be expressed by a power equation similar to that of the normal type concrete but with a different trend for different moisture conditions. The compressive strength increased evidently with the increase of the moistening condition for up to 7 days of immersion in water. Beyond this limit, no appreciable improvement was observed. The results are convergent to those continuously cured in water. Relative compressive strength, which is defined as the ratio of compressive strength at 28 days for specimens of different moistening conditions to those continuously cured in water, indicated that 7 days of moistening is the most effective duration for all the HSCC mixtures. The mix, HSCC-3, with a highest w/cm ratio obtained the highest relative strength.
4. CONCLUSIONS

1. The rate of strength development of HSSCC at 3 and 7 days with reference to 28 days cured by different methods was higher than the rate previously predicted by ACI for normal-type and normally cured concrete.

2. A very slight difference was observed in the compressive strength of specimens cured by wet burlap and specimens cured by the immersion method. Both methods were the most effective methods of curing. They produced the highest level of compressive strength.

3. Moistening the specimens for 3 to 7 days as a minimum time of curing by water for HSSCC is necessary to achieve the best results.

4. The bituminous coating method of curing produces the lowest compressive strength. This phenomenon occurs because the moisture movement formed in the concrete specimens are higher in this method and does not prevent the concrete from drying.

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