MODELLING OF GAS PERMEABILITY IN SELF-COMPACTING CONCRETE

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Abstract

The past years, the applicability of self-compacting concrete (SCC) has already been proven. As this kind of concrete can be placed without any compaction some health risks as well as environmental problems can be avoided and durability problems related with badly vibrated concrete would be reduced. Two of the essential properties of SCC, a high flowability and a high segregation resistance, are obtained by a large amount of fine particles and the use of superplasticizers.

Earlier research on the pore structure pointed out an important difference between SCC and traditional concrete (TC). Since the transport properties of concrete are strongly depending on its pore structure, the question rises to what extent the gas permeability of SCC gets affected by the change in mixture design. The first part of this paper reflects a more extended investigation on one SCC and one TC mixture. In the following part, the gas permeability of 16 SCC mixtures and 4 TC mixtures is being evaluated with special attention to the difference between SCC and TC, and the influence of the following parameters: type of cement, fineness of filler, type of filler, cement/powder ratio, powder content, water/cement ratio and type of aggregate. It was concluded that the gas permeability of SCC is about 5 times lower than the gas permeability of TC. The parameter with the largest impact on the gas permeability seems to be the water content and secondly, the powder content. Finally a model based on the capillary porosity is presented to predict the gas permeability of both concrete types.

1. Introduction

In the most recent international conferences on SCC, the issues which have been studied the most, seem to be the mixture design, workability, rheology and mechanical properties [1, 2, 3]. By means of case studies where SCC has been used in the field, also the applicability of SCC has been demonstrated. However still a lot of questions need to be solved when it comes to the actual performance of the material in general, and the durability in particular. The change in pore structure due to a different mixture design has an influence on the transport properties and the durability of the material. To what extent this difference matters, has to be investigated thoroughly. The transport mechanisms in SCC, as well as its relation with durability are studied in the Magnel Laboratory for Concrete Research [4, 5].

2. Mixture design

In this paper, the gas permeability of 16 mixtures of SCC and 4 mixtures of TC is determined experimentally (Table 1).

Table 1: Mixture design

	CEM I 42.5 R [kg/m³]	CEM I 52.5 [kg/m³]	CEM III/A 42.5 LA [kg/m³]	CEM I 52.5 HSR [kg/m³]	limestone filler P2 [kg/m³]	water [kg/m³]	sand 0/5 [kg/m³]	river gravel 4/14 [kg/m³]	calcareous rubble 2/14 [kg/m³]	glenium 51 [l/m³]	W/C [-]	C/P [-]	compressive strength [MPa]
SCC1	360				240	165	853	698		2.3	0.46	0.60	57.3
SCC2		360			240	165	853	698		2.5	0.46	0.60	68.0
SCC3			360		240	165	853	698		2.3	0.46	0.60	66.1
SCC4				360	240	165	853	698		2.2	0.46	0.60	70.1
SCC5	360				240 (*)	165	853	698		2.8	0.46	0.60	56.9
SCC6	360				240 (**)	165	853	698		2.8	0.46	0.60	66.2
SCC7	300				300	165	853	698		2.2	0.55	0.50	46.5
SCC8	400				200	165	853	698		2.9	0.41	0.67	64.2
SCC9	450				150	165	853	698		3.0	0.37	0.75	68.7
SCC10	300				200	137	923	755		3.4	0.46	0.60	60.1
SCC11	400				300	192	782	640		2.6	0.48	0.57	55.9
SCC12	450				350	220	712	583		2.7	0.49	0.56	50.9
SCC13	360				240	144	865	707		3.6	0.40	0.60	68.7
SCC14	360				240	198	835	683		1.8	0.55	0.60	46.6
SCC15	360				240	216	825	675		2.0	0.60	0.60	40.3
SCC16	360				240	165	816		734	1.8	0.46	0.60	74.7
TC1	360					165	640	1225			0.46	1.00	48.6
TC2			360			165	640	1225			0.46	1.00	49.7
TC3				360		165	640	1225			0.46	1.00	50.2
TC4	400					165	626	1200			0.41	1.00	53.7

(*) limestone filler S instead of limestone filler P2; (**) fly ash instead of limestone filler P2

In Table 1 the mixture proportions are given together with the compressive strength at 28 days measured on cubes 150 mm. The amount of superplasticizer (polycarboxylic ether) was determined in order to obtain a suitable flowability without segregation. The first four SCC mixtures have exactly the same proportions for cement, limestone filler (BETOCARB P2), sand (0/5), gravel (4/14) and water, but the type of cement is varied: Portland cement (CEM I 42.5 R, CEM I 52.5 and CEM I 52.5 HSR) and blast furnace slag cement (CEM III/A 42.5 LA). The amount of powder P (cement and filler) is 600 kg/m³. The influence of the type of filler is studied by mixtures SCC5 and SCC6 where repectively a limestone filler with a finer grading (superfine S) and fly ash are used. In the next three mixtures (SCC7, SCC8 and SCC9), the amount of water, gravel, sand and powder is kept the same, but the C/P ratio is varied. In the next three mixtures SCC10, SCC11 and SCC12 the total amount of powder is varied (500, 700 and 800 kg/m³). The amount of water is varied in mixtures SCC13, SCC14 and SCC15 (144, 198 and 216 kg/m³). The influence of the type of coarse aggregate is studied by replacing river gravel by calcareous rubble (SCC16). Based on an equal W/C ratio, the four TC mixtures correspond with respectively mixtures SCC1, SCC3, SCC4 and SCC8.

3. Gas permeability

The gas permeability is a measure of the flow of gas through a porous material caused by a pressure head and it depends on the open porosity prevailing in this material. For this reason it is important to take into account the moisture content of the concrete since the acting gas pressure in the pores is not sufficient to move the water and the pores will remain blocked not being able to let the gas pass. Besides the open porosity also other parameters like pore connectivity, tortuosity and isotropy of the pore network have an influence.

3.1. Test method

For each mixture, one prism 400 x 400 x 100 mm³ is made and stored in a climate room at 20 ± 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 from the centre of these cores, samples with 50 mm height were taken. Until the beginning of the test, at the age of three months, the samples are stored in a climate room at 20 ± 2°C and more than 90 % R.H.. The testing procedure is carried out following the Cembureau-method according to "Rilem TC 116-PCD: Recommendations" [6]. In order to avoid a change of the pore structure during the test, the gas used should not react chemically with the concrete and for this reason oxygen is used [7].

As mentioned before, the saturation degree of the samples is an important issue with regard to the determination of the gas permeability and so the test is performed at three different saturation degrees S of which one is the completely dry state of the sample. The drying of the samples is reached according to a fixed procedure, starting from vacuum saturation of the samples after drying them at 80°C. At this moment the concrete is completely filled with water (S = 100 %) and any flow of gas through the samples is blocked. Further drying of the samples at 80°C makes it possible to attain two different saturation degrees S_1 and S_2. Finally the samples are dried at 105°C to reach a saturation degree of 0 % (S_3). The test is performed at three different levels of inlet pressure for oxygen, namely 3, 4 and 5 bar.

The apparent gas permeability k_a can be calculated by means of relationship (1) based on the Hagen-Poiseuille relationship for laminar flow of a compressible fluid through a porous body with small capillaries under steady-state conditions [8].

$$k_a = \frac{4.04Q}{A}\frac{LP_2}{\left(P_1^2 - P_2^2\right)}.10^{-16} \qquad [m^2] \qquad (1)$$

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], 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 viscosity of oxygen is $2.02.10^{-5}$ Nsm^{-2}.

3.2. Extended study

The extended study has been carried out on the reference mixtures TC1 and SCC1. For those two mixtures the gas permeability test has been performed at five different saturation degrees and at ten different inlet pressures P_1 (1.5 bar till 6 bar). In Figure 1 the apparent gas permeability k_a is plotted against the inlet pressure P_1. Generally speaking k_a is inversely proportional to P_1. Although, for high saturation degrees and at high inlet pressures it is not the case anymore. At lower pressures the contribution of the slip flow increases, which causes an increased apparent gas permeability.

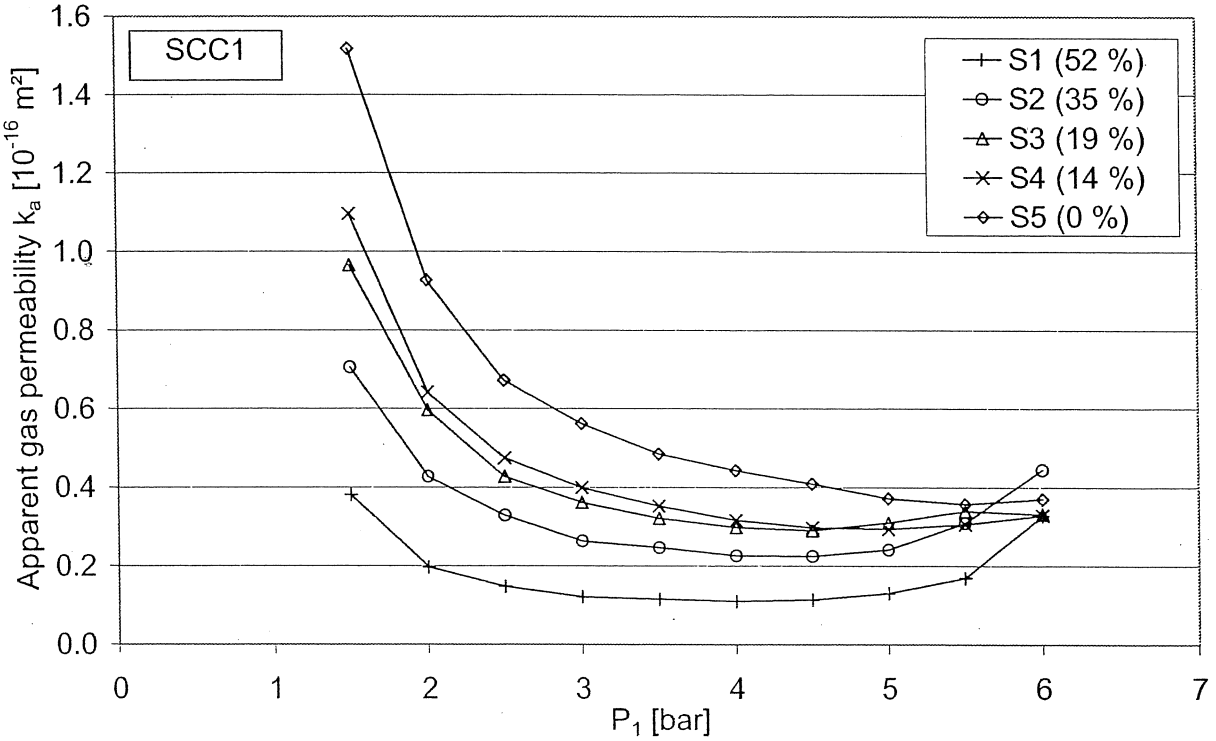

Figure 1: Apparent gas permeability plotted versus the inlet pressure

When the flow Q is plotted versus the pressure gradient (P_1^2-P_2^2), at inlet pressures lower than 5.5 bar, a linear relationship can be noticed. This indicates a laminar flow, one of the conditions of formula (1). Also an indicative calculation of the number of Reynolds confirms that a laminar flow can be assumed. The influence of the saturation degree at a given inlet pressure can be investigated by means of the introduction of the relative gas permeability $k_r(S,P)$ (2) [9]. For this purpose the assumption is made that the moisture in the sample is homogeneously distributed. The drying procedure mentioned above was carried out in such way that this assumption was met.

$$k_r(S,P) = \frac{k_{(S=x)}}{k_{(S=0)}} \qquad [-] \qquad (2)$$

With $k_{(S=x)}$ and $k_{(S=0)}$ respectively the apparent gas permeability at a certain inlet pressure at a certain saturation degree (S=x) and at the completely dry state (S=0) of the sample. Van Genuchten, mainly active in the field of soil physics, proposed the following equation to relate the relative gas permeability with the saturation degree [9].

$$k_r(S) = \sqrt{(1-S)}.(1-S^b)^{2/b} \qquad [-] \qquad (3)$$

With b a constant parameter and S the saturation degree. In Figure 2, for several inlet pressures, the relative gas permeability of SCC1 is plotted versus the saturation degree. One can see that at low pressures the curves approximately coincide with each other. For TC1 the same was concluded. At higher inlet pressures, from approximately 5 bar on, the curves do not longer overlap.

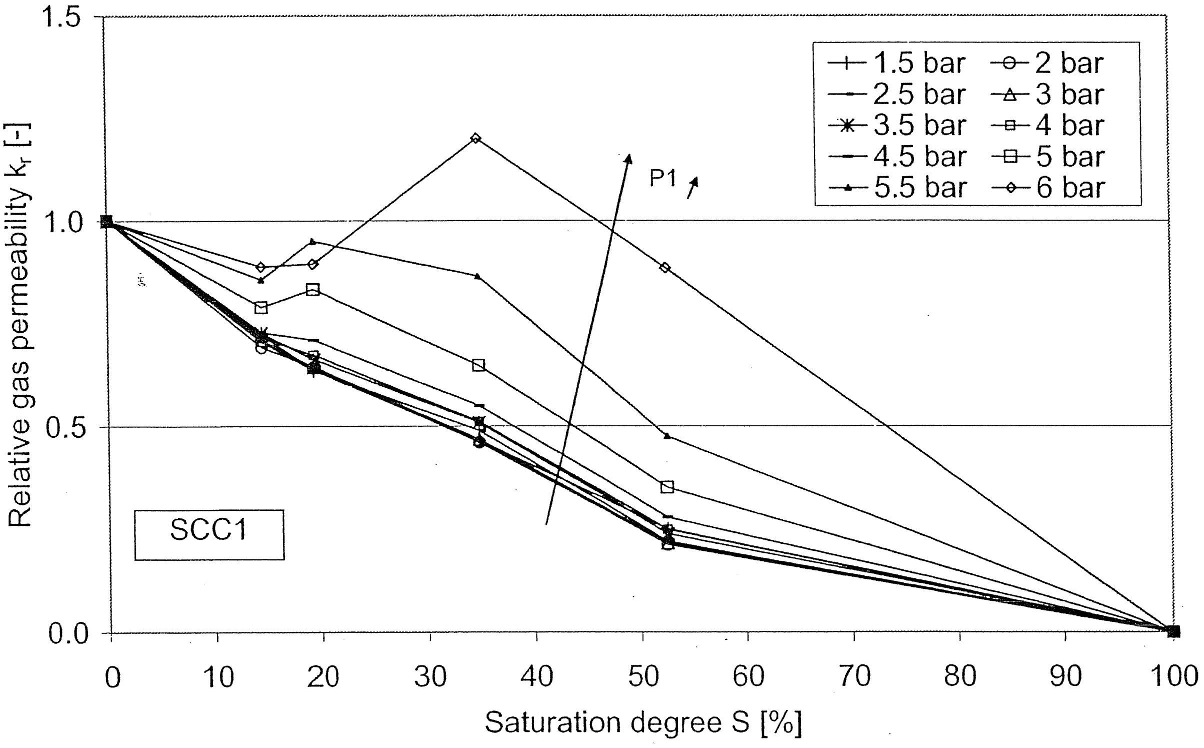

Figure 2: The relative gas permeability plotted versus the saturation degree

By means of Figure 3 it has been investigated if the proposed equation of Van Genuchten can be used to write the relative gas permeability as a function of the saturation degree. As can be seen from Figure 3, this works quite well. This has been found not only for

SCC1 and TC1, but for all mixtures described in Table 1. The values of b typically are in the order of 1 and tend to have slighly higher values for self-compacting concrete than for traditional concrete. From these results follows that it is possible to determine the gas permeability at a certain saturation degree once the gas permeability at the dry state is known, according equation (4).

$$k_{(s=x)} = k_{(s=0)} \cdot \sqrt{(1-s)}.(1-s^{b})^{2/b} \qquad [m^2] \qquad (4)$$

For this reason, in section 3.4 the potential to theoretically determine the gas permeability $k_{(s=0)}$ as a function of the mixture design, the hydration degree and the inlet pressure is investigated.

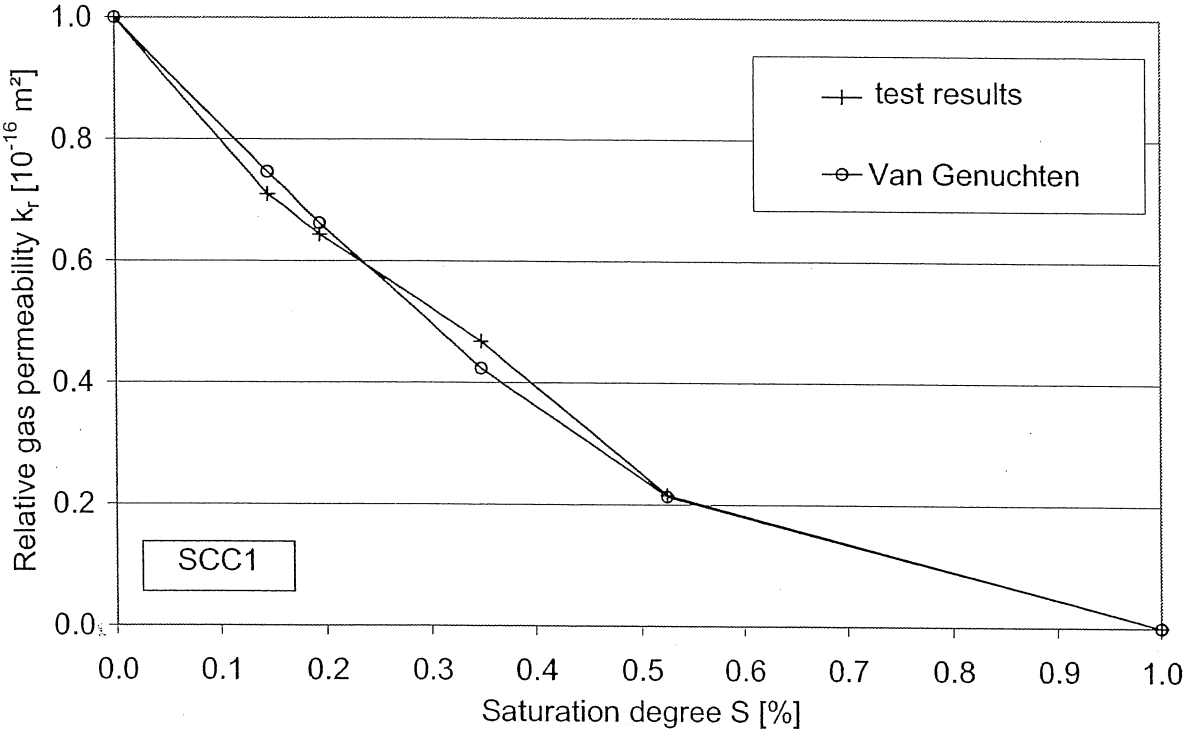

Figure 3: Testing of the model of Van Genuchten

From the extended study it can be concluded that the parameter study is preferably carried out on completely dry samples. Preference should be given for an inlet pressure between 2 and 5 bar. The expression of Van Genuchten seems to be valid for self-compacting concrete as well as for traditional concrete, but the expression can only be used for inlet pressures lower than 4 to 5 bar. For a certain mixture, the expression remains more or less the same at different inlet pressures lower than 4 to 5 bar.

3.3. Parameter study

For this purpose, only the results of the tests with an inlet pressure of 3 bar and at saturation degree S_3 (0 %) will be discussed. A complete representation of the results on the gas permeability is given in [10]. The coefficients of apparent gas permeability achieved by performing the test with an inlet pressure of 3 bar and on completely dry specimens, are plotted in Figure 4. From this figure it follows that the apparent gas permeability of all SCC mixtures is only about 20 % of the gas permeability of the corresponding TC mixtures. The important difference between SCC and TC is due to a different pore structure. By means of mercury intrusion porosimetry tests it has been found that a traditional cement paste has a higher critical pore size compared to a self-compacting cement paste [11]. The cement pastes in this study were designed according the mixture proportions of the concrete mixtures presented in Table 1.

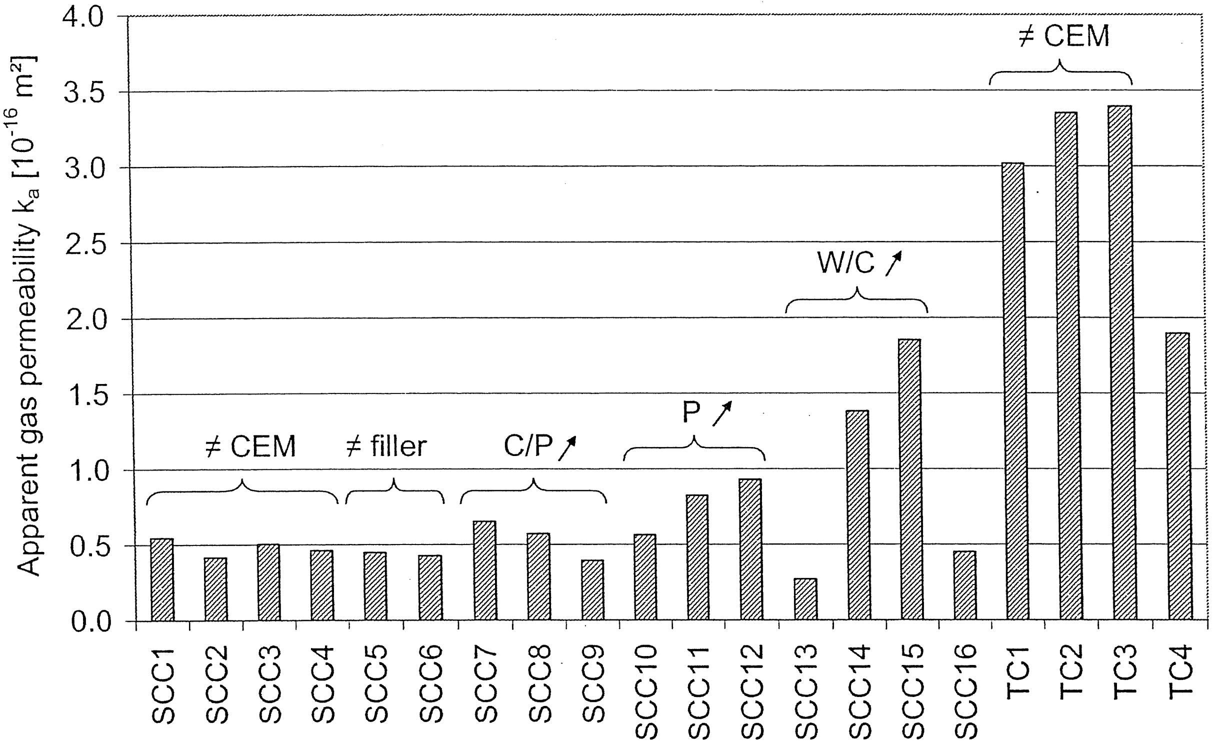

Figure 4: The apparent gas permeability at an inlet pressure of 3 bar

When blast furnace slag CEM III A 42.5 LA or Portland cement CEM I 52.5 HSR are used instead of Portland cement CEM I 42.5 R, a higher apparent gas permeability is noticed for traditional concrete. This effect is not noticed for the SCC mixtures, merely the opposite is observed. The influence of the type of cement (blast furnace slag cement versus portland cement) seems to be somewhat lower than the influence of the fineness of the cement (42.5 versus 52.5). When the amount of cement is increased from 360 kg/m³ to 400 kg/m³, there is a significant decrease of the apparent gas permeability for traditional concrete, induced by a lower porosity because of the lower W/C ratio [11]. For the corresponding SCC mixtures SCC1 and SCC8, there is only a small difference in apparent gas permeability.

Using a finer filler of the same type (SCC5) gives a more dense microstructure and for this a lower gas permeability. When replacing limestone filler by fly ash (SCC6), the puzzolanic properties of fly ash cause a more dense microstructure in favour of a lower gas permeability.

For mixtures SCC7, SCC1, SCC8 and SCC9 the C/P ratio is varied from 0.50 to 0.75 with a constant amount of powder and water. This means that an increasing C/P ratio equals decreasing the W/C ratio, which densifies the microstructure by diminishing the capillary pores [11]. As such, the gas permeability decreases with an increasing C/P ratio.

When the powder content is increased from 500 kg/m³ (SCC10), over 600 kg/m³ (SCC1) and 700 kg/m³ (SCC11) to 800 kg/m³ (SCC12), the gas permeability increases. The C/P, W/C and W/P do not change that much, but the total amount of paste per m³ increases, making the concrete more porous.

Mixtures SCC13, SCC1, SCC14 and SCC15 have an increasing W/C ratio, from 0.40 to 0.60. The amount of cement is kept the same, but the amount of water is varied. The higher the amount of water, the bigger the surplus of water not used by the hydration process, causing a higher capillary porosity [11]. According to the experiments, increasing the W/C ratio indeed gives an increase in gas permeability.

Mixtures SCC7 and SCC14, have the same W/C ratio (0.55), achieved by changing the cement content as well as the amount of water. The apparent gas permeability of SCC14, having the highest water content of both mixtures, has a much higher apparent gas permeability.

Using calcareous rubble 4/14 (SCC16) instead of round river gravel 4/14 (SCC1) gives a lower gas permeability. Possibly the porosity of the matrix around the calcareous rubble is finer due to the difference in surface texture compared with gravel.

3.4. Modelling of the gas permeability

A strong link has been found between the capillary porosity and the water permeability for the mixtures mentioned in Table 1 [4]. In this paper it is verified whether there is also a possible link between the calculated capillary porosity and the gas permeability. The calculation of the capillary porosity is based on Powers' model. Free water is the initial amount of water (water) minus the gelwater and the bounded water.

$$\begin{aligned}
V_{cap} &= \text{capillary pores} + \text{free water} \\
&= \text{capillary pores} + \text{water} - \text{gelwater} - \text{bounded water} \\
&= 0.185\frac{Ch}{\rho_c} + \frac{W}{\rho_w} - \frac{0.28}{0.72}\left(\frac{Ch}{\rho_c}(1-0.185) + \frac{0.23\,Ch}{\rho_w}\right) - \frac{0.23\,Ch}{\rho_w} \\
&= -0.1319\frac{Ch}{\rho_c} + \frac{1}{\rho_w}(W - 0.3194\,Ch)
\end{aligned} \tag{5}$$

with V_{cap} the volume of capillary pores [m³], C the amount of cement [kg], W the initial amount of water [kg], h the degree of hydration [-], ρ_c and ρ_w the mass density of respectively cement and water [kg/m³].

$$\begin{aligned}
V_{concrete} &= V_{water} + V_{cement} + V_{coarse\ aggregate} + V_{sand} + V_{filler} \\
&= \frac{W}{\rho_w} + \frac{C}{\rho_c} + \frac{A+S+F}{\rho_{agg}}
\end{aligned} \tag{6}$$

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 capillary porosity is calculated as V_{cap} divided by $V_{concrete}$. From the mixture composition, the parameters W, C, A, S and F are known. For the mass densities, a value of 1000 kg/m³ is used for water, 2650 kg/m³ for the aggregates, sand and filler, 3100 kg/m³ for Portland cement and 2950 kg/m³ for the blast furnace slag cement. The density of the fillers was measured and turned out to be 2650 kg/m³. The densities of river sand, river gravel and calcareous rubble equal respectively 2625 kg/m³, 2625 kg/m³ and 2689 kg/m³. The test specimens are stored until the testing age (90 days) in a climate room at 20°C ± 2 °C and at least 90% R.H., and are taken from the centre of a prism. This means that the degree of hydration will not strongly differ from the ultimate degree of hydration that could be determined, in case of Portland cement, by the formula of Mill [12]:

$$h_{ultim} = \frac{1.031\ {}^{W}\!/_{C}}{0.194 + {}^{W}\!/_{C}} \qquad (7)$$

For cement types with a higher fineness and for blastfurnace slag cement the ultimate degree of hydration is increased. For the mixture with fly ash as filler material, the W/C ratio in formula (7) is replaced by the effective W/C ratio with an efficiency factor of 0.3.

Based on the capillary porosity, formula (8) has been proposed in order to estimate the apparent gas permeability $k_{a(s=0)}$.

$$k_{a(s=0)} = c.a.\varepsilon_c^{2.4}.k_{a,ref} \qquad [m^2] \qquad (8)$$

With $k_{a,ref}$ a reference value equal to 10^{-16} m², ε_c the capillary porosity [-], the factor a taking into account the inlet pressure and the factor c taking into account the difference in microstructure between SCC and TC [-]. The differnce in microstructure can be seen as a function of the critical pore size. In Figure 5, at an inlet pressure of 3 bar, the estimated apparent gas permeability is plotted versus the calculated apparent gas permeability. A rather good correlation can be found.

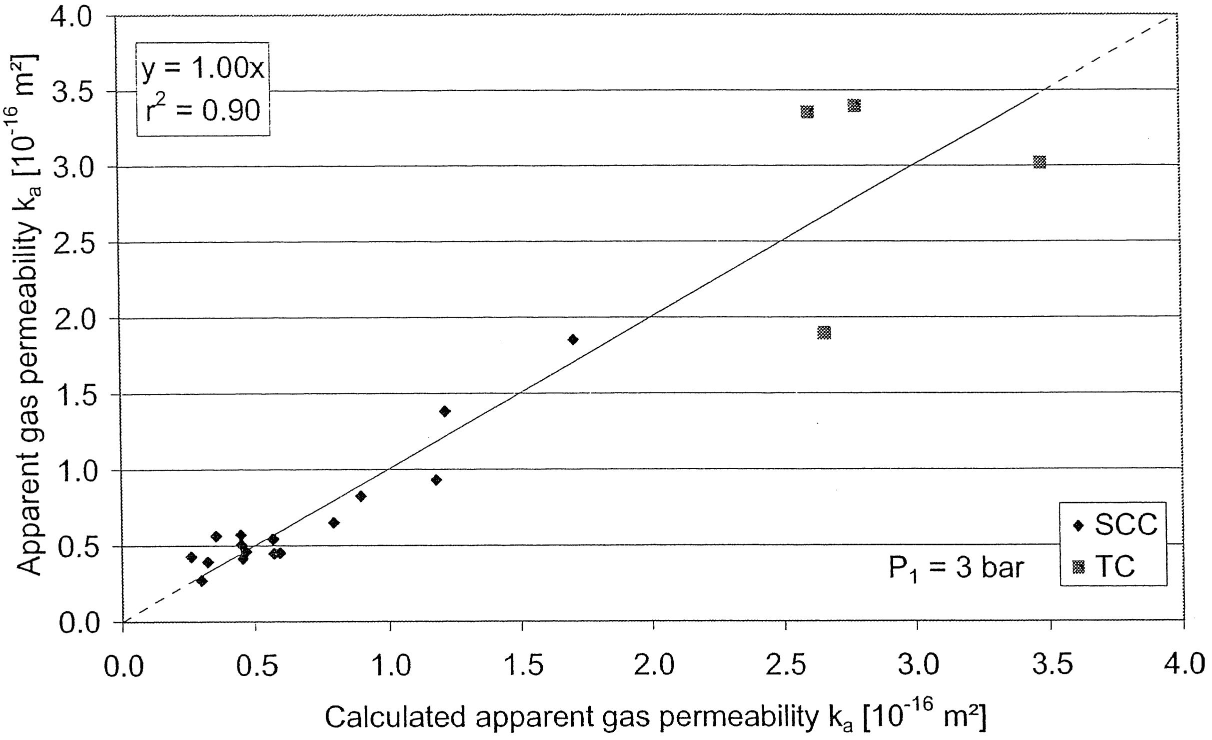

Figure 5: The apparent gas permeability plotted versus the calculated apparent gas permeability

4. Conclusion

Regarding the transport properties, the gas permeability is one of the parameters giving an indication of the resistance of concrete against several kinds of deterioration. The parameter with the largest impact on the gas permeability seems to be the water content and secondly, the powder content. Based on the capillary porosity and the critical pore size it is possible to estimate the apparent gas permeability of both SCC and TC. The influence of the saturation degree on the gas permeability can be taken into account by applying the proposed model of Van Genuchten.

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