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Porosity of self-compacting concrete

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Abstract

The construction industry demands more durable concrete with high performance. Self-compacting concrete (SCC) is developing gradually to meet many aspects of construction technology, especially reinforced concrete. On the other hand, durability properties still need some enhancements particularly in term of microstructure properties. Furthermore, there is a lack of research on non-destructive testing of self-compacting concrete. Question arises: are the contexts on the strength of conventional normal concrete (NC) extendable on the strength of SCC? Laboratory tests were carried out at the BME, Department of Construction Materials and Technologies. Aim of the research was to determine the service life of SCC with respect to normal concrete. Constant and variable parameters were determined to the concrete mixes. Constant parameters were: type of cement CEM III-A 32.5 N-MS and grading curve of the aggregate. Variable parameters were: water-cement ratio, content of cement, content of limestone powder. The purpose of this study is to analyze the implementation of economical non-pozzolanic filler additive (limestone) into the concrete matrix of SCC. Normal and self-compacting concrete mixes were prepared to reach a correlation between porosity indicators. Results indicated that SCC mixtures had more reliable rebound index and lower total porosity values than NC; whereas water absorption in SCC was found to show considerably higher values than references NC mixes.

Keywords: Durability; Porosity; Self-compacting concrete; Strength; Surface hardness.

1. Introduction

Progress in concrete technology has led to the advancement of a new type of concrete, which is known as self-consolidating concrete or self-compacting concrete (SCC). It is a highly flowing concrete that spreads through dense reinforcement, reaches every corner of the formwork, and is consolidated under its own weight without vibration or any other means of compaction [1]. Nowadays, SCC is becoming more popular and demandable worldwide due to its workability and efficiency. Generally, SCC components are typically identical to normal concrete (NC) with high filler content added, i.e. fly ash limestone powder and others. SCC has been distinguished from NC in term of “pore microstructure” mainly to the implemented filler materials and human non-intervention factors (vibration). Hence durability and pore structure are interconnected and relatively different in SCC. Concrete must be durable against several exposure circumstances which lead to deterioration processes. These processes can be categorized as mechanical (impact, fatigue and abrasion), physical and chemical i.e. (freeze and thaw cycles, carbonation, sulfate attack and others). Absorption-related properties test is applied to indicate the porosity and potential durability of concrete [2]. In this study, our target is to investigate the water absorption and total porosity of SCC, related to the
experimental results of surface hardness test (Schmidt hammer) and evaluate if SCC has a well-defined higher resistance than NC with respect to durability and structural integrity.

2. Experimental program

2.1. Materials

Danube aggregates, slag cement, limestone powder, tap water and polycarboxylate-based high range water reducing admixtures were applied to produce several NC and SCC mixtures. Local natural sand is used as fine aggregates with a fraction between (0-4 mm). A fixed proportion of particle size distribution is divided as 45% (0-4 mm), 20% (4-8 mm), and 35% (8-16 mm) respectively. Gravel extracted from river was used as coarse aggregates is based on a maximum diameter size of $D_{\text{max}}=16$ mm. Limestone powder produced from carboniferous limestone (98% of CaCO$_3$ content) with corresponding specific gravity (2.7) is implemented as a filler for SCC. “Duna-Drava CEM III/A 32.5 N-MS” is used in the concrete mixtures. It has a special characteristic of moderate sulfate corrosion resistance. New generation (Sika ViscoCrete Neu-5) is applied as HRWRA. It is an aqueous solution of modified polycarboxylates. On the other hand a stabilizer is used in the case of excess use of water or superplasticizer (Sika stabilizer 4R). In this study, a total of fifteen SCC and NC concrete mixtures were prepared with various cement content. Three separate water to cement ratios ($w/c$) were permanent with respect to limestone variation into the mixtures. Grading curve and cement type were constant parameters whereas cement and limestone fine-content ($w/f$) content were variable parameters. For more details, mixtures proportions are shown in table 1-2 respectively.

|                        | SCC-1 | SCC-2 | SCC-3 | SCC-4 | SCC-5 | SCC-6 | SCC-7 |
|------------------------|-------|-------|-------|-------|-------|-------|-------|
| CEM III 32.5 N-MS      | 320   | 360   | 400   | 320   | 360   | 400   | 320   |
| Water                  | 180   | 180   | 180   | 180   | 180   | 180   | 180   |
| Limestone              | 300   | 260   | 220   | 260   | 220   | 180   | 200   |
| Agg (0-4 mm)           | 700   | 701   | 703   | 717   | 719   | 721   | 744   |
| Agg (4-8 mm)           | 311   | 311   | 312   | 319   | 319   | 320   | 330   |
| Agg (8-16 mm)          | 544   | 545   | 547   | 558   | 559   | 560   | 578   |
| Sika 5 Neu             | 1.28  | 1.84  | 2.0   | 1.28  | 1.8   | 2.2   | 1.744 |
| Sika 4-R               | -     | -     | 0.6   | -     | -     | 0.66  | 0.216 |
| $w/c$                  | 0.561 | 0.5   | 0.45  | 0.561 | 0.5   | 0.45  | 0.561 |
| $w/f$                  | 0.29  | 0.29  | 0.29  | 0.31  | 0.31  | 0.31  | 0.34  |
Table 2. Mixture proportions of fresh concrete (kg/m³).

|           | SCC-8 | SCC-9 | SCC-10 | SCC-11 | SCC-12 | NC-1 | NC-2 | NC-3 |
|-----------|-------|-------|--------|--------|--------|------|------|------|
| CEM III 32.5 N-MS | 360   | 400   | 320    | 360    | 400    | 320  | 360  | 400  |
| Water     | 180   | 180   | 180    | 180    | 180    | 180  | 180  | 180  |
| Limestone | 160   | 120   | 160    | 120    | 80     | -    | -    | -    |
| Agg.(0-4 mm) | 746   | 747   | 762    | 763    | 833    | 817  | 802  | 802  |
| Agg.4-8 mm) | 332   | 332   | 338    | 339    | 341    | 370  | 363  | 356  |
| Agg.(8-16 mm) | 580   | 581   | 592    | 593    | 596    | 648  | 635  | 623  |
| Sika 5 Neu | 1.548 | 1.76  | 1.408  | 1.44   | 1.4    | 0.672| 0.594| 0.76 |
| Sika 4-R  | 0.216 | -     | 0.216  | -      | -      | 0.033| -    | -    |
| w/c       | 0.5   | 0.45  | 0.561  | 0.5    | 0.45   | 0.561| 0.5  | 0.45 |
| w/f       | 0.34  | 0.34  | 0.375  | 0.375  | 0.375  | 0.5625| 0.5  | 0.45 |

2.2. Specimens

Fourteen 150 mm cubes were prepared and evaluated for compressive strength. Specimens were tested on a 3000 kN compression test machine (Form-Test Alpha 3000). Surface hardness was determined using N-type Schmidt hammer. Total porosity and water absorption tests were executed. Cubes were removed from their formwork after 24 h of casting and kept for 28 days in water for curing.

2.3. Surface hardness determination

The most widespread non-destructive test for concrete strength is the portable Schmidt hammer. According to EN 12504-2 [3], hardness of the concrete surface can be determined on cube specimens areas (150×150 mm) of NC and SCC at the age of 28 days. In order to understand the behavior of this instrument, it is important to recognize the factors that are affecting the rebound distance. The energy absorbed by the concrete depends on the stress-strain relationship of concrete. Thus, the absorbed energy depends on the strength and stiffness of concrete. The surface texture influences the rebound value. When the test is performed on a rough concrete surface, we might have some local crushing under the plunger and the reflected value will be lower than the actual one [4]. N-type hammer is applied on our specimens. it is designed for concrete testing elements with 100 mm or more thickness, or concrete with maximum gravel size less than or equal to 32mm. This type of hammer provides rebound values which are recorded as a bar chart on the scale of the rebound hammer. Similar conditions applied for all specimens: horizontal direction of the Schmidt hammer impacted on a centrally 100×100 mm surface area tested with 10 independent points respectively on the surface.

3. Total porosity

“Pore” is a term designated for gaps or opening between 1 nm and 1 mm. Pores are voids filled with air or liquid. These cavities are formed between crystals in the solid material or as gas bubbles in hydration phase. Among pore types, open and closed pores are formed. Open ones are those into which gas or liquid might flow and designate permeability. In order to determine the total porosity, it is important to understand the difference between the density of solid material and not the solid body where pores are not included in the latter. The density of solids in the material not the solid body is illustrated by the term “true density”. Hence Pyknometry method is applied for the determination of absolute density in accordance with EN 725-7[5].

\[
\rho_t = \frac{m_{\text{solid}}}{V_{\text{solid}}}
\]
Where:
\( \rho_t \): absolute density of the material
\( m_{\text{solid}} \): mass of solid material without pores
\( V_{\text{solid}} \): volume of solid without pores

Whereas “Bulk density” is the terminology showing the ratio of mass to the total volume of a sample (volume of solid and pores):

\[
\rho_b = \frac{m_b}{V_b}
\]  

Where
\( \rho_b \): bulk density of the material
\( m_b \): bulk mass of the material with pores
\( V_{\text{solid}} \): volume of solid with pores

Porosity \( (P_t) \) of a body can be determined as follows,

\[
P_t = 1 - \frac{\rho_b}{\rho_t}
\]  

3.1. Absorption in hardened concrete

Permeation, diffusion and capillary sorption illustrate the transport mechanisms of liquid, gases in hardened concrete. SCC in comparison with NC of similar concrete strength reveal a denser microstructure. Through capillary pores and internal micro cracks penetration of water occurs. Mainly interconnected capillary pores which are related to water to cement ratio affect the flow of water in the hydrated cement paste and total porosity of hardened concrete. The prediction of water absorption is related to concrete components e.g. (amount of cement, silica fume, limestone etc.)[6]. In this analysis, the volume of permeable pores was determined based on ASTM recommendations [7]. Thus apparent porosity was calculated with respect to the following formula:

\[
P_a = \frac{n \cdot \rho_b}{100 \cdot \rho_w}
\]  

Where
\( \rho_b \): bulk density of the material
\( \rho_w \): density of water
\( n \): moisture content

4. Results

Table 3, 4 and 5 show respectively the results of fresh concrete, mechanical properties of specimens and durability indicators for all NC and SCC mixtures [8,9].

4.1. Mechanical properties

Mixtures with relatively high water to cement ratio resulted in a material with low strength with respect to low water to cement ratio mixtures with higher strength. SCC mixtures SCC-1, SCC-4, SCC-7 and SCC-10 which hold similar water to cement ratio \( (w/c=0.561) \) showed relatively a higher compressive strength (by 56%) compared to those with lowest water to fine-content ratio \( (w/f) \) in comparison with the highest water to fine-content mixtures and NC-1 mixture. Whereas SCC mixtures SCC-2, SCC-5, SCC-8 and SCC-9 which represent a similar water to cement
ratio \((w/c=0.5)\) showed a strength variation of 39% between different water to binder ratios and NC-2. Moreover with decrease of water cement ratio (SCC-3, SCC-6, SCC-9 and SCC-12) and variation of water to fine-content ratio, the latter exhibit a strength increase of 30% with variation of limestone filler. Due to the implementation of limestone powder with the cement, an optimized concrete skeleton is obtained which results in a higher strength which varies with respect to water content. Comparatively, even though SCC mixtures with the highest water to fine-content ratios contain an insignificant amount of filler (limestone), they still tend to have a higher compressive strength with respect to NC.

**Table 3. Fresh and hardened concrete properties.**

|                   | SCC-1 | SCC-2 | SCC-3 | SCC-4 | SCC-5 | SCC-6 | SCC-7 |
|-------------------|-------|-------|-------|-------|-------|-------|-------|
| Flowability (mm)  | 750   | 645   | 625   | 800   | 785   | 810   | 810   |
| Slump (mm)        | -     | -     | -     | -     | -     | -     | -     |
| Viscosity (s)     | 7.6   | 11.19 | 11.9  | 5.6   | 4.8   | 4.7   | 4.2   |
| Classification    | SF2   | SF1   | SF1   | SF3   | SF3   | SF3   | SF3   |
| \(f_{cu}(N/mm^2)\) | 47    | 57    | 65    | 46    | 50    | 56    | 46    |
| Avg. rebound index| 44.3  | 47.07 | 46.83 | 42.1  | 43.13 | 48.97 | 43.37 |

**Table 4. Fresh and hardened concrete properties.**

|                   | SCC-8 | SCC-9 | SCC-10 | SCC-11 | SCC-12 | NC-1 | NC-2 | NC-3 |
|-------------------|-------|-------|--------|--------|--------|------|------|------|
| Flowability (mm)  | 795   | 750   | 750    | 790    | 720    | -    | -    | -    |
| Slump (mm)        | -     | -     | -      | -      | -      | 525  | 555  | 505  |
| Viscosity (s)     | 5.5   | 6.1   | 4.3    | 4.8    | 5.1    | -    | -    | -    |
| Classification    | SF3   | SF2   | SF2    | SF3    | SF2    | F4   | F4   | F4   |
| \(f_{cu}(N/mm^2)\) | 49    | 57    | 30     | 41     | 50     | 27   | 32   | 40   |
| Avg. rebound index| 42.03 | 46.67 | 39.87  | 40.57  | 42.9   | 32.9 | 33.05| 32.8 |

**Figure 1. Normal distribution density function for surface rebound index of concrete mixtures.**

It is important to distinguish between SCC and NC pore structure behavior. As shown in Fig.1, SCC mixtures tend to have a lower standard deviation with respect to NC. The deviation varies dramatically when the impact of the
Schmidt hammer on the contact surface of concrete (Non homogenous material) is directly applied on an aggregate or highly porous surface. Therefore, SCC shows more reliable values due to denser microstructure.

4.2. Durability properties

Capillary pores have the major influence on the durability of concrete due to connectivity and continuity of pore structure. Based on the higher amount of filler material and exclusion of vibration, SCC must have a denser interfacial zone and more uniformly dispersed microstructure [10].

![Figure 2. NC and SCC analyzed photograph using Image C software.](image)

Pore size, shape and distribution properties are interconnected towards concrete strength. Figure (1) present two photos of NC and SCC cases with similar water to cement ratio (0.5). As shown in the left side of the figure, NC hold equivalently more pores which tend to be in modest deviations from equidimensional with respect to SCC. The later has more rounded angularity in comparison with NC.

| Table 5. Durability indicators. |
|---------------------------------|
| | SCC-1 | SCC-2 | SCC-3 | SCC-4 | SCC-5 | SCC-6 | SCC-7 |
| Total porosity% | 13.565 | 9.261 | 8.498 | 13.29 | 12.209 | 11.973 | 15.245 |
| Apparent porosity% | 6.18 | 4.68 | 3.05 | 2.43 | 4.51 | 3.18 | 5.37 |

| Table 5. Durability indicators. |
|---------------------------------|
| | SCC-8 | SCC-9 | SCC-10 | SCC-11 | SCC-12 | NC-1 | NC-2 | NC-3 |
| Total porosity% | 14.083 | 8.901 | 14.409 | 13.505 | 11.594 | 14.191 | 13.322 | 12.912 |
| Apparent porosity% | 4.75 | 2.75 | 4.57 | 4.52 | 3.61 | 2.74 | 2.52 | 2.14 |

Fine-content and total porosity are interconnected. SCC mixtures with (0.29) water to fine-content ratio have an average total porosity of 10.36%. This value tends to increase with the ratio of water to fine-content (0.375) about 27% to reach an average of 13.16% of porosity. On the other hand, Tab.5 shows that NC has a higher resistance to water absorption with respect to SCC by 65%. This could be explained by the continuity on which the paste hold in the matrix during the hydration. However, NC has a higher aggregate content in where the matrix tend to have more discontinuity between capillaries. In case of SCC capillaries can be connected and form a capillary system in the
relatively high fine-content, on the other hand in case of NC the capillary is interrupted by the aggregate. Thus curing is more sensitive in case of SCC.

5. Conclusions

Based on the completing of this study, the following conclusions can be drawn:

- In higher water to cement ratio, limestone filler is more effective in compressive strength,
- Surface hardness test is more reliable in SCC with respect it’s to total porosity,
- Total porosity tend to increase in SCC with respect to water to binder ratio,
- Surface hardness standard deviation is more likely to increase with the growth of the pore structure,
- Capillary suction is higher in SCC about 65%.

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