Influence of Capillary Porosity on the Transport Properties of Self Compacting Concrete

by K. Audenaert, V. Boel, and G. De Schutter

Synopsis: Self compacting concrete (SCC) is a new kind of concrete that combines a high flowability and a high segregation resistance obtained by a large amount of fine particles or the presence of a viscosity modifying agent and the use of superplasticizers. As self compacting concrete does not need external compaction, the pore structure, and more specifically the amount of capillary pores, is not influenced by the compaction method. These capillary pores play a very important role in the transport of water and gases in concrete and are of major importance for the understanding of degradation mechanisms.

In order to verify the correlation between the transport properties and the capillary pores, tests were carried out. Water and gas permeability, capillary absorption, carbonation and chloride penetration tests were performed on 11 self compacting concrete mixtures and 1 traditional concrete mixture. The selection of the mixtures is made in order to consider some important parameters like the cement/powder and water/cement ratio, the amount of water, the amount of powder and the type of filler (limestone filler with two different grading curves).

The amount of capillary pores was calculated by the method of Powers. The calculated values were compared with the test results and gave very good correlations.

Keywords: capillary absorption; capillary pores; carbonation; chloride penetration; gas permeability; water permeability

This is a preview. Click here to purchase the full publication.

K. Audenaert is an assistant at the Magnel Laboratory for Concrete Research at Ghent University Belgium. Her research is focussed on the penetration of potentially aggressive fluids in self-compacting concrete, and its importance related to the durability of self-compacting concrete.

V. Boel is a scientific researcher at the Magnel Laboratory for Concrete Research at Ghent University Belgium. Her main topic deals with the importance of the pore structure of self-compacting concrete in relation with the properties of this new cementitious material.

G. De Schutter is professor at the Magnel Laboratory for Concrete Research, Ghent University Belgium. His main research interests are early age concrete, massive concrete, durability of concrete structures and self-compacting concrete.

INTRODUCTION

Self compacting concrete (SCC) is a recently developed type of concrete that combines a high flowability and a high segregation resistance obtained by a large amount of fine particles or the presence of a viscosity modifying agent and the use of superplasticizers. In this research, no viscosity modifying agents were used. As the conception of SCC is totally different from traditional concrete (TC) and no external compaction is needed, the pore structure, and more specifically the amount of capillary pores, will be influenced. These capillary pores play a very important role in the transport of water and gases in concrete and are of major importance for the understanding of degradation mechanisms.

In order to verify the correlation between the transport properties and the capillary pores, tests were carried out. In this project, water and gas permeability, capillary absorption, carbonation and chloride penetration tests were performed on 11 self compacting concrete mixtures and 1 traditional concrete mixture. The selection of the mixtures is made in order to consider some important parameters like the cement/powder and water/cement, the amount of water, the amount of powder and the type of filler (limestone filler with two different grading curves).

The amount of capillary pores was calculated by the method of Powers. The calculated values were compared with the test results and gave good correlations.

EXPERIMENTAL PROGRAM

Concrete composition

At the Magnel Laboratory for Concrete Research, 11 self compacting concrete mixtures (SCC) and 1 traditional concrete mixture (TC) were investigated. In the first 5 mixtures a constant amount of powder (cement and filler) is considered: 600 kg/m³, as well as a constant amount of water, sand and gravel, respectively 165 kg/m³, 853 kg/m³ and 698 kg/m³. In the first four mixtures, the cement/powder is varied. In the next mixture, a limestone filler with a finer grading is used (Figure 1). In the next three mixtures, the amount of powder is varied (500 kg/m³, 700 kg/m³ and 800 kg/m³). In the following three mixtures, the

This is a preview. Click here to purchase the full publication.

amount of water is varied (144 kg/m³, 198 kg/m³ and 216 kg/m³). In the traditional concrete mixture, the same water/cement and amount of cement is considered as for SCC1. The cement used in this research is CEM I 42.5 R, which is a portland cement with a C_3S, C_2S, C_3A and C_4AF content of respectively 58.2, 12.7, 8.2 and 9.1%.

The amount of superplasticizer, which is a modified polycarboxylether, was determined in order to obtain a suitable flowability without segregation. The flowing time in the V-funnel was also measured (values between 5s and 10s), air content (values between 1% and 3%) and the U-box requiring self levelling. In Table 1, the mixture composition is given together with the compressive strength at 28 days measured on concrete cubes with a side of 150 mm.

Test method

Water permeability - For the determination of the water permeability, Darcy's law for laminar flow through porous materials is used:

$$\frac{dq}{dt}\frac{1}{A}=\frac{K'\rho g}{\eta}\frac{h}{L}$$

with dq/dt the flow velocity of the fluid [m³/s], A the cross section of the test specimen [m²], h the pressure head over the specimen [m], L thickness of the specimen [m], η the dynamic viscosity of the fluid [Ns/m²], ρ the mass density of the fluid [kg/m³] and g the gravity constant m/s². K′ is the intrinsic permeability coefficient in m², which is a material constant independent of the fluid. In the tests described in this article, only water is used which leads to the formula of the water permeability coefficient K [m/s]:

$$K=\frac{K'\rho g}{\eta}$$

When water is used, $\rho = 1000$ kg/m³ and $\eta = 1 \,.\, 10^{-3}$ Pa.s at 20 °C. When the pressure head is not constant in time, the formula for K becomes:

$$K=\frac{L}{t_2-t_1}\ln\left(\frac{h_2}{h_1}\right)$$

with h_1 and h_2 the pressure head at time t_1 and t_2 respectively. When the steady state flow is reached, K could be directly determined with this formula.

At the Magnel Laboratory for Concrete Research a new testing device was developed in order to determine the water permeability of concrete and is based on test methods found in literature for low pressure heads. Detailed information is given in (1). The test specimen with a diameter of 80 mm and a height of 25 mm is sawn from the middle of a concrete cube 150 mm and is glued in a PVC tube with epoxy. The specimens are tested at a concrete age between 55 and 666 days, due to the long duration of the test and the limited amount of testing devices. Until the testing date, they are stored in a climate room at 20 °C ± 2 °C and at least 90% R.H.. Before the start of the test, the test specimens are vacuum saturated following the Belgian standard NBN B05-202. The pressure head is approximately 500 mm. For each concrete mixture, at least 3 specimens are tested.

Gas permeability - The gas permeability is experimentally determined by means of the Cembureau-method according to (2). For each mixture, one prism 400 x 400 x 100 mm³ is made and stored in a climate room at 20 °C ± 2 °C and more than 90% R.H.. At the age of 28 days, three cores of 150 mm diameter were drilled for each concrete mixture and

This is a preview. Click here to purchase the full publication.

from the center of these cores, samples with 50 mm height were taken. Until the beginning of the test, at the age of three months, the samples were stored in a climate room at 20 °C ± 2 °C and more than 90% R.H. In order to avoid a chemical reaction between the gas and the concrete, oxygen is used. The saturation degree of the samples is of major importance. The test is performed at three different levels of inlet pressure, namely 3, 4, and 5 bar. In this article, only test results performed on dry specimens (dried at 105 °C for 1 week) and at an inlet pressure of 3 bar are discussed.

The apparent gas permeability K [m²] can be calculated based on the Hagen-Poiseuille relationship for laminar flow of a compressible fluid through a porous body with small capillaries under steady-state conditions (3):

$$K = \frac{4{,}04 P_2 Q L . 10^{-16}}{A(P_1^2 - P_2^2)}$$

with Q the volume flow rate of the fluid measured during the test with a bubble flow meter [ml/s], L the thickness of the specimen in the direction of the flow [m], A the cross-sectional area of the specimen [m²] and P_1 and P_2 the inlet and outlet pressure of oxygen [bar]. This formula is valid for tests performed at 20°C for which the dynamic viscosity of oxygen is $2{,}02.10^{-5}$ Nsm^{-2}.

Capillary suction - From the mixtures described above, cubes with a side of 150 mm were manufactured. These concrete cubes were stored in a climate room at 20 °C ± 2 °C and more than 90% R.H.. At the age of 28 days, these concrete cubes were stored for a minimum of 2 and a maximum of 3 weeks (the tests for capillary suction were started on monday) at 40 °C ± 5 °C and 40 ± 3% R.H. Then, the cubes were placed on stable supports in water, so that the water level is 5 ± 1 mm above the lower face of the specimen. Before the test and after 3, 6, 24, 72, and 168 hours the mass of the specimen is determined.

The test was performed in an environment at 20 °C ± 3 °C and 60 ± 3% R.H. These tests were carried out on three specimens for each concrete mixture. First, the water will penetrate the concrete at the surface. This surface zone is more porous than the concrete core. Therefore, the mass increase will be strong in the beginning. After a certain time, as the water penetrates the core, the mass increase will proceed more slowly. To model this behavior, two capillary absorption coefficients are determined by linear regression: W based on the measurements during the first 24 hours and S based on the measurements at 72 and 168 hours. In this article only the values of S are discussed.

Carbonation - From the mixtures described above, 100 mm cubes were made. These concrete cubes were stored in a climate room at 20 °C ± 2 °C and more than 90% R.H. At the age of 28 days, an epoxy coating was applied to all faces, except on the face that will be exposed to CO_2. The concrete cubes were stored permanently in a carbonation room at 20 °C, 60% R.H. and 10 vol.% CO_2. At regular times (8, 12, 16, 20, and 24 weeks) the carbonation depth was examined experimentally. At each time, a slice with a thickness of 1 cm was sawn from each specimen. This slice was sprayed with a phenolphtalein solution in order to determine the carbonated zone. This pH indicator changes from colourless to purple as the pH rises from 8.3 to 10.0. The test indicates the depth to which the calciumhydroxide has been depleted. After sawing the slices, the remaining concrete specimen was covered again with the carbon resisting epoxy coating and the carbonation was continued.

This is a preview. Click here to purchase the full publication.

The carbonation of concrete can be considered as a Fickian problem and is governed by the following equation:

$$x = A\sqrt{t}$$

in which x is the carbonation depth, t is the exposure time and A is a constant depending on the diffusion resistance of the material.

After sawing a slice of the concrete cube, the carbonation depth is determined at 10 points and the mean value is calculated. For each composition, two concrete cubes are made in order to obtain a mean carbonation depth. With the carbonation depths at several times, and with the above mentioned equation, a regression value for A can be determined.

Chloride penetration – 150 mm cubes were manufactured and stored in a climate room at 20 °C ± 2 °C and more than 90% R.H. in order to determine the chloride penetration. At an age of 21 days, three cores with a diameter of 100 mm and a height of 50 mm were drilled from each cube. Afterwards the concrete cores, were placed back in the climate room until the age of 28 days. On these cores, a non-steady state migration test was performed following the method of Tang et al.(4). Firstly, the specimens are vacuum saturated with a saturated $Ca(OH)_2$ solution. Afterwards an external electrical potential (for the tests described in this paper between 25V and 40V) is applied across the specimen for 24 hours and forces the chloride ions to migrate into the specimens. Afterwards the specimen is axially split and a silver nitrate solution is sprayed on to the freshly split sections. The chloride penetration depth can then be measured on each section at 7 points from the visible white silver chloride precipitation, after which the chloride migration coefficient can be calculated from these penetration depths with:

$$D = \frac{RT}{zFE}\frac{x - \alpha\sqrt{x}}{t}$$

with: $E = \frac{U-2}{L}$ and $\alpha = 2\sqrt{\frac{RT}{zFE}}\,erf^{-1}\left(1 - \frac{2c_d}{c_o}\right)$

and D the non steady state migration coefficient (m²/s), z the absolute value of ion valence, for chloride z equals 1, F the Faraday constant: 9.648×10^4 J/(V.mol), U the absolute value of the applied voltage (V), R the gas constant: R = 8.314 J/(K.mol), T the average value of the initial and final temperatures in the anolyte solution (K), L the thickness of the specimen (m), x the average value of the penetration depths (m), t the test duration (s) and erf^{-1} the inverse of the error function. c_d and c_0 are respectively the chloride concentration at which the color changes, c_d = 0.07 N for portland cement concrete and the chloride concentration in the catholyte solution, c_o = 2N.

Test results

From the test results, the following could be concluded (with SCC1 as reference):

Effect of cement/powder with the same amount of water (Figure 2) - If the amount of cement and powder is changed, but the used amount of water and powder is maintained constant, a lower W/C and a higher C/P are leading to lower transport properties (SCC2, SCC1, SCC3, SCC4). Due to lower transport properties, the carbonation and chloride penetration will decrease. If a higher W/C is used, more water is present to hydrate the cement, but there is also more water that remains unused in the concrete matrix. A higher

This is a preview. Click here to purchase the full publication.

amount of remaining water, leads to a higher amount of pores in the internal concrete structure, which results in higher transport coefficients.

Effect of type of filler (Figure 3) - Replacing limestone filler P2 by limestone filler S (SCC5) with a finer grading curve, does not change significantly the transport properties and durability behavior.

Traditional concrete – self compacting concrete (Figure 3) - The difference between SCC and TC with the same amount and type of cement and the same W/C concerning transport properties is very small except for the gas permeability and carbonation. The high gas permeability of the traditional concrete can be explained based on the differences in pore structure and the transition of laminar to turbulent flow. This is explained in Reference 5. The lower carbonation of traditional concrete, even if the concrete strength is lower than for self compacting concrete, will be studied in further research.

Effect of the amount of powder (Figure 4) - If the W/C and the C/P are maintained constant, an increase in the amount of powder includes an increase in the amount of water. In these mixtures (SCC6, SCC1, SCC7 and SCC8), a higher amount of water than needed for the hydration of the cement (for portland cement, the W/C needed for complete hydration is approximately 0.42) is used. An increase in the amount of water with constant W/C leads to a higher amount of water that is not needed for the hydration and is resulting in more pores. Moreover, an increase in the amount of powder leads to an increase in the amount of paste for the same amount of concrete. Due to the presence of the pores in the paste, more paste leads to more pores for the same amount of concrete. Therefore, the mixture with the highest amount of powder will also have the highest amount of pores, resulting in the highest water transport. This is corresponding with the test results. The carbonation and chloride penetration are also increasing with an increasing amount of powder.

Variation of the amount of water (Figure 5) - If the amount of water increases, the W/C increases, leading to more pores and an increase of the transport properties and carbonation and chloride penetration (SCC9, SCC1, SCC10, and SCC11).

DISCUSSION

In literature, it is written that the transport properties of concrete are mainly determined by capillary pores (6,7). Therefore, the model of Powers is used to determine the capillary porosity to verify the possible link between the capillary pores and the transport properties.

$$
\begin{aligned}
V_{cap} &= \text{capillary pores} + \text{free water} = \text{capillary pores} + \text{water} - \text{gel water} - \text{bounded water} \\
&= 0.185\frac{Ch}{\rho_c} + \frac{W}{\rho_w} - \frac{0.28}{0.72}\left(\frac{Ch}{\rho_c}(1-0.185) + \frac{0.23Ch}{\rho_w}\right) - \frac{0.23Ch}{\rho_w} \\
&= -0.1319\frac{Ch}{\rho_c} + \frac{1}{\rho_w}(W - 0.3194Ch)
\end{aligned}
$$

with V_{cap} the volume of capillary pores [m^3], C the amount of cement [kg], W the amount of water [kg], h the degree of hydration [-], ρ_c and ρ_w the mass density of cement and water [kg/m^3], respectively.

This is a preview. Click here to purchase the full publication.

$$V_{concrete} = V_{water} + V_{cement} + V_{coarse\ aggregate} + V_{sand} + V_{filler}$$

$$= \frac{W}{\rho_w} + \frac{C}{\rho_c} + \frac{A+S+F}{\rho_{agg}}$$

$$capillary\ porosity = \frac{V_{cap}}{V_{concrete}}$$

with $V_{concrete}$ the volume [m³], A the amount of coarse aggregate [kg], S the amount of sand [kg], F the amount of filler [kg] and ρ_{agg} the mass density of aggregate [kg/m³].

The parameters W, C, A, S and F are known from the mixture proportions. For the mass densities, a value of 1000 kg/m³ is used for water, 2625 kg/m³ for the aggregates, sand and filler and 3115 kg/m³ for portland cement.

The test specimens are stored until the testing age in a climate room at 20 °C ± 2 °C and at least 90% R.H. for at least 28 days. This means that the degree of hydration will not strongly differ from the ultimate degree of hydration that could be determined, by the Mill formula (8):

$$h_{ultim} = \frac{1.031\ {}^{W}\!/_{C}}{0.194 + {}^{W}\!/_{C}}$$

The calculated values for the capillary porosity are given in Table 1. The correlation between water permeability (Figure 6), gas permeability (Figure 7) and capillary absorption (Figure 8) and capillary porosity is good (R^2 is respectively 0.92, 0.81 and 0.91). For carbonation (Figure 9) and chloride penetration (Figure 10), the correlation is not as good as the correlation for the transport properties (R^2 is 0.79 and 0.71 respectively). This leads to the conclusion that not only transport properties determine the durability behavior. This could be explained by the chemical reactions taking place during carbonation and chloride penetration.

CONCLUSIONS

In this article, the water permeability, gas permeability, capillary absorption, carbonation and chloride penetration of 11 self compacting concrete mixtures and of 1 traditional concrete mixture is discussed. The selection of the mixtures is made in order to consider some important parameters like type of filler (limestone filler with two different grading curves), the cement/powder and water/cement, the amount of water and the amount of powder (cement and filler). The results of these tests are discussed and compared with the capillary porosity calculated by the method of Powers et al. The following conclusions were made:

- Using a filler with a finer grading has no influence on the transport properties and durability behavior.
- If the W/C and the C/P are maintained constant, an increase in the amount of powder leads to an increase in transport properties, carbonation and chloride penetration.

This is a preview. Click here to purchase the full publication.

- The transport of water and gas is strongly influenced by the water/cement and cement/powder. Decreasing one of these ratios or both is leading to a slower transport.
- The difference concerning transport properties between SCC and TC with the same amount and type of cement and the same W/C is small except for the gas permeability.
- The transport properties could be modelled based on the capillary porosity. For carbonation and chloride penetration, other influencing factors are also important.

REFERENCES

1. Audenaert, K., and De Schutter, G., "Water permeability of self compacting concrete"; International Symposium on Advances in Concrete through Science and Engineering, March 2004, Evanston, USA. CD-Rom, Rilem, Paper 39 in session 'Durability', pp. 9.
2. Rilem TC 116-PCD, "Permeability of Concrete as a Criterion of its Durability, Recommendations"; *Materials and Structures*,Vol. 32, April 1999, pp. 174-179.
3. Kollek J.J., "The determination of the permeability of concrete to oxygen by the Cembureau method — a recommendation"; *Materials and Structures*, Vol. 22, 1989, pp 225 – 230.
4. Tang, L., and Nilsson, L., "Rapid determination of chloride diffusivity of concrete by applying an electric field"; *ACI Materials Journal*, Vol. 89, Jan.-Feb. 1992, pp. 49-53.
5. Audenaert, K.; Boel, V.; and De Schutter, G., "Relation between gas permeability and carbonation in self compacting concrete"; International Conference on Concrete and Reinforced Concrete – Development Trends, September 2005, Moscow, Russia, pp. 333-339.
6. CEB-FIP MODEL CODE 1990, Design Code, Thomas Telford, London, England, 1993.
7. Marsh, B.; Day, R.; and Bonner, D., "Pore structure characteristics affecting the permeability of cement paste containing fly ash"; *Cement and Concrete Research*, 1985, Vol. 15, pp. 1027-1038.
8. Van Breugel, K., "Simulation of hydration and formation of structure in cement based materials", PhD thesis, TUDelft, 1991, pp. 54-57.

This is a preview. Click here to purchase the full publication.

Table 1-- Mixture Composition

	CEM I 42.5 R [kg/m³]	limestone filler S [kg/m³]	limestone filler P2 [kg/m³]	water [kg/m³]	sand 0/5 [kg/m³]	gravel 4/14 [kg/m³]	superplasticizer [l/m³]	W/C [-]	C/P [-]	compr. strength [MPa]	Capillary porosity [%]
SCC1	360		240	165	853	698	2.3	0.46	0.60	57.3	7.33
SCC2	300		300	165	853	698	2.2	0.55	0.50	46.5	8.51
SCC3	400		200	165	853	698	2.9	0.41	0.67	64.2	6.61
SCC4	450		150	165	853	698	3.0	0.37	0.75	68.7	5.76
SCC5	360	240		165	853	698	2.8	0.46	0.60	56.9	7.33
SCC6	300		200	137	923	755	3.4	0.46	0.60	60.1	6.16
SCC7	400		300	192	782	640	2.6	0.48	0.57	55.9	8.78
SCC8	450		350	220	712	583	2.7	0.49	0.56	50.9	10.07
SCC9	360		240	144	865	707	3.6	0.40	0.60	68.7	5.63
SCC10	360		240	198	835	683	1.8	0.55	0.60	46.6	10.03
SCC11	360		240	216	825	675	2.0	0.60	0.60	40.3	11.51
TC1	360			165	640	1225		0.46	1.00	48.6	7.11

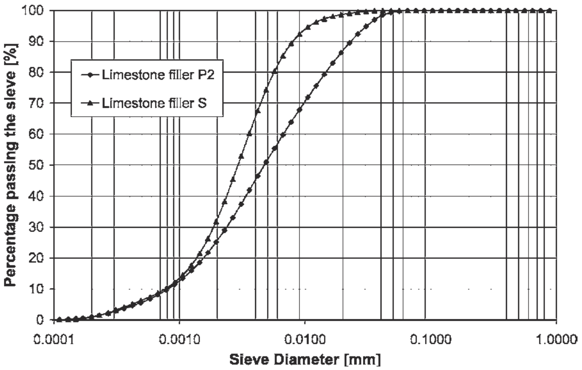

Fig. 1 -- Particle size distribution of limestone fillers

This is a preview. Click here to purchase the full publication.

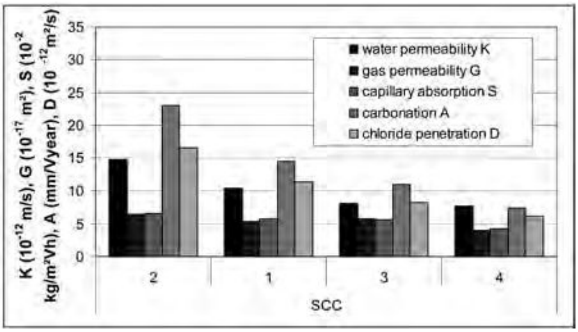

Fig. 2 -- Effect of cement/powder on the properties of SCC

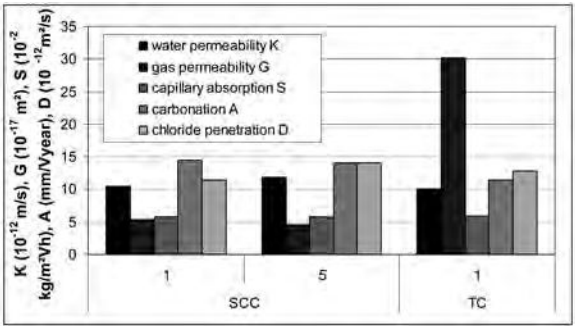

Fig. 3 -- Effect of type of filler on the properties of SCC – comparison SCC-TC

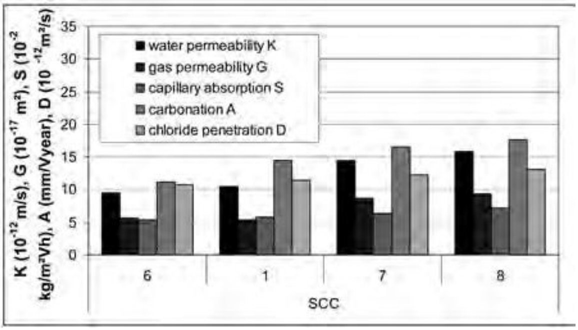

Fig. 4 -- Effect of the amount of powder on the properties of SCC

This is a preview. Click here to purchase the full publication.