Capillary water absorption of self-compacting concrete under different curing conditions

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This paper reports an experimental study carried out to investigate the influence of addition of pozzolanic materials and curing regimes on the mechanical properties and the capillary water absorption (sorptivity) characteristics of self-compacting concrete (SCC). Portland cement (PC) concrete and two types of SCC, SCC-I with fly ash (30\% FA/70\% PC) and SCC-II with silica fume (10\% SF/90\% PC), specimens were prepared and cured in three different curing conditions (standard 20°C water, sealed and air cured) for the periods of 3, 7, 14 and 28 days. At the end of each curing period, compressive and tensile strengths and ultrasonic pulse velocity (UPV) values were determined; sorptivity coefficients were determined at 28 days. The results indicated that SCC-II specimens gave higher compressive and tensile strength and lower sorptivity coefficient values than those of corresponding SCC-I and PC concrete specimens, regardless of curing regimes and age of concrete. The results also showed a good correlation between the strength development of concrete and its sorptivity, i.e., as the compressive and tensile strengths increased due to the hydration, the sorptivity coefficients decreased significantly.

Self-compacting concrete (SCC) first developed in Japan in the late 1980s\(^1\) can be considered as a relatively new material in civil engineering applications. It spreads into various shapes of formwork of construction elements, e.g., highly congested reinforced column or wall, under its own weight and it provides good compaction without vibration. It has excellent deformability and high resistance to segregation\(^2\). Due to the enhanced rheological properties of SCC and its placing method into construction elements, it provides number of benefits both to the environment and to the contractors, e.g., faster construction, better surface finish, reduced noise level and safer working environment. It is estimated that using SCC may result in up to 40\% faster construction than using PC concrete\(^3,4\).

SCC mixes essentially contain superplasticizer, high content of fines, e.g., cement, pozzolans and filler (particles including in sand smaller than 0.125 mm), and/or viscosity modifying admixture (VMA). Superplasticizer incorporated in concrete plays an important role in maintaining the fluidity, while the fine material provides stability of the mix yielding resistance against bleeding and segregation. As fine materials are substantial constituents of SCC, use of fly ash (FA), silica fume (SF), ground granulated blast furnace slag (GGBS), or limestone filler in SCC contributes significantly to its fresh and hardened properties as well as to reducing its cost\(^5-7\).

Curing of freshly placed concrete is an important requirement to achieve optimum performance\(^8\). The research carried out by Yazicioglu et al.\(^9\) shows that for both SCC and PC concrete the water cured specimens gave highest compressive and tensile strength and ultrasonic pulse velocity (UPV) values followed by sealed and air cured specimens highlighting the role of water during the early ages of concrete. Bentz et al.\(^10\) also reported the significance of curing of concrete on the degree of hydration of cement. Their research pointed out that for specimens (initially cured at 100\% relative humidity (RH) for 6 or 12 h) exposed to 90\% RH, hydration process discontinued due to evaporation of all remaining capillary water. Nevertheless, curing under sealed condition, particularly for concretes with w/c of 0.4 or over, or keeping the surface as saturated was

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adequate. Although, the minimum level of saturation required for full hydration is not known as the effects of exposure to environments below 100% RH have not been sufficiently quantified, most concrete elements contain sufficient water, which maintains the complete hydration under sealed conditions. Problem may arise due to the lack of curing measures, where by evaporation from the surface takes place and moisture from either the environment or the interior of the concrete may be insufficient to replace lost water. This may have damaging effects on concrete surface properties and, possibly, on the overall performance of concrete during its service life under loading conditions.\textsuperscript{11}

To examine the durability characteristics of concrete, permeability (measure of the flow of water or various gases through the specimen under pressure gradient) is generally employed. This method can be considered significant where concrete is exposed to water pressure, such as water retaining structures. Capillary water absorption (sorptivity) characteristics of concrete for structures located above the ground level would be more appropriate. Sorptivity coefficient can be determined by means of a simple test allowing one face of concrete specimen be in contact with water and the mass (non-destructive) or height (destructive) of water absorbed by capillary suction is measured at predefined intervals.\textsuperscript{12,13}

The objectives of this study were to examine the influence of different pozzolanic admixtures (fly ash and silica Fume) and curing conditions (standard 20°C water, sealed and air cured) on the mechanical properties and capillary water absorption (sorptivity) characteristics of SCC.

**Experimental Procedure**

**Materials and specimen preparation**

For this study, three concrete types were selected, namely PC concrete, SCC-I and -II. Fly ash and silica fume were used as cement component in SCCs. While the PC concrete contained only ordinary Portland cement, the SCC-I and -II contained combination of PC/FA (70/30%) and PC/SF (90/10%), respectively.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Cement (kg/m(^3))</th>
<th>FA (kg/m(^3))</th>
<th>SF (kg/m(^3))</th>
<th>W/B(^a)</th>
<th>Sand (kg/m(^3))</th>
<th>Aggregates, 5-10 (kg/m(^3))</th>
<th>Aggregates, 10-20 (kg/m(^3))</th>
<th>SP (l/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>310</td>
<td>—</td>
<td>—</td>
<td>0.58</td>
<td>680</td>
<td>520</td>
<td>720</td>
<td>—</td>
</tr>
<tr>
<td>SCC-I</td>
<td>350</td>
<td>150</td>
<td>—</td>
<td>0.39</td>
<td>955</td>
<td>469</td>
<td>300</td>
<td>9.1</td>
</tr>
<tr>
<td>SCC-II</td>
<td>400</td>
<td>—</td>
<td>40</td>
<td>0.37</td>
<td>1090</td>
<td>470</td>
<td>335</td>
<td>8.4</td>
</tr>
</tbody>
</table>

\(^a\) W/B is water to binder (PC+FA or PC+SF) ratio

<table>
<thead>
<tr>
<th>Mix</th>
<th>Slump (m)</th>
<th>T(_{5\text{min}}) (s)</th>
<th>V-funnel</th>
<th>L-box</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>74</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>SCC-I</td>
<td>74(^b)</td>
<td>3.6</td>
<td>8.00</td>
<td>11.0</td>
</tr>
<tr>
<td>SCC-II</td>
<td>685(^b)</td>
<td>2.8</td>
<td>8.02</td>
<td>9.5</td>
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\(^b\) Slump Flow [mm]

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\(^b\) Slump Flow [mm]
Portland cement, fly ash and silica fume are given in Table 1. Details of the concrete mix compositions and properties of fresh concretes are given in Tables 2 and 3, respectively. Natural gravel with maximum particle size of 5-10 mm and 10-20 mm and natural sand (< 5 mm) were used for PC and self compacting concretes. To achieve desired rheological behaviour for SCC, e.g., a slump flow value of 650-800 mm, a superplasticizer (Viscocrete 3075) was used in both SCC mixes, whilst the PC concrete did not contain superplasticizer.

Mix designs for self-compacting concretes were developed by means of trial mixes based on guidance given in EFNARC. For self compacting concretes, slump flow, $t_{50cm}$ (Fig. 1), L-box and V-funnel tests (Fig. 2) as described in EFNARC were carried out. The results obtained from these tests (Table 3) showed that SCC mixes had good filling and passing ability as well as segregation resistance.

All PC concrete specimens were cast on a vibrating table to ensure optimum compaction, whilst the SCC specimens were cast without any vibration. Standard 150 mm cube and cylindrical (with a diameter of 150 mm and a height of 300 mm) specimens were produced. In the following day of casting, the specimens were de-moulded and located in three different curing conditions, namely standard 20°C water, sealed and air cured for the periods of 3, 7, 14 and 28 days.

Test methods

At the end of each curing period, a total of 3 specimens were tested for each concrete property. The compressive and ultrasonic pulse velocity (UPV), time required for the pulse to pass from one side to the other side of the specimen (km/s), tests were carried out on the 150 mm cube specimens, whilst the splitting tensile tests were carried out on the cylindrical specimens (150 mm diameter × 300 mm height). All the tests performed during this study were conducted at 3, 7, 14 and 28 days for all curing conditions. The performance of SCCs has been examined with respect to relevant properties of PC concrete.

Water absorption tests were carried out to determine the sorptivity coefficient of concrete specimens, which were preconditioned in oven at 105°C for 24 h and then cooled down within desiccators for 24 h to achieve a constant moisture level. Then, four sides of the concrete specimens were sealed by electrician tape to avoid evaporative effect as well as to maintain uniaxial water flow during the test and the opposite faces were left open (see Fig. 3). Before the specimens were located on water, their initial weights were recorded. One face of the specimen was in contact with water whilst the water absorption at predefined intervals was measured with scale of 0.1 g readability. The sorptivity coefficient can be calculated by the following expression:

$$\text{sorptivity coefficient} = \frac{\text{weight absorbed}}{\text{area} \times \text{time}}$$

Fig. 1—Slump flow $$[(d1+d2)/2]$$ test for self-compacting concrete.

Fig. 2—Details of testing equipment for SCC (a) V-funnel and (b) L-box (all units are in mm).
\[ S = \frac{(Q/A)}{\sqrt{t}} \]  

Where \( S \) is the sorptivity (cm/s\(^{1/2}\)), \( Q \) is the volume of water absorbed in cm\(^3\), \( A \) is the surface area in contact with water in cm\(^2\) and \( t \) is the time (s). It was obtained from the slope of the linear relationship between \( Q/A \) and \( \sqrt{t} \).

**Results and Discussion**

**Compressive strength**

The results obtained from compressive strength tests on PC concrete, SCC-I and -II for all concrete ages and curing conditions are given in Figs 4a, b and c, respectively. It can be seen in these figures that the compressive strength results of SCC-I and -II specimens (with w/b ~0.38) were higher than those of corresponding PC concrete specimens (with w/b ~0.58) for all curing methods. It is also indicated that the highest compressive strength values were obtained from water cured specimens followed by the sealed and air cured specimens regardless of the concrete types. This shows the role of curing methods on the early age compressive strength of concretes, i.e., the higher the moisture level the specimens were exposed to the higher the compressive strength was achieved. When the SCCs are compared, it can be seen that the SCC-II containing 10% SF as a cement component provided higher compressive strength than those of SCC-I containing 30% FA, regardless of curing conditions indicating the role of SF in strength development.

**Tensile strength**

The tensile strength results for three types of concrete, PC and SCC-I and -II, in three different curing methods for the 3, 7, 14 and 28 day curing periods are shown in Figs 5a, b and c, respectively. It is indicated in these figures that the development of tensile strengths of PC concrete was the lowest followed by SCC-I and II. Figure 5 shows that use of SF in concrete as cement component contributed significantly to the tensile strength particularly in the early ages. When the influence of curing methods on the tensile strength of concretes are examined, it can be seen that the highest values were obtained from water cured specimens followed by sealed and air cured specimens, regardless of concrete types.
Ultrasonic pulse velocity (UPV)

Figures 6a, b and c give the UPV test results for PC, SCC-I and –II concretes, respectively, at 3, 7, 14 and 28 days for all curing conditions. The highest UPV values were obtained from the SCC-I followed by PC and SCC-II concretes. This may be due to higher amount of fine materials (<125 µm) incorporated within the SCC-I and indicates the filling and packing capacity of fly ash particles. Water cured specimens for all concrete types gave the highest values then followed by sealed and air cured specimens again indicating the role of moisture level on the hydration and strength development.

Comparison of tensile and compressive strength

The tensile and compressive strength results of PC, SCC-I and –II concretes are compared in Figs 7a and b on the basis of curing methods and concrete types,
respectively. It is indicated in Fig. 7a that as the compressive strength of concretes increased, the tensile strength also increased, though the rate of increase in compressive strength was greater than that in tensile strength. It is also shown that at the lower strength levels, i.e., at early ages, there was not big difference between the tensile strength values of different concretes. However, as the compressive strength increased (typically beyond 40 N/mm²), difference between the tensile strength values started to appear. The SCCs gave higher tensile strength values than those of PC concrete in particular the SCC containing SF as a cement component, indicating its role during the strength development stage. SF basically consumes the calcium hydroxide crystals released from the hydration process leading to the formation of further calcium-silicate-hydrate (C-S-H) and contributing to the interfacial bond strength between aggregate particles and matrix.

It is seen in Fig. 7b that the relationships between the compressive and tensile strengths were examined regardless of the curing method that the specimens were exposed to. It is indicated that as the compressive strength of concretes increased, the tensile strength also increased. In general, the correlation between the values of compressive strength and those of tensile strengths were good with $R^2$ values of over 0.90. The SCC-II gave the highest values whilst the SCC-I and PC concretes were closer.

Sorptivity

The results of sorptivity tests are given in Fig. 8 on the basis of curing conditions and concrete types. It is indicated that SCC-II gave the lower sorptivity values
followed by SCC-I and then PC concretes in all curing conditions. The highest sorptivity value (1.5 \times 10^{-3} \text{ cm/s}^{1/2}) was obtained from the PC concrete cured in air, whilst the lowest sorptivity value (0.2 \times 10^{-3} \text{ cm/s}^{1/2}) was obtained from SCC-II cured in water. It can be suggested, therefore, that a proper curing as well as using pozzolanic admixture such as FA or SF as cement component can enhance the resistivity of concretes against water absorption significantly.

Figure 9 gives a comparison between sorptivity and both compressive and tensile strength of concretes, regardless of curing conditions. In general, very good correlation has been observed between the sorptivity and the strength values, i.e., as the strengths of concretes increased due to hydration, the sorptivity reduced significantly indicating a denser microstructure.

Conclusions

On the basis of the experimental investigation carried out, the following conclusions can be drawn:

(i) The compressive and tensile strengths of self-compacting concretes (with w/b \sim 0.38) were higher than those of PC concrete (with w/b \sim 0.58) for all testing ages and for all curing conditions.

(ii) The SCC containing SF as a cement component gave higher strength values than SCC with FA. For all concretes, the water cured specimens gave highest compressive strength values followed by sealed and air cured specimens.

(iii) Proper curing and using pozzolanic admixture such as FA or SF as cement component enhanced the resistivity of concretes against water absorption significantly.

(iv) A good correlation was observed between the sorptivity and the strength values, i.e., as the strengths of concretes increased due to hydration, the sorptivity reduced significantly indicating a denser microstructure.

References