Effect of Curing Methods on Compressive Strength of Sustainable Self-Consolidated Concrete

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Abstract. Concrete can only achieve the desired compressive strength and durability if cured properly for a prescribed period. For most building codes, concrete structural components and systems are designed for the 28-day compressive strength. Nonetheless, concrete structures are cured typically for only 3 to 7 days. There is an increasing use of curing techniques that involve chemical compounds such as acrylic-based compounds. The emergence of such techniques requires investigation of their effectiveness, compared to traditional curing methods. This article presents the findings of a study to compare the compressive strength of concrete cured using three methods, namely submersion in water, air curing under elevated temperature, and curing with a chemical compound. Compressive strength was determined on standard 150 mm x 150 mm x 150 mm cubes made of sustainable self-consolidated concrete (SCC) in which 90% of ordinary Portland cement content was replaced with combinations of high volume ground granulated blast furnace slag (GGBS), silica fume, and fly ash. A total of 20 mixes were tested, the first set of 10 mixes prepared with water to be binder (w/b) ratio of 0.33 and the second set of 10 mixes prepared with w/b of 0.36. For all mixes, samples cured under air with 45 °C temperature produced the highest 28-day compressive strength compared to other curing methods. Similarly, concrete samples cured using the chemical compound produced higher compressive strength compared to the traditional curing method. The sustainable SCC mix producing the highest compressive strength of 76.22 MPa under air curing was prepared with w/b of 0.33, 72.5% slag replacement ratio, 12.5% silica fume replacement ratio, 10% fly ash while Portland cement represented only 10% of the total binder content.

1. Introduction

Proper curing of concrete structural elements is essential for hydration reaction to continue and to develop concrete compressive strength over time. Hydration of concrete and strength development will continue for years, but at decreasing rate, if water is available to cement within concrete structural element and temperature is reasonable. The most known curing method in the concrete construction industry is to apply water all over the freshly casted structural element continuously for three days to seven days or retaining water in the structural elements while covered with material to entrap the vapor and cease water evaporation [1]. These curing methods are functional and serve their purpose but are time consuming and consume substantial amounts of water to cure an entire structure [1]. On the other hand, membrane-forming curing compounds affect compressive strength development differently, depending on the type of compound, however, most curing compounds enhance durability of concrete.
Curing compounds that come in the form of emulsion are applied to the surfaces of the concrete structural element. They provide a membrane that prevents moisture from evaporating through the surface of the structural element and allow hydration reaction to continue and strength to develop. These compounds help in reducing the usage of water in construction industry, therefore conserve water consumption, especially in parts of the world where water is scarce. ASTM C309 [2] identifies two types of curing, clear compounds with or without dyes, and white pigmented compounds.

Xue et. al [1] studied the effect of four types of chemical curing compounds on concrete durability and strength, namely acrylic-based, paraffin-based, silicate based and composite-based. The study looked at compressive and flexural strength, drying shrinkage, impermeability test, and concrete crack resistance. Microscopic analysis of concrete samples showed a proper hydration reaction with a homogenous microstructure along with an increase in compressive and flexural strength. Both permeability and drying shrinkage of concrete samples decreased. The results showed also that acrylic-based compounds performed better than the other compounds.

Saarthak et. al [3] used different durability tests to assess the effectiveness of five chemical compounds on concrete curing. The authors concluded compressive strength is not sensitive to curing compounds. Oxygen permeability index, water sorptivity index, and non-steady-state migration coefficient were used to assess durability of concrete. The results of two controlled mixes showed that the most consistent results are those from oxygen permeability index test.

Ibrahim et. al [4] examined the effect of curing methods on mechanical properties of concrete with normal Portland cement and silica fume cement. The authors studied four types of curing compounds including water-based, acrylic-based, bitumen-based and coal tar epoxy. The effect of curing method on concrete was evaluated through compressive strength, water absorption, and chloride permeability tests. The authors noted the durability and strength of concrete cured using chemical compounds was the same or better than that of concrete cured using the traditional method of covering concrete with a wet burlap. Curing method had a limited effect on concrete compressive strength but had a more pronounced effect on durability. The best concrete performance was noted for samples cured using bitumen-based curing compound.

Yash et. al [5] explored the effect of the curing method on concrete samples made with four w/b ratios 0.45, 0.5, 0.55, and 0.6. Total of four curing techniques were used in the study, air curing where the samples are left exposed in room temperature, water bath curing, saturated wet covering where samples are covered with wet burlap cotton mats till the testing date and curing compounds where a total of 7 chemical compounds are used. The authors concluded that using membrane curing through chemical compounds produced concrete properties that are 80% to 90% of concrete samples cured using conventional water methods.

Al-Gahtani [8] investigated the effect of the curing method on concrete in which cement was partially replaced with combinations of silica fume and fly ash. Various samples were cured by covering them under wet burlap for 7-days or using chemical compounds. Two types of chemical compounds were assessed, acrylic-based and water-based. 28-day compressive strength tests showed that samples curing under traditional wet burlap produced higher strengths compared to sample curing using curing compounds. Acrylic-based chemical curing compounds, on the other hand, produced higher 28-day compressive strength compared to water-based chemical compounds.

In the current study, 90% of Portland cement in a control mix is replaced with a high volume GGBS in all mixes, along with lower percentages of silica fume and fly ash. GGBS, fly ash, and silica fume are amongst the supplementary cementitious materials (SCM) that are known to impart favourable short-term and long properties. Replacement of cement with a high volume of recycled SMC contributes to the reduction of CO₂ emissions by decreasing the use and production of cement. Concrete containing high volume of SCC exhibits lower strength development at an early age, but the associated decrease in heat of hydration contributes to a reduction of cracking in high volume concrete at early ages [9].
2. Experimental study

A total of 18 sustainable self-consolidated concrete (SCC) mixes along with two control mixes were developed to study the effect of the curing method on strength development. The control mixes were prepared with 100% Portland cement. In all sustainable SCC mixes, 90% of total cement content was replaced with different combinations of high-volume GGBS, silica fume, and fly ash. One set of 9 sustainable SCC mixes along with one control mix was developed with w/b ratio of 0.36 and a second set of the same number of mixes was developed with a w/b ratio of 0.33.

To investigate the effect of the curing method on the compressive strength, a total of 120 standard 150 mm x 150 mm x 150 mm cubes were prepared, cured, and tested. The 28-day compressive strength was determined for 40 cubes in each of the three curing methods under consideration. Each reported compressive strength value is the average for two cubes.

All SCC mixes were developed to reach final flow diameter of 550 mm ± 50 mm with the aid of a high range water reducer (HRWA) produced by BASF Corporation under the commercial name MasterGlenium Sky 504.

The content of cementitious materials in each of the sustainable SCC mixes is kept constant at 480 kg/m³ of which only 10% is conventional Portland cement. The remaining 90% of the cementitious material is combinations of fly ash, silica fume, and GGBS. Coarse crushed aggregate content is kept constant for each SCC mix at 800 kg/m³ with maximum aggregate size of 10 mm. Fine aggregates used in each mix consisted of 582.4 kg/m³ black sand and 313.6 kg/m³ dune sand. Table 1 lists the 20 SCC mixes along with the various cementitious materials in each mix. The name of each mix begins with the letter G (e.g. G1.1, G1.2) which stands for green referring to replacement of 90% of the cement with supplementary cementitious materials. GGBS offers significant strength and durability advantages to self-consolidating concrete [7]. Therefore, the authors in the study chose to study high volume GGBS mixes in which GGBS ranged from 60% to 80% of the total binder content as shown in Table 1.

High volume GGBS concrete mixes are prone to segregation depending on the w/b ratio. Therefore, two w/b ratios were assessed in this study, namely 0.36 and 0.33. All mixes with G2.1 to G2.9 made with w/b of 0.33 were more stable and exhibited better segregation resistance compared to mixes G1.1 to 1.9 made with w/b ratio of 0.36.

In this study, three curing methods were used to examine their effect on 28-day compressive strength. To contribute to concrete sustainability, particularly in areas where water is scarce, reduction in water usage through use of chemical curing compounds is evaluated. The three curing methods used in this study include:

- Submerging the samples in water bath under room temperature for 28 days.
- Submerging the samples for 3 days in water then placing them for 25 days under direct exposure to sun until the age of 28 days. Measured average lowest daily temperature outside the laboratory was 31 °C and average highest daily temperature was 44 °C. This is typical temperature during the month of July in Abu Dhabi, UAE.
- Applying acrylic chemical curing compound to concrete samples until the test day.

An acrylic-based chemical curing compound was chosen in this study due to its superior performance compared to paraffin-based or silicate-based compounds [1]. The acrylic-based compound used in this study was produced by BASF Corporation under the commercial name MasterKure 181 and conforms to ASTM C309 Type 1 and class B (a resin translucent compound without dye). Physical properties of MasterKure 181 are shown in Table 2. The compressive strength of samples was determined according to BS EN 12390-3:2009 [6], using a 3000 kN testing machine.
3. Experimental results and discussion

Compressive strength results of samples cured using three curing methods are shown in Figure 1 for w/b of 0.36 and Figure 2 for w/b of 0.33. For the control mixes G1 and G2, the curing methods do not exhibit a pattern of a significant difference for either w/b ratio. Figure 1 and Figure 2 also show that for most SCC mixes, sun-curing leads to the highest compressive strength development after 28 days.

SCC mixes containing 12.5% and 15% micro-silica (G1.4, G1.5, G2.4, and G2.5) exhibited the highest compressive strength under sun curing conditions compared to curing with chemical compound and conventional water bath curing. This is consistent with findings in the literature [7] indicating that 15% is optimum replacement ratio of Portland cement with micro silica to produce the highest 28-day compressive strength in sustainable SCC mixes, amongst replacement ratios ranging 5% and 20% reported in that study.

Concrete samples cured using acrylic-based compound produced higher compressive strength on virtually all SCC mixes compared to samples cured under water bath.

Table 1. Green SCC Mixes

| No. | Name | Cement % | Fly ash % | Mico Silica % | GGBS % | W/C |
|-----|------|----------|-----------|---------------|--------|-----|
| 1   | G1   | 100      | 0         | 0             | 0      | 0.36 |
| 2   | G1.1 | 10       | 5         | 5             | 80     | 0.36 |
| 3   | G1.2 | 10       | 5         | 7.5           | 77.5   | 0.36 |
| 4   | G1.3 | 10       | 5         | 10            | 75     | 0.36 |
| 5   | G1.4 | 10       | 5         | 12.5          | 72.5   | 0.36 |
| 6   | G1.5 | 10       | 5         | 15            | 70     | 0.36 |
| 7   | G1.6 | 10       | 10        | 5             | 75     | 0.36 |
| 8   | G1.7 | 10       | 15        | 5             | 70     | 0.36 |
| 9   | G1.8 | 10       | 20        | 5             | 65     | 0.36 |
| 10  | G1.9 | 10       | 25        | 5             | 60     | 0.36 |
| 11  | G2.0 | 100      | 0         | 0             | 0      | 0.33 |
| 12  | G2.1 | 10       | 5         | 5             | 80     | 0.33 |
| 13  | G2.2 | 10       | 5         | 7.5           | 77.5   | 0.33 |
| 14  | G2.3 | 10       | 5         | 10            | 75     | 0.33 |
| 15  | G2.4 | 10       | 5         | 12.5          | 72.5   | 0.33 |
| 16  | G2.5 | 10       | 5         | 15            | 70     | 0.33 |
| 17  | G2.6 | 10       | 10        | 5             | 75     | 0.33 |
| 18  | G2.7 | 10       | 15        | 5             | 70     | 0.33 |
| 19  | G2.8 | 10       | 20        | 5             | 65     | 0.33 |
| 20  | G2.9 | 10       | 25        | 5             | 60     | 0.33 |

Table 2. Physical properties of MasterKure compound

| Form       | Liquid | Flammability | Flammable |
|------------|--------|--------------|-----------|
| Color      | Yellowish | Lower explosion limit | 0.6% (V) |
| Odour      | Solvent-Like | Upper explosion limit | 6.5%(V) |
| PH value   | Slightly alkaline | Vapor pressure | Approx. 300 mbar (38 C) |
| Boiling temp. | Approx. 145-210 C | Density | 0.8 g/cm3 (20C) |
| Flash point | 42 C    | Self-ignition | Temperature approx. 210C |
4. Conclusions
This study presented the effect of the curing method on compressive strength development of sustainable self-consolidating concrete samples. In all mixes, 90% of cement was replaced with recycled combinations of fly ash, silica fume, and GGBS. Nine SCC mixes and one control mix were prepared with w/b of 0.36 and a second set of nine SCC mixes and a control mix were prepared with w/b ratio of 0.33.

- Sustainable mixes with 90% cement replacement achieved standard cube compressive strength as high as 76 MPa with w/b ratio of 0.33 and 70 MPa with w/b ratio of 0.36. The high performing mixes contained 72.5% (G2.4) or 70% (G1.4) slag replacement and 12.5% (G2.4) or 15% (G1.4) silica fume replacement of Portland cement.
- Compressive strength test results showed that curing under direct sun produced the highest strength development after 28 days of curing compared to using a curing compound or using traditional method of submerging concrete samples in water. In addition, using acrylic-based curing compound resulted in a higher strength development compared to traditional curing method submerging concrete samples under water for 28 days.
- In environments where water is scarce or when it is desired to conserve the use of water, using curing compounds is advisable and could produce compressive strength that is suitable for most practical applications.
Acknowledgment
The authors gratefully acknowledge the financial support of Abu Dhabi Department of Education and Knowledge (ADEK) through the 2017 ADEK Award for Research Excellence (AARE) 2017. Authors also acknowledge the financial support of the Office of Research and Sponsored Programs at Abu Dhabi University under grant # 19300074.

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