Available online at www.sciencedirect.com
ScienceDirect
Construction and Building Materials 21 (2007) 1909–1917
Construction and Building MATERIALS
www.elsevier.com/locate/conbuildmat

Estimates of self-compacting concrete 'potential' durability

Stéphan Assié [a,*], Gilles Escadeillas [a,*], Vincent Waller [b,1]

[a] Laboratoire Matériaux et Durabilité des Constructions, INSA-UPS Département Génie Civil, 135, Avenue de Rangueil, 31077 Toulouse cedex 4, France
[b] CTG, Italcementi Group, Rue des Technodes, 78931 Guerville cedex, France

Received 2 August 2005; received in revised form 15 June 2006; accepted 30 June 2006
Available online 15 November 2006

Abstract

The building industry is progressively trying to use self-compacting concrete (SCC) in order to improve many aspects of construction, principally reinforced concrete. However, the problem of its durability still exists, particularly in terms of physicochemical properties which are essential to avoid corrosion of rebars. The purpose of this project was to qualify the 'potential' durability of self-compacting concrete and reference vibrated concrete (VC) with similar compressive strength according to French recommendations. To do this, general indicators of durability (water porosity, chloride diffusion, oxygen permeability) and additional properties necessary for a better understanding (mercury porosity, water absorption by capillarity, carbonation and ammonium nitrate leaching) were examined. Various mixes of SCC and VC were therefore made with the same raw materials in identical proportions (except for the high-performance concrete). The tests conducted on the concretes studied revealed that the durability of both concretes could be regarded as equivalent. So, at the same level of compressive strength, self-compacting concrete can be considered to be as durable as vibrated concrete.

Keywords: Self-compacting concrete; Porosity; Permeability; Durability; Compressive strength

1. Introduction

This study concerns the durability of self-compacting concrete (SCC). Since its first use in Japan at the end of the eighties [1], SCC has been increasingly used in ready-mixed concrete and in the precast industry to improve several aspects of construction. SCC is expected to replace vibrated concrete (VC) in many applications in the long term because of its various advantages: reduction of the harmful effects of sound in urban environments, possibility of pouring in strongly reinforced places or with complex geometry, and reduction in the industrial process costs.

But some questions remain unanswered, for example: is SCC as durable as VC, especially in terms of physicochemical durability, at the same level of compressive strength?

The few results available [2–4] partly answer this question but they usually concern high-performance concrete (HPC). Few studies provide results on SCC with low or average compressive strength [5].

This research program was therefore set up to study concrete with a compressive strength of about 20–70 MPa. The main goal of the project was to compare the durability properties of SCC and VC with equivalent compressive strength. The properties studied were those recommended by the French Association of Civil Engineering (AFGC) for evaluation and prediction of reinforced concrete durability by means of durability indicators [6].

These durability indicators are easily quantifiable parameters which appear to be fundamental in the evaluation of the service life of a concrete and the building where it is used. They are used as a supplement to the basic char-

* Corresponding authors. Tel.: +33 5 61 55 99 33; fax: +33 5 61 55 99 49.
E-mail addresses: assie@insa-toulouse.fr (S. Assié), Gilles.Escadeillas@insa-toulouse.fr (G. Escadeillas), vwaller@ctg.fr (V. Waller).
[1] Tel.: +33 1 34 77 78 99; fax: +33 1 34 77 79 40.

0950-0618/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2006.06.034

acteristics of the concrete like strength or water/cement ratio.

Two families of indicators are considered: the general indicators (which characterize porosity, transport properties and basicity) and the replacement indicators (which contribute to the determination of these same properties). In this study, the following general indicators were determined: water porosity, chloride diffusion, oxygen permeability and portlandite content. Some replacement indicators were also studied: mercury porosity (considered as equivalent to water porosity), water absorption by capillarity, carbonation and ammonium nitrate leaching.

SCC and VC mixes were cast with the same granular components in identical proportions. The use of limestone filler and a greater quantity of superplasticizer in the SCC mixes were the only differences.

2. Materials and experimental program

2.1. Materials

2.1.1. Components

Two cements were used (see Table 1):

- a CEM II/A-LL 32.5 R, containing 15.8% limestone filler, with a 28-day compressive strength of 45 MPa (Blaine fineness: 400 m^2/kg; density: 3030 kg/m^3). This lower cost cement is generally used in France for ordinary buildings subject to no severe exposure (class of concrete strength C20 or C25, according to EN 206-1 [7]);
- a CEM I 52.5 N, whose 28-day compressive strength was 63 MPa (Blaine fineness: 380 m^2/kg; density: 3130 kg/m^3). This cement is generally used for average and high-performance concrete (class of concrete strength C35–C60, according to EN 206-1 [7]).

The aggregates used were siliceous round aggregates of grade 0/4 mm for sand and 4/12 mm or 4/20 mm for the gravel.

The limestone filler used in SCC mixes had the following characteristics: fineness 406 m^2/kg, density close to 2710 kg/m^3 and activity factor (i_{28}) 0.74 [8].

A polycarboxylate modified superplasticizer was used as a water reducer in SCC and VC. Its density was 1.05, its chloride ion content was below 0.1% and it contained 20% of dry matter.

2.1.2. Mix properties

Mix proportions of SCC were chosen in accordance with the French recommendations [9] (high volume of paste, typically 330–400 l/m^3; high fines content, about 500 kg/m^3; low gravel content, e.g. a gravel–sand ratio of about 1).

As can be seen in Table 2, the SCC mixes differed from VC mixes mainly by containing mineral additives and greater quantities of superplasticizer and water. The latter were necessary to obtain an acceptable slump flow for the SCC mixes.

Another significant difference between SCC and VC mixes was the volume of paste (see Table 3), which could affect the physicochemical properties of the concrete [10].

Although the greater quantity of water used in the SCC mixes led to a higher Water/Cement (W/C) ratio, the Water/Binder (W/B) ratio of the two types of concrete remained comparable (in W/C ratio, C is the mass of commercial cement; in W/B ratio, according to European standard [7], B is the sum of the mass of ordinary portland cement without admixtures and the mass of authorized admixtures (like limestone filler) multiplied by a coefficient (for limestone, the coefficient is equal to 0.25)).

Moreover, aggregate proportions were similar in both concretes for C20 and C40 classes of concrete. The Gravel/Sand (G/S) ratio of VC 20 and VC 40 mixes may be considered a little low according to French standards [11]. The VC 60 mix was therefore prepared with a higher G/S ratio (1.45 instead of 0.90).

2.2. Experimental program

The concrete was mixed using a 125-l vertical-axis planetary mixer. The mix sequence was as follows. First, the dry aggregates were humidified for 10 min, then cement was introduced and mixed with the aggregates for 30 s. The water and part of the additives were then introduced and mixed for a further 90 s. Finally, the remaining additives were added and mixed with the batch for 2 min.

The samples of VC were set up using vibration (vibrating switches or tables) and those of SCC were set up only by gravity, with no vibration. Afterwards, specimens were stored for 24 h in a room maintained at 20 °C without humidity exchange (the low bleeding of SCC makes it more vulnerable to the effects of plastic shrinkage). They were then demolded and stored in a wet room at 20 ± 1 °C and 100% RH.

- Compressive strength was measured on cylindrical samples (∅11 × H22 cm) with a 3000 kN hydraulic press and a loading rate of 0.5 N/mm^2/s.

Table 1
Cement characteristics

Components (%)	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	Insoluble residue	Loss on ignition
CEM II/A-LL 32.5 R	60.31	17.57	4.07	2.87	1.25	3.15	1.31	0.13	1.55	8.43
CEM I 52.5 N	63.93	20.40	4.53	2.31	2.39	3.20	0.87	0.18	0.16	0.94

Table 2
Mix proportions (kg/m^3)

Composition (kg/m^3)		Mix					
		VC 20	SCC 20	VC 40	SCC 40	VC 60	SCC 60
Cement	CEM II/A-LL 32.5 R	315	315				
	CEM I 52.5 N			350	350	450	450
Limestone filler		–	150	–	140	–	70
Sand		981	900	962	888	751	884
Gravel	4/12 mm			857	791	1088	793
	4/20 mm	841	771				
Superplasticizer		1.4	8.0	6.9	12.6	5.9	13.5
Water		189	205	175	191	164	189

Table 3
Mix characteristics

Properties	Mix					
	VC 20	SCC 20	VC 40	SCC 40	VC 60	SCC 60
Water/Cement ratio	0.60	0.65	0.50	0.55	0.36	0.42
Water/Binder ratio	0.60	0.65	0.50	0.50	0.36	0.40
G/S ratio (by mass)	0.86	0.86	0.89	0.89	1.45	0.90
Volume of paste (l/m^3)	317	380	305	374	318	377

In terms of physicochemical properties, the experimental results concern durability properties such as water porosity, chloride diffusion and oxygen permeability. The French Association of Civil Engineering (AFGC) [6] considers these characteristics as general indicators of the potential durability of concrete (performance based evaluation, independent of the future site of exposure of concrete). The tests performed on these properties were performed after 28 days of water curing, according to others AFGC recommendations [12]:

- Water porosity was calculated from three masses (weighed hydrostatically or in air): apparent mass of saturated concrete samples (5 cylinders ∅15 × H5 cm) after immersion (liquid saturation under vacuum) (M_{water}), mass in the air while they were still soaked (M_{air}) and mass of dry samples (drying at 80 ± 5 °C until they reached a constant mass) (M_{dry}).Water porosity (ε) is given by the following equation:

$$\varepsilon = \frac{M_{\text{air}} - M_{\text{dry}}}{V} = \frac{M_{\text{air}} - M_{\text{dry}}}{M_{\text{air}} - M_{\text{water}}} \times \rho_{\text{water},\theta} \times 100 \tag{1}$$

where $\rho_{\text{water},\theta}$ denotes the density of water at testing temperature (θ K).
- Chloride diffusion was estimated by a migration test (determination of the effective coefficient of diffusion [13]). This test was performed in saturated material and at steady state. An external potential of 12 volts was applied to the samples (3 cylinders ∅11 × H4 cm) and forced the chloride ions outside to migrate into the concrete. The effective coefficient of chloride diffusion (D_{eff}) was calculated by chloride loss determination. The relationship used was as follows:

$$D_{\text{eff}}(t) = \frac{RTJ(t)}{CFE} \tag{2}$$

where R is the perfect gas constant (8.32 J/mol K), T the temperature (Kelvin), $J(t)$ the chloride flow migrating into the concrete (mol/m^2 s), C the average chloride concentration during the test (mol/m^3), F the Faraday constant (96,487 C/mol) and E the potential difference applied (V/m).The chloride diffusion test was performed using an aggressive solution composed of deionized water and various ion species: sodium chloride ([NaCl] = 12 g/l), sodium hydroxide ([NaOH] = 1 g/l) and potassium hydroxide ([KOH] = 4.65 g/l).
- The oxygen permeability test was conducted using a CEMBUREAU experimental device [14]. The flow of oxygen through concrete samples (5 cylinders ∅15 × H5 cm) was measured at steady state against the test pressure and the material saturation rate. The apparent coefficient of permeability (k_{A}) was calculated for laminar flow of a compressible viscous fluid through a porous material from the Hagen–Poiseuille relationship:

$$k_{\text{A}} = \frac{2Q\mu LP_{\text{atm}}}{A(P_i^2 - P_{\text{atm}}^2)} \tag{3}$$

where Q is the measured oxygen flow (m^3/s), μ the dynamic viscosity of oxygen (N s/m^2), L the thickness of the sample (m), P_{atm} atmospheric pressure (Pa), A the cross-sectional area of the sample (m^2) and P_i the absolute pressure applied (Pa).

The fourth general indicator, i.e. the portlandite content ($Ca(OH)_2$, given in kg/m^3) was estimated from the following formula, usable for CEM I cements [6] :

$$\text{Ca(OH)}_2 = \sup\left[0; \left\{m_{\text{C}} \cdot \left(\frac{C_3S}{100}\right) \cdot \left\langle \inf\left(1; \frac{W/C}{0.418}\right)\right\rangle \cdot 0.422 - 0.617 \cdot m_{\text{S}}\right\}\right] \tag{4}$$

where m_C represents the cement mass (kg/m^3), C_3S the tricalcic silicate percentage in the cement used, W/C the Water/Cement ratio and m_S the mass of pozzolanic additions used (kg/m^3).

For this study, replacement indicators were also examined: mercury porosity, water absorption by capillarity, carbonation (accelerated test) and ammonium nitrate leaching. The last two were set up to confirm the results of the principal indicators studied.

The tests were carried out as follows:

- Mercury porosity was obtained from a specific test: mercury was introduced into the porous medium under very high pressure (200 MPa) using a porosimeter. By modelling the pores as cylindrical channels, the test pressure (p) can be connected to the radius of these cylinders by the Washburn–Laplace law:

$$p = \frac{2\sigma \cos\theta}{r} \tag{5}$$

  where p defines the mercury injection pressure (Pa), σ the surface stress applied to the liquid (N/m), θ the contact angle (rad) and r the radius of the cylinder (m).
- Capillary absorption was assessed on dry concrete samples (5 cylinders $\varnothing 15 \times$ H5 cm). To evaluate the water absorption of concrete, the water inflow was measured at pre-set times for a specific duration (24 h). The results obtained were in line with a well-known equation for water absorption [15]:

$$A(t) = S \cdot t^{1/2} \tag{6}$$

  where A represents the water intake (kg/m^2), S the sorptivity (kg/m^2 s$^{1/2}$), and t the testing time (s).
- The carbonation accelerated test was conducted on concrete samples (3 square prisms $7 \times 7 \times 28$ cm) stored in special environmental conditions (after being water-cured for 28 days) [12]. The carbon dioxide rate was maintained at $50 \pm 1\%$ (the other 50% was ambient air) and the relative humidity was $65 \pm 5\%$. Such conditions engendered substantial degradation of the concrete. The degraded depth was made visible by spraying on a phenolphthalein solution. Measurements were made at typical times: 7 days, 14 days, 28 days and 56 days. This accelerated test is generally used to assess the long-term behavior of a reinforced concrete.
- The leaching accelerated test was carried out on concrete samples (2 cylinders $\varnothing 11 \times$ H22 cm) immersed in a saturated ammonium nitrate solution (500 g/l) at 20 ± 1 °C (after being water-cured for 28 days). The measurement of degraded depth was made using the same carbonation test process. According to some authors [16], this decalcification test accelerates the rate of leaching due to deionized water 100 times. This accelerated test is used in France to predict the long-term behavior of a concrete in an aggressive atmosphere with a low pH.

3. Results

3.1. Concrete properties

The first results (Table 4) concern the workability of concrete characterized (according to AFGC recommendations [9]) by: (i) unconfined flowability, determined by the slump-flow test (the target values are generally in the range of 60 to 75 cm, with no visible segregation at the end of the test); (ii) confined flowability, determined by the L-box test (the filling ratio must be greater than 80%); (iii) stability, i.e. resistance to segregation and bleeding, determined by a specific French test called the screen stability test (the stability is satisfactory when the percentage of laitance by weight is lower than 15%, critical when the percentage of laitance is in the range of 15–30% and very poor when the percentage of laitance is higher than 30%).

Table 4 shows that the SCC mixes complied with these AFGC recommendations [9].

The VC mixes showed a somewhat high air content (due to air trapping as a secondary effect of the superplasticizer used when the slump was too low) and a slump characteristic of plastic to fluid concrete (class S2 to S3, according to the European standard EN 206-1 [7]).

Moreover, these results show that SCC had a compressive strength similar to that of VC (for each strength class), despite a higher W/C ratio (but a similar W/B ratio).

3.2. Physicochemical properties

Diffusion, permeability and absorption are accepted to be the main physical processes which transport aggressive substances into concrete. The tests performed on these processes made it possible to characterize the durability of concrete by measuring the penetration potential.

Table 4
Concrete properties in fresh and hardened state

Properties	Mix					
	VC 20	SCC 20	VC 40	SCC 40	VC 60	SCC 60
Slump/slump flow (cm)	12.5 (slump)	67 (slump flow)	5 (slump)	74 (slump flow)	14 (slump)	70 (slump flow)
Segregation (GTM test, %)	–	0.6	–	7.8	–	2.2
Filling rate (L-Box test)	–	0.80	–	0.92	–	0.87
Air content (%)	5.2	2.1	4.0	2.2	1.6	1.6
R_{C28} (MPa)	21.8	26.4	50.8	49.6	68.6	69.2

3.2.1. Water and mercury porosity

The results of water and mercury porosity are presented in Fig. 1 for SCC and VC mixes.

– Water porosity is slightly higher (from +1% to +1.5%) for the SCC mixes than the corresponding VC whatever the strength class. This result can be (partly) explained by the higher W/C ratio of SCC mixes.
– The results of mercury porosity lead to a similar conclusion: SCC presents a slightly higher mercury porosity (+0.1% to +1.2%) than VC.
– Mercury porosity is lower than water porosity for both concretes [6] and its order of magnitude is characteristic of each concrete class (ordinary concrete, structural concrete and high-performance concrete).

3.2.2. Chloride diffusion

The results of this test are presented in Fig. 2.

These results indicate that SCC and VC have an equivalent effective coefficient of diffusion (for each strength class) and that it is of the same order of magnitude (even for concrete C20 which is not recommended for this type of exposure).

However, the test used in this study underestimates the effective coefficient of chloride diffusion. Unlike in other tests [17], the measurements concern the chloride ions which come into the concrete and not those flowing through the samples (concrete keeps some of them). The values obtained were therefore adjusted to give a better scale of comparison for the concrete under study (see Table 5).

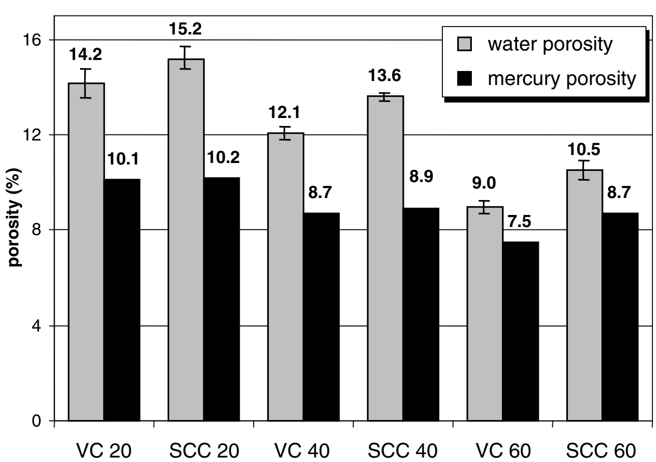

Fig. 1. Water and mercury porosity of concretes studied.

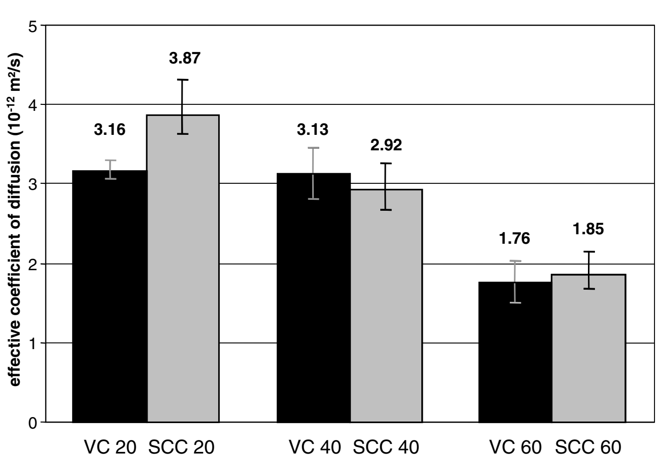

Fig. 2. Effective coefficient of chloride diffusion of concretes studied.

3.2.3. Oxygen permeability

The results of the oxygen permeability test (see Fig. 3) were obtained for a 0.2 MPa test pressure and in dry material. Although this does not represent concrete in normal conditions of use, the pore saturation rate was chosen to evaluate an intrinsic property of the concrete studied.

Fig. 3 reveals that the oxygen permeability of SCC is lower than that of VC (especially for C20 class) [18].

– The oxygen permeability of ordinary concrete (1.08–4.95×10^{-16} m^2) has the same order of magnitude for both concretes and it is characteristic of C20 concrete. According to some researchers [6], the oxygen permeability of a C25 vibrated concrete (under the same conditions) is believed to be between 2 and 10×10^{-16} m^2 (and no comparison with SCC is available).
– For structural concrete, the oxygen permeability of SCC is slightly lower than that of VC and the measured values (0.43–0.60×10^{-16} m^2) are specific to C40 concrete [4].
– Finally, the HPC gave an equivalent oxygen permeability (0.51–0.67×10^{-16} m^2) for both types of concrete (slightly lower for the SCC). These values are higher than those of structural concrete. This tends to show that high-performance concretes are more sensitive to the preconditioning applied: the microcracking generated by drying (at 80 °C) becomes more significant on HPC than on concrete with a higher W/C ratio (namely SCC 40 and VC 40).

3.2.4. Water absorption (by capillarity)

The results of water absorption by capillarity (at 24 h) are presented in Fig. 4 for SCC and VC mixes.

According to these results, the capillary absorption of SCC is higher than that of VC with a similar order of magnitude.

Moreover, our results do not clearly differentiate the various strength classes: for example, the capillary absorption coefficient of VC 60 mix is comparable to that of VC 20 mix. This result would place these two types of concrete in the same durability class. It can also explain why this physical property has not been chosen as a general durability indicator.

Table 5
Durability indicators

Durability indicators	Mix					
	VC 20	SCC 20	VC 40	SCC 40	VC 60	SCC 60
Water porosity (%)	14.2	15.2	12.1	13.6	9.0	10.5
Potential durability (corresponding class of concrete)	Low (C25–C40)	Low (C25–C40)	Mean (C30–C60)	Mean (C30–C60)	High (C55–C80)	High (C55–C80)
Mercury porosity ($P_{Hg} = 200$ MPa) (%)	10.1	10.2	8.7	8.9	7.5	8.7
Potential durability	Mean	Mean	High	High	High	High
Diffusion coefficient (10^{-12} m^2/s)	35.0	29.5	8.6	9.4	3.7	3.8
Potential durability	Low	Low	Mean	Mean	High	High
Apparent oxygen permeability (10^{-18} m^2)	495.3	108.2	59.6	43.2	67.1	50.5
Potential durability	Low	Mean	High	High	High	High
$Ca(OH)_2$ content (% of the cement mass)	–	–	27.3	27.3	23.5	26.1
Potential durability with regard to corrosion of reinforcements			Very high	Very high	High	Very high

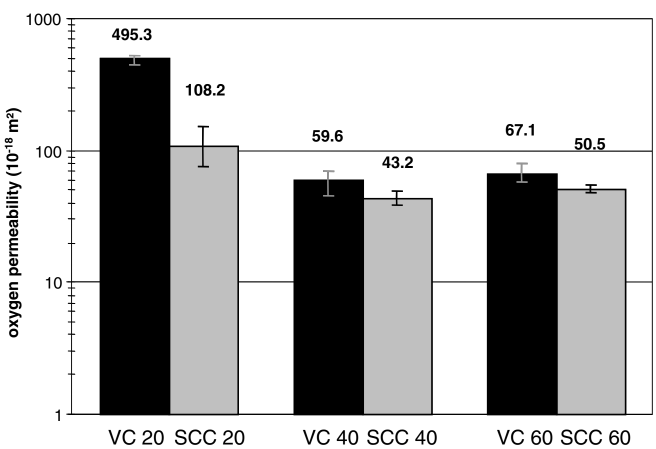

Fig. 3. Apparent oxygen permeability of concretes studied ($P_{applied} = 0.2$ MPa, dry material).

3.3. Additional tests

3.3.1. Carbonation (accelerated test)

The graph for the carbonation accelerated test (see Fig. 5) proves that the degradation of SCC increases as quickly as for the corresponding VC [3].

Moreover, for these concretes and in such conditions, these carbonated depths remain small, i.e. less than 25 mm after 28 days of testing (which would be reached after 40 years in natural conditions [19]) for ordinary concrete and less than 10 mm at 56 days for structural concrete (which would be reached after 200 years in natural conditions [20]).

3.3.2. Ammonium nitrate leaching

The results of ammonium nitrate leaching (see Fig. 6) show that SCC and VC were equally degraded.

For each strength class, the kinetics of the reaction was similar for the two types of concrete and this confirms that

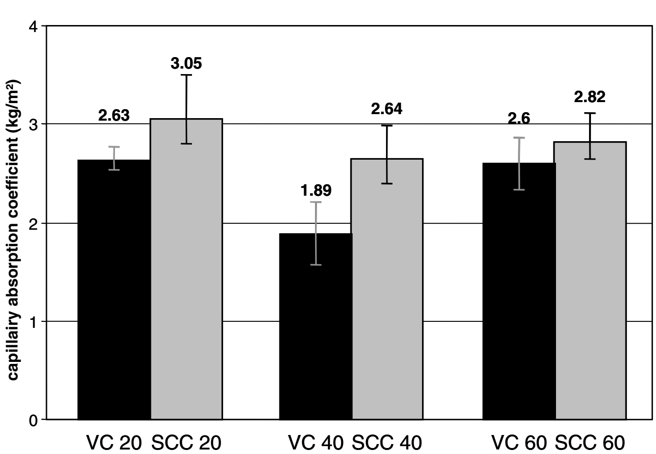

Fig. 4. Capillary absorption coefficient (at 24 h) of concretes studied.

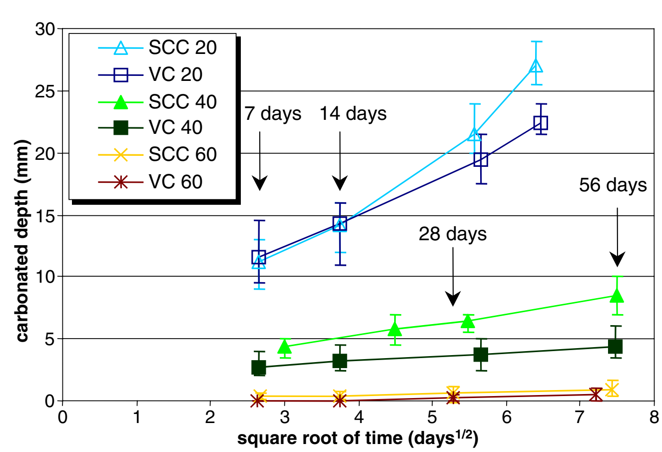

Fig. 5. Carbonated depth of concretes studied ($t_0 = 28$ days).

the durability of SCC to acid attack can be regarded as equivalent to that of VC.

3.4. Discussion

3.4.1. AFGC durability indicators

The results presented above for the transport properties (porosity, diffusion and permeability) can be analyzed according to recommendations of AFGC [6] to classify the durability of the concrete studied. In these recommendations, five classes of "Potential durability" are defined: very low, low, mean, high and very high. For classified in each class, specific values are given for each durability indicator. Then, global analysis give an idea of the 'potential' lifetime of the material considered.

Results are summarized in Table 5.

First of all, these results show that the potential durability of the two types of concrete is different according to the characteristic studied:

- water porosity and diffusion coefficient indicate the same "durability class" for SCC and VC mixes.
- mercury porosity and apparent oxygen permeability reveal an equivalent durability for SCC and VC, except in the case of SCC 20 and VC 20 mixes where the lower apparent oxygen permeability of SCC implies a higher durability than for VC. The 'potential' durability class reflected for the two types of concrete by mercury porosity and apparent oxygen permeability is higher than that given by water porosity and diffusion coefficient.
- the portlandite content estimate shows that all the concretes studied can be considered as "very high potential durability" with regard to the corrosion of reinforcements.

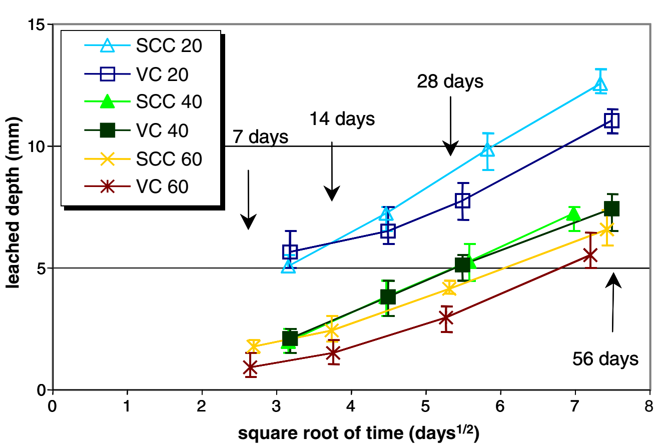

Fig. 6. Depth degraded by ammonium nitrate in concretes studied ($t_0 = 28$ days).

Table 5 gives also general durability class in corresponding with the type of concrete to each mix studied.

The ordinary concrete (SCC 20 and VC 20) has a low potential durability and corresponds well to concrete of class C25. The structural concrete (SCC 40 and VC 40) has an average potential durability and is representative of C30–C60. Lastly, the potential durability of the high-performance concrete (SCC 60 and VC 60) is classified as high and it is specific to C55 to C80 concrete.

According to these results, no significant difference in the potential durability of the two types of concrete was observed for the three strength classes considered.

This conclusion is confirmed by the results on concrete degradation (by accelerated carbonation or ammonium nitrate leaching) (see Table 6).

The results of accelerated carbonation (see Fig. 5) were expressed according to the square root of time (t, in days). The rate of carbonation (K) is determined by the diffusion of carbon dioxide into concrete and the carbonated depth (x) can be expressed from Fick's first law of diffusion as follows: $x(t) = Kt^{1/2}$.

The equivalent kinetics of carbonation between SCC and VC is not consistent with the results of water absorption and oxygen permeability: VC has a greater permeability and a lower capillary absorption but a slightly lower carbonation rate than SCC. This tends to show that the absorption process prevails in concrete carbonation (under accelerated conditions). The pore saturation rate (neither fully dry, nor fully saturated) was such that absorption was more significant than permeability and diffusion processes during this test.

The depth leached by ammonium nitrate has also been represented according to the square root of time (see Fig. 6) for the same reasons as for carbonation. In this test, the samples were maintained immersed in the aggressive solution. The diffusion of liquids therefore became the dominating transport process in this reaction. Thus, the leaching kinetics of SCC and VC comply with the results

Table 6
Accelerated degradation results

Properties	Mix					
	VC 20	SCC 20	VC 40	SCC 40	VC 60	SCC 60
Carbonated depth at 28 days (mm)	19.5	21.5	3.8	6.5	0.3	0.7
Accelerated carbonation kinetics (K, mm/day$^{1/2}$)	3.57	4.04	0.70	1.20	0.12	0.13
Leached depth at 28 days (mm)	7.8	9.2	5.1	5.3	3.0	4.2
Leaching kinetics (L, mm/day$^{1/2}$)	1.48	1.68	1.24	1.37	1.03	1.04
Average pore radius (nm)	32.4	27.8	28.6	22.6	21.1	19.7

of chloride diffusion (although it is not the same ion species).

The results of these two degradation tests are consistent with the conclusions drawn from the results for transport properties (see Table 5): degradation of self-compacting and vibrated concrete decreases with their compressive strength and their 'potential' durability increases with their resistance to the penetration of aggressive agents.

3.4.2. Additional analysis

The transport properties of concrete are mainly controlled by the volume of paste, the porous structure of the cement matrix and the interfacial transition zone (ITZ).

Mercury porosity tests provided the porous distribution curves of the concrete studied (see Fig. 7). These results complete the analysis of transport properties.

The pore distribution indicates two principal categories of pore for each strength class studied.

- For ordinary concrete (SCC 20 and VC 20): a first type refers to pores whose radius is about 65 nm for SCC and near 56 nm for VC. The second category has a radius around 11 nm for SCC and 6 nm for VC. The ranges of these categories are close.
- For structural concrete (SCC 40 and VC 40): the first category of pores refers to those with a radius close to 36 nm for SCC and 38 nm for VC. The second characteristic peak is located around 8 nm for SCC and 6 nm for VC. The pore categories of the two types of concrete are very close for this strength class.
- For high-performance concrete (SCC 60 and VC 60): the first category refers to the pores with radius close to 20 nm for SCC and 25 nm for VC. The second category consists of pores whose radius is about 7 nm for SCC and 6 nm for VC. As for the other strength classes, the high-performance SCC and VC have comparable categories and distributions of pores.

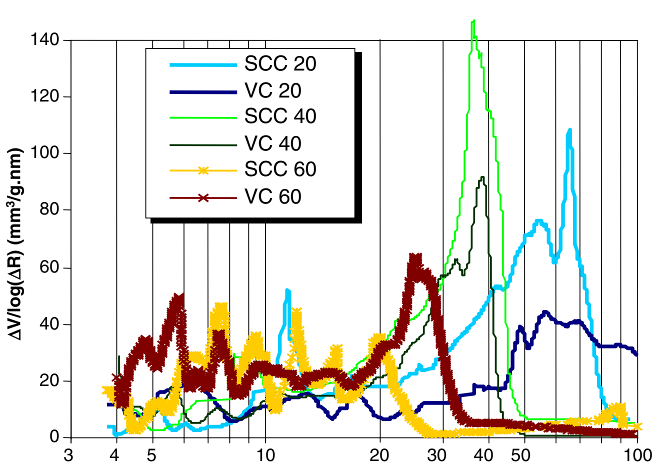

Fig. 7. Pore distributions of concretes studied.

With regard to transport processes, the differences perceived are to the advantage of SCC for average and high-performance concrete and VC for ordinary concrete.

On the one hand, the results of oxygen permeability are consistent with these comments and the results of average pore radius (see Table 6): SCC permeability is lower than that of VC, whatever the strength class.

On the other hand, chloride diffusion proves that the denser microstructure of SCC does not engender a better resistance to the penetration of chloride. This tends to show that the transport properties also depend on other material characteristics such as the tortuosity or the interconnection of the porous network [4].

The porous structure and the ITZ have a real effect on capillary absorption. The use of limestone filler in SCC mixes generates a weaker ITZ porosity than for VC [2]. Moreover, the water absorption by capillarity is inversely proportional to the pore radius (forces acting on water in capillary pores are all the higher when the pore radius is small). In this case, SCC has a smaller average pore radius (−7% to −21%) than VC (see Table 6). The slightly higher absorption coefficient for SCC is therefore consistent with the observations of porous structure.

4. Conclusions

This research project was set up to answer some questions about the durability of self-compacting concrete (SCC) in comparison to that of vibrated concrete (VC). To that end, various mixes of the two types of concrete were prepared with the same raw materials in identical proportions. Some differences remained between the two concretes, such as the use of limestone filler and a greater quantity of superplasticizer in SCC. The mixes studied covered a strength range from ordinary concrete (compressive strength close to 20 MPa) to high-performance concrete (strength higher than 60 MPa), passing through structural concrete (compressive strength around 40 MPa).

According to French recommendations of indicators of durability, various transport processes (chloride diffusion, oxygen permeability and water absorption) and different durability properties of concrete (porosity, accelerated carbonation, ammonium nitrate leaching) have been discussed in this article. The tests performed on these processes made it possible to determine significant physical properties with regard to the durability of concrete.

Although some differences exist between SCC and VC, the results obtained for the three strength classes studied lead to several conclusions.

1. In spite of a higher Water/Cement ratio (but an equivalent Water/Binder ratio), SCC has a compressive strength equivalent to (or even better than) that of VC.
2. The results of chloride diffusion and water absorption revealed that the transport properties of both concretes were equivalent. The oxygen permeability proved that SCC was more resistant to gas ingress than VC.

3. SCC and VC had a similar resistance to deterioration by aggressive agents (such as carbon dioxide and ammonium nitrate) and presented equivalent kinetics of reaction.

These results are consistent with several other studies and confirm that, at the same level of compressive strength, self-compacting concrete can be considered to be as useful and durable as vibrated concrete in terms of physicochemical properties.

Acknowledgement

The authors would like to thank the Italcementi Group for its contribution to this research program.

References

[1] Okamura H et al. Self-compacting high performance concrete. In: Proceedings of the fifth EA SEC, vol. 3. 1995. p. 2381–8.
[2] Trägårdh J. Microstructural features and related properties of field self-compacting concrete. In: Proceedings of the first international symposium on self-compacting concrete (PRO 7), Stockholm, Sweden, 13–15 September 1999. p. 175–86
[3] Audenaert K, De Schutter G. Influence of moisture on the carbonation of self-compacting concrete. In: Proceedings (SP 212) of the sixth CANMET/ACI international conference on durability of concrete, Greece, June 2003. p. 451–65.
[4] Zhu W, Quinn J, Bartos PJM. Transport properties and durability of self-compacting concrete. In: Proceedings of the second international symposium on self-compacting concrete, Tokyo, Japan, 23–25 October 2001. p. 451–8.
[5] Persson B. A comparison between mechanical properties of self-compacting concrete and the corresponding properties of normal concrete. Cem Concr Res 2001;31(2):193–8.
[6] Guide AFGC. Conception des bétons pour une durée de vie donnée des ouvrages. Maîtrise de la durabilité vis-à-vis de la corrosion des armatures et de l'alcali-réaction, Etat de l'art et Guide pour la mise en place d'une approche performantielle et prédictive sur la base d'indicateurs de durabilité, Association Française de Génie Civil, animateur BAROGHEL-BOUNY V., July 2004.
[7] EUROPEAN STANDARD NF EN 206-1, Béton, partie 1: spécification, performances, production et conformité, Association Française de Normalisation (AFNOR), février 2002.
[8] NORME FRANÇAISE NF P 18-508, Additions pour béton hydraulique – Additions calcaires – Spécifications et critères de conformité, AFNOR, July 1995.
[9] AFGC Interim recommendations for use of Self-Compacting Concrete, July 2002, Association Française de Génie Civil.
[10] Neville AM. Properties of concrete. 4th ed. Pitman Publishing Co.; 1995.
[11] Dreux G, Festa J. Nouveau guide du béton. 7th ed. Eyrolles ed.; 1995.
[12] Journées Techniques AFPC-AFREM, Durabilité des bétons Méthodes recommandées pour la mesure des grandeurs associées à la durabilité, 1997, Toulouse, France.
[13] Truc O, Ollivier JP, Carcasses M. A new way for determining the chloride diffusion coefficient in concrete from steady state migration test. Cem Concr Res 2000;30(2):217–26.
[14] Kollek JJ. The determination of the permeability of concrete to oxygen by Cembureau method – a recommendation. Mater Struct 1989;22:225–30.
[15] Basheer L, Kropp J, Cleland DJ. Assessment of the durability of concrete from its permeation properties: a review. Constr Build Mater 2001;15(2–3):93–103.
[16] Carde C, Escadeillas G, François R. Use of ammonium nitrate solution to simulate and accelerate the leaching of cement pastes due to deionised water. Mag Concr Res 1997;49(181):295–301.
[17] Tang L, Nilsson L-O. Rapid determination of chloride diffusivity of concrete by applying an electric field. ACI Mater J 1992;89(1):49–53.
[18] De Schutter G, Audenaert K, Boel V, Vandewalle L, et al. Transport properties in self-compacting concrete and relation with durability: overview of a Belgian research project. In: Proceedings of 3rd international RILEM symposium on self-compacting concrete (PRO 33), Reykjavik, Iceland, 17–20 August 2003. p. 799–807.
[19] Miragliotta R, Rougeau P, Aït Mokhtar K. Carbonatation des bétons – Optimisation de l'enrobage des armatures, CERIB report, Ref. DDE 31, July 2003.
[20] Miragliotta R, Rougeau P, Aït-Mokhtar A, Amiri O. A methodology for predicting the advance of carbonation in concrete: influence of the microstructure of the skin layer on concrete carbonation kinetics. 16th BIBM international congress, Venetia (Italy), Ref. 210, 1999. p. 73–8.