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Permeation properties of self-compacting concrete

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Abstract

Permeation properties, which include permeability, absorption, diffusivity etc., have been widely used to quantify durability characteristics of concrete. This paper presents an experimental study on permeation properties of a range of different self-compacting concrete (SCC) mixes in comparison with those of selected traditional vibrated reference (REF) concretes of the same strength grade. The SCC mixes with characteristic cube strength of 40 and 60 MPa were designed containing either additional powder as filler or containing no filler but using a viscosity agent. The results indicated that the SCC mixes had significantly lower oxygen permeability and sorptivity than the vibrated normal reference concretes of the same strength grades. The chloride diffusivity, however, appeared to be much dependent on the type of filler used; the SCC mixes containing no additional powder but using a viscosity agent were found to have considerably higher diffusivity than the reference mixes and the other SCCs.

Keywords: Permeability; Absorption; Diffusion; Durability; Self-compacting concrete

1. Introduction

Since its inception in the late 1980s, self-compacting concrete (SCC) has brought in a wave of change for the construction industry. SCC has been considered as a 'quiet revolution' in the concrete construction process, with major benefits in increased productivity, enhanced construction quality, and much improved working environment on site [1]. Already, it is rapidly gaining acceptance throughout the industry and being viewed by many as having the potential of replacing most of the ordinary concrete currently produced [2,3]. Much research has been carried out regarding the fresh properties, mix design, placing methods and strength of various SCC mixes [4–6]. However, only very limited work has been done to systematically assess the durability performance of SCC, particularly in comparison with traditionally vibrated normal concrete. Both higher and lower permeation properties have been reported for SCC in comparison with normal concrete [7,8].

SCC mixes always contain a powerful superplasticizer and often use a large quantity of powder materials and/or viscosity-modifying admixtures. The superplasticizer is necessary for producing a highly fluid concrete mix (low yield value) while the powder materials or viscosity agents are required to maintain stability (sufficient viscosity) of the mix, hence reducing bleeding and segregation/settlement. The powder materials used often include limestone powder, pulverised fuel ash (PFA), granulated ground blast furnace slag etc. Furthermore, coarse aggregate content is much lower in SCC mixes than in traditional vibrated concrete mixes to reduce the risk of blocking of concrete flow by congested reinforcement and narrow openings in the formwork. Due to such significant differences in the mix proportions and also in placing and compaction processes between the SCC and traditional vibrated mix, it is uncertain that SCC would have the same durability characteristics as traditional concrete if their strength grade were similar. Due to this uncertainty and its great significance to the serviceability of concrete structure, knowledge of the durability performance of SCC mixes is urgently needed.

The main objective of this study was to systematically assess the durability by investigating the oxygen permeability, capillary absorption and chloride diffusivity of different types of SCC mixes in comparison with vibrated reference normal concretes of a same-strength grade.

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2. Experimental

2.1. Materials and concrete mixes used

Two grades of concrete mixes were examined: C40, having characteristic cube strength of 40 MPa, and C60, having characteristic cube strength of 60 MPa. For each grade, three different SCC mixes and two traditionally vibrated reference (REF) mixes were produced. A Portland cement (class 42.5), continuously graded crushed granite of 20-mm maximum size and natural sand (Zone M of British Standard [BS] 882 [9]) were used for all the concrete mixes. A fine limestone powder (98% <30 μm and 20% <2 μm) of high purity (99.3% $CaCO_3$) and a PFA to BS 3892, Part 1 [10], were used as an additional powder in selected SCC and reference mixes. A special superplasticizer, Viscocrete 2, provided by Sika was used in SCC mixes to achieve a slump flow value of 600–650 mm. A viscosity agent, Welan gum, was used in the SCC mixes, which contained no additional powder.

To cover the range of different mix variations, three SCC mixes in each strength grade were designed, namely, one using limestone powder, one using PFA and one using no additional powder but a viscosity agent. The SCC designs were determined by trial mixes or based on a previous European SCC project [6]. Two reference mixes in each strength grade were also selected, one using Portland cement only, the other using Portland cement and PFA as the binder material. The reference mixes with a medium workability (slump = 50–80 mm) were determined using the DOE method [11] and verified by trial mixes. Details of the concrete mix designs used and their basic properties are given in Tables 1 and 2, respectively. The slump flow values for the SCC mixes and the slump value for the C60 reference mix containing PFA (i.e., C60–REF 2) were achieved by adjusting the dosage of the superplasticizer. All the mixes showed good resistance to segregation and achieved the compressive strength required (i.e., within the normal range) for the C40 and C60 grades.

Table 2
Basic fresh properties and compressive strength of hardened concrete

Basic properties	REF 1		REF 2		SCC 1		SCC 2		SCC 3	
	C40	C60	C40	C60	C40	C60	C40	C60	C40	C60
Slump (mm)	65	80	50	60	–	–	–	–	–	–
Slump flow (mm)	–	–	–	–	620	630	630	600	600	600
7-day strength (MPa)	29.3	44.7	27.4	50.2	40.4	48.5	33.0	50.4	32.4	50.4
28-day strength (MPa)	45.5	61.8	42.9	68.5	50.9	56.9	49.9	71.3	41.6	66.8

2.2. Preparation of test specimens

Standard cube (150 mm) and cylinder (Φ 150 × 300) specimens were produced. The specimens for the SCC mixes were cast by pouring from a scoop without vibration, while the reference mixes were compacted on a vibrating table. The specimens were demoulded after 24 h and then water cured in accordance with BS. Further processing and preconditioning of specimens for testing of permeation properties were started at the age of 7 days due to the time limitation for the study. From the cylinder sample, a Φ 100-mm core was taken and a 15- to 20-mm-thick section from both ends was cut off and discarded. The remaining core was then sliced into approximately 50-mm thick disc specimens to be used for testing of permeability and diffusivity. Oxygen permeability, capillary water absorption and chloride diffusivity tests were made on preconditioned specimens to provide comparisons of permeation properties between the different SCC and reference mixes.

Table 1
Details of mix designs of SCC and reference conventional concrete mixes

Mix proportions (kg/m^3)	REF 1		REF 2		SCC 1		SCC 2		SCC 3	
	C40	C60	C40	C60	C40	C60	C40	C60	C40	C60
Granite (20–5 mm)	1105	1085	1045	1110	770	750	770	750	770	750
Natural sand (zone M)	715	620	695	625	875	915	875	915	990	930
Portland cement (42.5)	340	465	280	375	285	320	335	410	360	475
Fine limestone powder	–	–	–	–	265	230	–	–	–	–
PFA (BS 3892, Part 1)	–	–	120	95	–	–	145	100	–	–
Viscosity agent (Welan gum)	–	–	–	–	–	–	–	–	0.17	0.12
Superplasticizer (Viscocrete 2)	–	–	–	1.5	5.0	4.4	4.8	4.6	7.2	6.7
Free water	195	196	190	169	180	167	195	177	210	196
Cement + powder (kg/m^3)	340	465	400	470	550	550	480	510	360	475
Water/PC ratio	0.57	0.42	0.68	0.45	0.63	0.52	0.58	0.43	0.58	0.41
Water/(cement + powder) ratio	0.57	0.42	0.48	0.36	0.33	0.30	0.41	0.35	0.58	0.41
Volume of paste (l/m^3)	303	344	335	331	369	355	369	353	324	347

2.3. Testing of permeation properties

The ingress of gases, water or ions in aqueous solutions into concrete takes place through pore spaces in the cement paste matrix and paste–aggregate interfaces or microcracks [12]. Depending on the driving force of the process and the nature of the transported matter, the transport of fluids into concrete is usually classified into three main mechanisms, namely, diffusion, capillary absorption and permeation.

2.3.1. Oxygen permeability test

The test for determination of the permeability of concrete to oxygen recommended by Cembureau [13] and RILEM [14] was adopted. For each concrete mix, two replicate disc specimens (ϕ 100 × 50 mm) were conditioned in an oven at 55–60 °C for 2 weeks and then wrapped in cling film to cool down before testing. The test was carried out by applying a constant pressure head to the test specimen, and the flow rate of gas through the specimen at steady state under the pressure head was measured. This allows the permeability coefficient of the tested concrete to be determined. A set of four test pressures from 0.5 to 2.0 bars was used in this study.

2.3.2. Capillary water absorption test

The test determines the sorptivity, or rate of water absorption through the concrete surface. The experimental setup for the capillary absorption test is shown in Fig. 1. The capillary absorption test was carried out on the moulded side faces of the 150-mm cube specimens. The specimens were preconditioned in an oven at 105 ± 5 °C to constant weight. After cooling, the specimens were prepared and tested according to the procedures described in the RILEM TC 166 recommendation [14]. The uptake of water by capillary absorption was measured through the weight gain of the specimen at the set time intervals of 10 min, 30 min, 1 h, 4 h, and 24 h of concrete surface in contact with water. The uptake of water per unit area of concrete surface I followed a linear relationship with the square root of time for the suction periods t, namely, $I = C + St^{0.5}$, where the sorptivity S is the slope of the I vs. $t^{0.5}$ plot and can be obtained by linear regression.

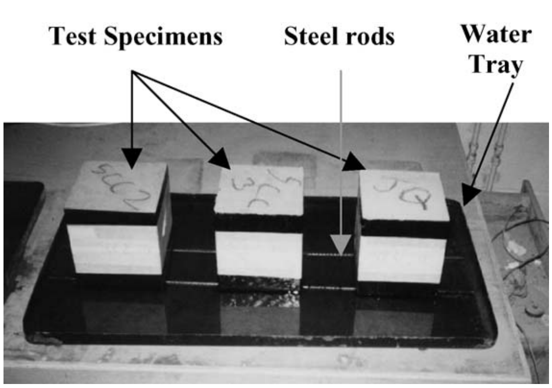

Fig. 1. Experimental setup for the capillary absorption test.

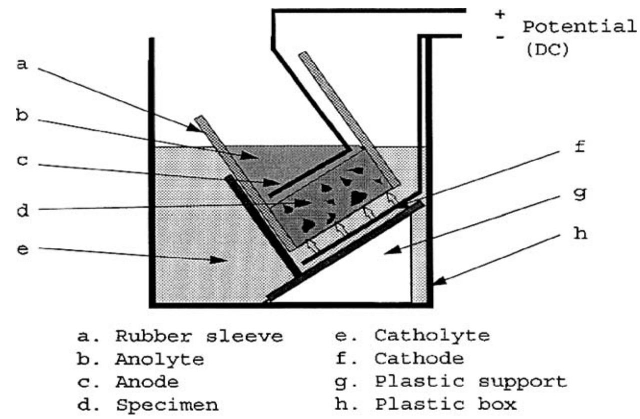

Fig. 2. Experimental arrangement of the CTH Rapid Test [8].

2.3.3. Chloride diffusivity test

The CTH Rapid Test [8,15] was employed for determination of chloride diffusivity in concrete. The test arrangement for the CTH rapid method is shown in Fig. 2. This is an electrically accelerated method providing rapid measurement of diffusivity (i.e., coefficient of migration) of chloride ions in concrete. This test involves placing a ϕ 100 × 50-mm preconditioned concrete specimen in a test cell, with its test face in contact with a chloride solution and imposing an external potential of 10–60 V across the specimen to force the chloride ion migrating into the specimen. After a duration of up to 24 h, the fresh specimen is axially split in two, and the average depth of penetration, shown by the application of a 0.1-N silver nitrate solution, is measured. This average depth can then be used to calculate the coefficient of chloride migration. Two replicate specimens were tested for each concrete mix in this study and the specimens were preconditioned by vacuum treatment and saturation in a limewater solution.

3. Results and discussions

3.1. Oxygen permeability

The average coefficient of oxygen permeability and its standard deviation, obtained from two replicate specimens

Table 3
Results of coefficient of oxygen permeability

Concrete mixes	Average ± S.D. coefficient of permeability (10^{-17} m^2)	
	C40 mixes	C60 mixes
REF 1	12.8 ± 0.5	10.4 ± 0.3
REF 2	13.9 ± 1.1	5.0 ± 0.4
SCC 1	5.5 ± 0.2	4.5 ± 0.6
SCC 2	4.1 ± 0.2	2.9 ± 0.1
SCC 3	8.2 ± 1.5	7.3 ± 0.7

and each measured at four different pressure heads, are given in Table 3. The results clearly indicated that for the 40-MPa strength grade (C40), all three different SCC mixes had significantly lower coefficient of permeability than the REF concrete mixes. Particularly, for SCC mixes using PFA and limestone powder (i.e., SCC2 and SCC1, respectively), the coefficient of permeability is only 30–40% of the level for the reference concrete mixes. For the C60 mixes, the results appeared to show the same trend as that for the C40 mixes, although the reference mix containing PFA (REF 2) had a significantly lower coefficient of permeability than that of the REF 1 mix. The relatively low permeability coefficient of the C60–REF 2 mix is in agreement with previous findings that the permeability of concrete at the same strength level could be halved with the use of PFA as a partial replacement of 27% for OPC in combination with superplasticizing admixtures [16].

The results also indicated that at both strength grades, the SCC mix using no additional powder but a viscosity agent had considerably higher permeability coefficient than the other SCC mixes that used limestone powder or PFA as filler.

3.2. Sorptivity—capillary water absorption

The results of the capillary absorption test are presented in Fig. 3. As shown, the results indicated that at the 40-MPa (C40) strength level, the sorptivity was significantly lower for all the SCC mixes than for the REF concretes. At the C60 level, the reference mix containing PFA (REF 2) showed similar sorptivity value to those of the SCC mixes, while the sorptivity for REF 1 mix was clearly still higher than the rest. The results in Fig. 3 also suggested that for both C40 and C60 grades, there were no significant differences in sorptivity among the three types of SCC mixes studied; if anything, the SCC mix using PFA as filler seemed to have slightly lower sorptivity values than the other SCC mixes.

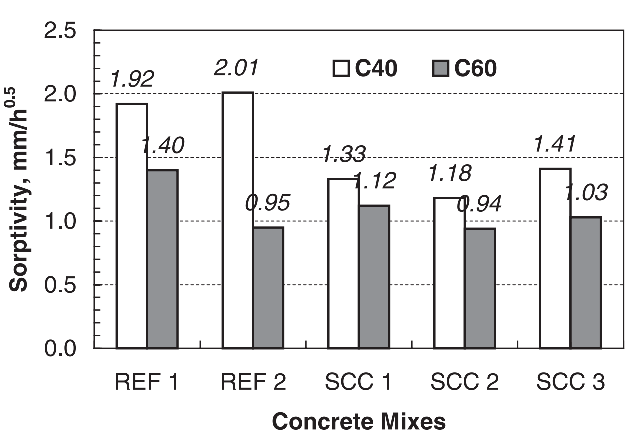

Fig. 3. Results of capillary absorption of water through concrete surface.

Table 4
Results of chloride migration coefficient

Concrete mixes	Test conditions (V, h)	Penetration depth (mm) (mean ± S.D.)	Migration coefficient (10^{-12} m^2/s)	
C40–REF 1				
Sample A	10, 22	29.8 ± 1.4	46.4	43.6
Sample B	15, 24	42.6 ± 2.3	40.8	
C40–REF 2				
Sample A	20, 24	16.5 ± 1.7	13.0	12.9
Sample B	30, 22	26.0 ± 1.6	12.8	
C40–SCC 1				
Sample A	10, 20	22.6 ± 1.9	39.3	41.9
Sample B	10, 24	29.2 ± 2.2	44.4	
C40–SCC 2				
Sample A	30, 20	12.6 ± 4.4	6.8	8.4
Sample B	30, 24	22.0 ± 7.7	10.0	
C40–SCC 3				
Sample A	10, 20	32.9 ± 1.7	57.2	54.6
Sample B	10, 24	33.9 ± 1.7	52.0	
C60–REF 1				
Sample A	25, 23	17.2 ± 2.5	10.2	9.4
Sample B	25, 23	14.7 ± 2.4	8.6	
C60–REF 2				
Sample A	35, 23	16.0 ± 3.3	6.4	6.6
Sample B	35, 23	17.1 ± 4.1	6.8	
C60–SCC 1				
Sample A	30, 24	26.5 ± 1.4	12.7	12.7
Sample B	30, 24	26.6 ± 1.8	12.6	
C60–SCC 2				
Sample A	35, 23	16.2 ± 2.6	6.6	6.3
Sample B	35, 23	14.7 ± 2.1	5.9	
C60–SCC 3				
Sample A	25, 23	24.8 ± 3.8	15.1	16.2
Sample B	25, 23	28.3 ± 3.3	17.3	

3.3. Chloride diffusivity

The main testing data and the results of the migration coefficient obtained from the CTH Rapid Test are given in Table 4. The results of coefficient of chloride migration clearly indicated that the chloride diffusivity was very much affected by the type of powders used in the concrete. Particularly, the concrete mixes containing PFA (i.e., REF 2 and SCC2) showed much lower migration coefficient compared to the other mixes, especially for the lower strength grade mixes. For example, the values of migration coefficient for REF 2 and SCC 2 were only 20–30% and 60–70% of that for the REF 1 mix at the strength grade of 40 and 60 MPa, respectively.

The results in Table 4 also showed that the SCC 3 mixes that contained no additional powder but a viscosity agent had the highest chloride diffusivity at both strength grades. While the data in the C40 mixes showed similar migration coefficient for REF 1 and SCC 1 mixes, the migration coefficient of SCC 1 was found to be higher than that of REF 1 in the C60 grade concretes.

3.4. General discussions

Theoretically, the main factors that control the permeation properties of concrete materials are the relative volume of paste matrix, the pore structure of the bulk matrix and the interfacial zone around the aggregate particles. It is thought that due to the enhanced stability of the fresh mix and/or the use of additional fine powder, together with the elimination of vibration, SCC mixes should have more homogeneous microstructures and denser interfacial zones since more efficient packing and less water bleeding and trapping may be expected. Limited studies on microstructure of SCC appeared to confirm that the interfacial zones around reinforcement and large aggregate particles were denser and their properties more homogeneous in SCC mixes than those in the traditional vibrated normal concrete mixes [17,18]. The significantly lower oxygen permeability and capillary water absorption for the SCC mixes observed in this study may be attributed to their less porous interfacial zone, and also the refined pore structure of the paste matrix.

The difference of the chloride diffusivity results between the different SCC and reference concrete mixes is more difficult to explain. This might lie in the fact that chloride diffusivity is measured in terms of penetration depth and so would be expected to be more sensitive to changes in tortuosity, instead of the total pore volume and size. The significant reduction of chloride diffusivity due to the incorporation of PFA may be partly explained by this mechanism since the spherical PFA particles could improve the particle packing density both in the matrix and in the interfacial zone. Poor dispersion of fine powders in some SCC was also suggested as a possible cause of high chloride diffusivity [8]. Other factors that may have contributed to the difference in chloride diffusivity of the various SCC and reference mixes may include: the relative magnitude of chloride diffusivity of the aggregates, the paste and the interfacial area; the enhanced water retainability of the fresh SCC mixes; and possibly the chemical and physical binding of chloride ions by filler particles and the cement hydration products. The results of this study seemed to suggest that equal strength grade, equal w/c ratio or equal water/binder ratio alone could not ensure different SCC mixes to have equal or lower chloride diffusivity than traditional vibrated concretes.

It is worth pointing out that due to the sensitivity of permeability and absorption measurements to the moisture content of concrete oven-dried specimens were studied in this project, which could be significantly different from concrete in practice. Also, different transport mechanisms are usually dealt with separately, as in this study, in order to identify and measure the fundamental parameters involved. In practical exposure conditions, however, several different transport mechanisms may act simultaneously or they may prevail in sequence during consecutive periods. Therefore, when dealing with real durability problems, such as the corrosion of reinforcement in concrete structures, different transport mechanisms and their interactions and relative importance, as well as reactions between the transport media and cement matrix have to be considered. More research is clearly required in this aspect.

4. Conclusions

Results of experiments on permeation properties, including oxygen permeability, capillary water absorption and chloride diffusivity, of a range of different SCC mixes have been presented in comparison with those of selected REF concrete mixes of the same strength grades of C40 and C60. For the range of SCC and reference mixes studied, the following conclusions can be drawn:

1. SCC mixes showed significantly lower values of coefficient of permeability and sorptivity of water absorption compared to the traditional, vibrated reference concretes of the same strength grade.
2. The chloride diffusivity was very much dependent on the type of additional powder used in concrete. Both the SCC and the reference mixes using PFA showed much lower values of chloride migration coefficient than the other mixes. The results also seemed to suggest that equal strength grade or equal w/c ratio alone could not ensure different SCC mixes to have equal or lower chloride diffusivity than the traditional vibrated concretes.
3. Among the three different SCC mixes, it appeared that the SCC mix using no additional powder but a viscosity agent to maintain stability of the fresh mix had the highest permeability, sorptivity and chloride diffusivity.

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