TRANSPORT PROPERTIES IN SELF-COMPACTING CONCRETE
AND RELATION WITH DURABILITY:
OVERVIEW OF A BELGIAN RESEARCH PROJECT

G. De Schutter¹, K. Audenaert¹, V. Boel¹, L. Vandewalle², D. Dupont²,
G. Heirman², J. Vantomme³, J. D’hemricourt³

¹Magnel Laboratory for Concrete Research, Ghent University, Belgium
²Catholic University of Leuven, Belgium
³Royal Military Academy Brussels, Belgium

ABSTRACT: The degradation mechanisms of a cementitious material are greatly influenced by the permeability of the material for potentially aggressive substances. As the pore structure might be different for SCC in comparison with traditional concrete, some changes in durability behaviour might be noticed. At this moment however, it is unclear how significant these differences will be with regard to the concrete practice. A fundamental bottleneck in this discussion is the lack of fundamental insight in the transport behaviour of potentially aggressive media in SCC. This aspect, as well as the relation with the durability of SCC is studied in the Belgian research project ‘Transport properties of potentially aggressive substances in self-compacting concrete and relation with durability’, sponsored by the Belgian Fund for Scientific Research Flanders (F.W.O.-VL). The research project is a cooperation between the Magnel Laboratory for Concrete Research of Ghent University, the Catholic University of Leuven, and the Royal Military Academy of Brussels. The ongoing research project has the following main objectives: 1) theoretical and experimental study of the transport behaviour of potentially aggressive media in SCC; 2) experimental study of the durability of SCC, and theoretical correlation with the fundamental transport mechanisms. Both objectives should lead to a better and more fundamental knowledge of the durability behaviour of the new cementitious material. An overview will be given of the whole research project. Furthermore, the first results will be presented, dealing with water permeability, water absorption, gas permeability, carbonation resistance, frost and frost-thaw action, ...

KEYWORDS: self-compacting concrete, durability, transport mechanisms, permeability

INTRODUCTION AND AIM

Self-compacting concrete (SCC) was developed in Japan in the 1980's. The aim was to develop concrete that could be placed without vibration. In this way, some health risks as well as environmental problems could be avoided ("white finger syndrome", noise, vibrations, …). Also durability problems related with badly vibrated concrete structures could be reduced. Ironically, the actual application of SCC might be somewhat riskfull due to a lack of knowledge concerning the actual durability of the new cementitious material! Besides the workability and the self-compactability, not much fundamental data has been published yet concerning e.g. hydration and durability. This is illustrated by the proceedings of some important international conferences dealing with SCC [1-3]: no fundamental durability results were presented. This lack of fundamental knowledge is illustrated once more by the lack of accurate specifications for the application of SCC. The existing recommendations mainly deal with workability, and hardly treat the behaviour during hardening nor the durability [4-6].
A lot of knowledge has been gathered concerning the composition and the workability of SCC, but no general and fundamental understanding of hydration and durability is acquired, although this is of extreme importance for a good and durable practice. As the conception of SCC is totally different from traditional concrete, traditional models cannot be extrapolated as such without any verification. This is e.g. illustrated by a preliminary experimental investigation of hydration, carried out at the Magnel Laboratory for Concrete Research. The hydration models valid for traditional concrete have to be altered when applied to SCC. Further research is going on concerning the fundamental reasons for the noticed difference.

As the pore structure might be different for SCC in comparison with traditional concrete, some changes in durability behaviour might be noticed as well. At this moment however, it is unclear how significant these differences will be with regard to concrete practice. A fundamental bottle neck in this discussion is the lack of fundamental insight in the transport behaviour of potentially aggressive media in SCC. This aspect, as well as the relation with the durability of SCC are studied in the ongoing Belgian research project “Transport properties of potentially aggressive media in self-compacting concrete and relation with durability”, funded by the National Fund for Scientific Research - Flanders. The research project is a co-operation between Ghent University (co-ordinator), Catholic University of Leuven, and Royal Military Academy Brussels.

**OBJECTIVES**
The ongoing Belgian research project has the following main objectives:
- Theoretical and experimental study of the transport behaviour of potentially aggressive media in SCC
- Experimental study of the durability of SCC, and theoretical correlation with the fundamental transport mechanisms

Both objectives should lead to a better and more fundamental knowledge of the durability behaviour of the new cementitious material. This evaluation is important as the conception and composition of SCC differ fundamentally from traditional concrete.

**Figure 1**: Interaction between Pore Structure, Transport Mechanisms and Degradation Processes
DESIGN AND METHODOLOGY

The degradation mechanisms of a cementitious material are greatly influenced by the permeability of the material for potentially aggressive media. The penetration itself is significantly dependent on the pore structure of the material. Furthermore, the ongoing degradation process might have an influence on the pore structure of the material. The interaction between ‘pore structure’, ‘transport mechanism’ and ‘degradation’ is schematically shown in figure 1. This interaction is the driving idea behind the objectives and methodology followed within the project.

The penetration of liquids and gasses in SCC is studied firstly by means of basic tests. For liquids, standard permeability tests available at the participating research institutes are used, including permeability tests, capillary absorption test, and immersion tests. For the study of the penetration of gasses, a new gas permeability-measuring instrument according to the RILEM-Cembureau method is used.

The basic tests should lead to the determination of the fundamental parameters governing the penetration behaviour of liquids and gasses in SCC. The correlation with pore structure will be investigated, and it will be verified whether traditional pore models can be applied to the new cementitious material.

The fundamental knowledge, obtained by means of the basic tests, will be applied to the study of frequently occurring degradation mechanisms in which transport of aggressive media is of importance. Carbonation and chloride penetration will be investigated firstly, by means of tests using special climate chambers, by immersion in chloride containing solutions, and by means of a test set-up for accelerated degradation in which the test specimens are cyclically dried and wetted with chloride containing solutions. Chloride diffusivity will be tested by means of an accelerated method based on electrochemical principles. Secondly, degradation mechanisms more attacking the concrete itself will be investigated: physical degradation (frost, and frost in combination with de-icing salts) and chemical degradation (alkali silica reaction, acid attack, sulphate attack). Several tests will be carried out by means of existing test set-ups, e.g. the already mentioned test set-up for accelerated degradation. The degraded specimens will be evaluated as well by means of non-destructive techniques: dynamic and ultrasonic measurements. This should lead to an accurate follow up of the damage evolution.

During the research some important parameters, which will presumably significantly alter the durability behaviour of SCC, will be varied: water-cement ratio, cement type, filler type… In total, a maximum of eight compositions will be investigated. It is explicitly not the purpose to realise an experiment-based optimisation of actual SCC compositions used in Belgium. The influence of the use of different types of plasticizers and of viscosity agents is not included in the research. By investigating only the most important parameters with regard to durability a fundamental insight in the relation between transport mechanisms and durability of SCC is looked for. An optimisation of a practical SCC composition can be carried out afterwards, based on the fundamental insights gained within the proposed project.

A more detailed outline of the project organisation is given in the sequel of this paper.
PART 1: Transport behaviour of potentially aggressive media in SCC

TASK 1-1: Study of the liquid transport in SCC
In this task, the fundamental parameters describing the liquid transport (capillarity, diffusivity, ...) will be investigated by means of basic experiments. The SCC will be tested in traditional test set-ups, and the permeability, capillarity, ... will be determined. From the obtained results some fundamental parameters will be determined based on fundamental physical laws (e.g. Darcy's laws). It will be investigated in how far the penetration behaviour is changed when considering other liquids than water, e.g. chloride containing water, sea water, ...

TASK 1-2: Study of the transport of gasses in SCC
The transport of gaseous agents in SCC will be studied fundamentally by means of a gas permeability measuring instrument. By means of this test set-up, the gas permeability coefficient of SCC can be studied following a method developed by RILEM TC 116-PCD "Permeability of concrete as a criterion of its durability".

PART 2: Relation with the durability behaviour of SCC

TASK 2-1: Creep and shrinkage
It is to be expected that creep and shrinkage behaviour of SCC largely depend on the diffusion behaviour of water in SCC. This will be verified by means of an extended experimental program with creep and shrinkage tests on SCC specimens stored at different environmental conditions. The results will be modelled by means of diffusion equations, as well as by means of existing code models. In this task, the effect of the addition of fibres on the shrinkage behaviour of SCC can be investigated simultaneously.

TASK 2-2: Carbonation and chloride penetration
Corrosion of steel reinforcement can be initiated by carbonation or by chlorides. In this experimental task, both phenomenons will be investigated for SCC. The correlation with the fundamental transport properties will be verified. The applicability of traditional carbonation and chloride penetration models will be investigated as well.

TASK 2-3: Frost and frost in combination with de-icing salts
By means of frost tests and frost tests in combination with de-icing salts, the frost resistance of SCC will be studied. Also in this case, the correlation with the fundamental penetration behaviour and the porosity of the material will be investigated thoroughly.

TASK 2-4: Chemical attack
By means of existing test set-ups (e.g. the test set-up for accelerated degradation), the sulphate and acid attack on SCC will be investigated. The correlation with porosity and transport behaviour is to be evaluated as well. Furthermore, the risk on alkali silica reaction will be studied experimentally by means of Oberholster tests. An evaluation by means of a fundamental characterisation is to be set up as well.

TASK 2-5: Damage evolution
During the different durability tests described in tasks 2-1 to 2-4, a permanent follow up of the evolving damage will be realised by means of non-destructive techniques (dynamic measurements, ultrasonic measurements). In this way, the evolution of the degradation mechanism and of the real damage can be followed on one particular specimen undergoing
the whole degradation cycle. The ultrasonic measurements can be carried out on small specimens. The results give an idea of the evolving porosity, permeability and stiffness. The first two parameters are of extreme importance within durability investigations. For this reason, the ultrasonic measurements are a fundamental part of the proposed research project. The stiffness can be considered as a macroscopic engineering property. Such macroscopic engineering properties can also be obtained by means of dynamic measurements on small slabs or beams. As for these measurements some larger specimens are needed (in comparison with the specimens needed for ultrasonic measurements), the dynamic measurements will be carried out only in a few cases. The advantage however of these dynamic measurements is the insight that is gained concerning the influence of the damage caused by the degradation mechanisms on the macroscopic mechanical behaviour of SCC. The non-destructive measurements can surely be considered as interesting supplementary measuring techniques, besides the traditional (mostly destructive) measuring methods that are carried out during the degradation tests.

FIRST RESULTS

Concrete composition

In the first stage, 4 concrete mixtures are studied: 3 SCC and 1 traditional concrete (TC). In the SCC mixes, a constant amount of fine particles (cement and filler) is considered: 600 kg/m³; as well as a constant amount of sand and gravel, respectively 853 kg/m³ and 698 kg/m³. The amount of water is varied in order to obtain a W/C ratio of 0.40, 0.46 and 0.55. The amount of superplasticizer was determined in order to obtain a suitable flowability without segregation. Also the value for the V-funnel was measured (values between 5s and 10s), air content (values between 1.5% and 3%) and the U-box requiring self-levelling.

In Table 1 the mix compositions are given together with the slump flow and the compressive strength at 28 days measured on concrete cubes 150mm.

<table>
<thead>
<tr>
<th>Table 1. Mix design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>CEM I 42.5 R [kg/m³]</td>
</tr>
<tr>
<td>limestone filler P2 [kg/m³]</td>
</tr>
<tr>
<td>water [kg/m³]</td>
</tr>
<tr>
<td>sand 0/5 [kg/m³]</td>
</tr>
<tr>
<td>gravel 4/14 [kg/m³]</td>
</tr>
<tr>
<td>glelenium 51 [l/m³]</td>
</tr>
<tr>
<td>W/C [-]</td>
</tr>
<tr>
<td>W/(C+F) [-]</td>
</tr>
<tr>
<td>slump flow [mm]</td>
</tr>
<tr>
<td>compressive strength [MPa]</td>
</tr>
</tbody>
</table>

Five types of tests were carried out: water absorption by immersion, water permeability test, gas permeability test, freezing and thawing in combination with de-icing salts and testing of alkali silica reactivity.

Water absorption by immersion

From the mixes described above, cubes 100 x 100 x 100 mm³ were made. These concrete cubes were stored in a climate room at 20°C ± 2 °C and at least 90% R.H.. At the age of 28
days, these concrete cubes were stored for 1 week at 20°C ± 3 °C and 60 ± 3 % R.H.. After this conditioning, the cubes are immersed in water until the change in weight during 24 hours is less than 0.1%. Afterwards, the cubes are dried in an oven at a temperature of 105 ± 5°C until the difference in weight during 24 hours is less than 0.1%. These tests were carried out on three specimens for each concrete mix. The results are given in Table 2 in % of the dry mass (W).

Water permeability
From the mixes described, cubes 150 x 150 x 150mm³ were made. These concrete cubes were stored in a climate room at 20°C ± 2 °C and at least 90% R.H. until the age of 90 days. Then, one core (diameter 80mm, height 25mm) from the centre of each cube was taken. Afterwards, these cores were vacuum saturated in water. The water permeability test was performed in a testing device as shown in Figure 2. Water is present at the upper side of the specimen, on the lower side there is no water. Hence the pressure head is known and the water permeability can be calculated with the following formula:

$$ K = \frac{A_r}{A_t} \frac{d}{t-t_0} \ln \left( \frac{h_0}{h} \right) $$

with $K$ the coefficient of permeability, $A_r$ the cross section of the tube, $A_t$ the cross section of the specimen, $d$ the thickness of the specimen, $t$ the time and $t_0$ the starting time, $h_0$ the height of water in the tube at $t_0$ and $h$ the height of water at time $t$.

![Figure 2: Testing device for water permeability](image)

These tests were performed on three specimens for each concrete mix. In table 2 the value of $K$ after 28 days is given.
Table 2. Test results

<table>
<thead>
<tr>
<th></th>
<th>W [%]</th>
<th>K [10^{-11} m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC1</td>
<td>4.8</td>
<td>1.44</td>
</tr>
<tr>
<td>SCC2</td>
<td>3.9</td>
<td>1.00</td>
</tr>
<tr>
<td>SCC3</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>TC1</td>
<td>4.8</td>
<td>1.66</td>
</tr>
</tbody>
</table>

From this table the following can be concluded:

- **W/C ratio**: the lower the W/C ratio, the lower the water absorption by immersion and the lower the water permeability.
- **SCC versus TC**: the water absorption by immersion is the same for the same W/C ratio; the water permeability is somewhat lower for SCC in comparison with TC.

**Gas permeability**

From the mixes described above, one prism 400 x 400 x 100mm³ was made. This concrete prism was stored in a climate room at 20°C ± 2°C and at least 90% R.H.. At the age of 21 days, three specimens of 150 mm diameter and 50 mm thickness were core drilled from the middle of the prism. These cores were then stored at 20°C ± 2°C and 90% R.H. until the age of approximately 12 weeks. At this moment the preconditioning of the samples starts. As the degree of saturation is important regarding the gas permeability, the permeability is measured at three degrees of saturation. First the specimens are vacuum saturated in water and furthermore dried in different steps. For each degree of saturation the oxygen permeability is measured for three pressure stages (3, 4 and 5 bar). At each pressure stage the flow rate is allowed to stabilise within 30 minutes. The flow Q is measured by means of a bubble flow meter. The apparent permeability coefficient $K_{app}$ for oxygen 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.

$$K_{app} = \frac{4.04 \cdot P_2 \cdot Q \cdot L \cdot 10^{-16}}{A \cdot (P_1^2 - P_2^2)} \quad (m^2)$$  \hspace{1cm} (2)

with $K_{app}$ the apparent coefficient of gas permeability, Q the flow rate, L the specimen thickness, A the specimen cross-sectional area and $P_1$ and $P_2$ respectively the upstream and downstream pressure.

In fig. 3 the apparent coefficient of gas permeability is plotted versus the degree of saturation for several pressure stages. The following conclusions can be made:

- **W/C ratio**: the lower the W/C ratio, the lower the gas permeability.
- **SCC versus TC**: the gas permeability is much lower.
The frost resistance in combination with de-icing salts of the mixtures mentioned above is studied as described in the Belgian document NTN 018. Cubes 150 x 150 x 150mm³ were made and stored in a climate room at 20°C ± 2°C and at least 90% R.H.. At the age of 28 days, cores of 100mm diameter and 100mm height were taken and 3 cylinders of each mixture were prepared for the test. After covering the original free surface of the specimens with a 5mm thick layer of 3% sodium chloride solution, the specimens went through 28 freezing/thawing cycles. The temperature in each cycle (24 hours) varied in between 20°C ± 2°C and -18°C ± 2°C. After 7, 14, 21 and 28 cycles scaling was measured. The loss of mass after 28 cycles (kg/m²) is given for each mixture in Table 3.

The mass loss increases with increasing W/C. The increasing amount of pores probably induces a more permeable concrete which makes it easier for the de-icing salt solution to penetrate. The reference mixture SCC1 has almost the same mass loss after 28 days as the corresponding TC1.

Alkali silica reaction

The risk on alkali silica reaction is studied experimentally by means of Oberholster tests. From the mixes described above, cubes 200 x 200 x 200mm³ were made. These cubes were stored in a climate room at 20°C ± 2°C and at more than 90% R.H.. At the age of 28 days, three cores of 50 mm diameter and 160 mm height were taken for each concrete mixture. These cores are stored for 20 days in an alkalic fluid (1 mole NaOH for 1 litre of water) at 80°C. The shortening or lengthening of the cores is daily measured by means of clock gauges. The change of length after 28 days (%) is for each mixture given in Table 3.

The expansion increases for an increasing W/C. This is possibly due to a less dense structure of the concrete, yielding a bigger mobility of alkali-ions. There is a significant difference
between SCC1 and TC1. This might be attributed to the special effect of the limestone filler. The difference in behaviour is subject for further research.

Table 3: Test results - freezing/thawing - alkali silica reaction

<table>
<thead>
<tr>
<th></th>
<th>mass loss [kg/m²]</th>
<th>change of length [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC1</td>
<td>5.012</td>
<td>0.149</td>
</tr>
<tr>
<td>SCC2</td>
<td>0.443</td>
<td>0.022</td>
</tr>
<tr>
<td>SCC3</td>
<td>9.207</td>
<td>0.181</td>
</tr>
<tr>
<td>TC1</td>
<td>5.041</td>
<td>-0.034</td>
</tr>
</tbody>
</table>

CONCLUSIONS

A Belgian research project on transport properties in SCC and relation with durability is outlined. The whole project consists of a combination of fundamental basic tests, which must yield a good insight in the transport behaviour of potentially aggressive media in SCC, and of simulation tests, in which real degradation mechanisms are induced in an accelerated way. This combination must lead to a more fundamental understanding of the durability behaviour of SCC. The applicability of traditional models, developed for traditional concrete, will be evaluated, and if necessary modified, or even new models will be proposed.

First results were given, leading to the following preliminary conclusions:
- The water permeability of SCC is somewhat lower in comparison with TC with the same W/C ratio.
- The water absorption by immersion of SCC is comparable with the values obtained for TC.
- The gas permeability of SCC seems to be much lower than for TC.
- The resistance to freezing and thawing in combination with de-icing salts is comparable for SCC and TC.
- The expansion during the Oberholster test seems to be higher for SCC in comparison with TC.

ACKNOWLEDGMENT

The financial support of the National Fund for Scientific Research – Flanders is greatly acknowledged.

REFERENCES