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Extrudable Reactive Powder Concretes
Hydration, shrinkage and transfer properties

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RÉSUMÉ. *Le comportement de cinq bétons de poudres réactives (BPR), dont quatre présentent des propriétés d'extrudabilité, a été étudié depuis les premières minutes après leur fabrication jusqu'à plus de 90 jours de maturation. La force d'extrusion, la cinétique d'hydratation, le développement du retrait endogène libre au jeune âge, les propriétés mécaniques et les paramètres de durabilité ont été mesurés. L'analyse des performances a montré l'intérêt d'une substitution partielle de la fumée de silice par du quartz broyé sur les propriétés des BPR. L'analyse coût/performances a mis en évidence que le principal avantage de l'utilisation des BPR réside dans leur potentiel de durabilité, 10 à 100 plus élevé que celui de bétons ordinaires ou à hautes performances, selon la propriété considérée.*

ABSTRACT. *The behavior of five reactive powder concretes (RPC), with four of them being extrudable, has been studied since the first minutes up to more than 90 days. The extrusion force, hydration rate, free autogenous shrinkage at early age, mechanical properties and durability parameters were measured. The performance analysis showed the benefits of a partial substitution of silica fume with crushed quartz on the RPC properties. The cost/performances analysis highlighted that the main advantage of using RPC lies in their potential of durability, which is 10 to 100 times higher than that of ordinary or high-performance concretes, according to the property considered.*

MOTS-CLÉS : *Béton de poudres réactives, extrusion, hydratation, retrait, durabilité*

KEYWORDS: *Reactive powder concrete, extrusion, hydration, shrinkage, durability*

1. Introduction

Reactive Powder Concretes (RPC) constitute a particular type of cementitious materials developed in the early 1990s (Richard *et al.*, 1994, 1995; Aïtcin 2000) and characterized by ultra-high mechanical performances and very low porosity. After a specific heat treatment, their compressive strength lies between 200 and 800 MPa. RPC are mainly used in civil engineering projects as bridges or airports (Aïtcin 2000), or as repair materials for concrete structures (Denarié *et al.*, 2006; Lee *et al.*, 2007). Also, the low porosity of RPC gives excellent durability and transport properties, suitable for the storage of nuclear waste (Matte *et al.*, 1999). Their proportioning principles are based on the optimization of the microstructure (Bonneau *et al.*, 2000), by enhancing the granular packing and minimizing the inter-particle porosity. This is obtained by combining fines mineral particles (Portland cement, crushed filler, silica fume, fine sand) in the range of 0.02 to 600 microns, with very low water-to-cement ratio and high amount of high-range water-reducing superplasticizer (Richard *et al.*, 1994).

This cocktail of constituents, with very different physico-chemical properties and particle size distributions, results in a particularly dense skeleton with a wide range of rheological behaviors, from very viscous (Kuder *et al.*, 2007a) to highly flowable (Liu *et al.*, 2008). Nevertheless, the mix design of RPC remains a complex process because of the sensitivity of the mixture properties to even small changes in the constituent dosages. Another major obstacle to the wide use of these materials is their high cost compared to that of high or very high-performance concretes (Blais *et al.*, 1999).

The use of industrial making processes could enable to overcome these issues by ensuring both compliance with the mix design throughout the production chain and high production rates. From this point of view, the extrusion process seems to meet such requirements: it is an advanced processing technique already applied to a wide range of materials (food, polymer, clay and metal). In the field of cement-based materials, extrusion has proved to be an efficient technique, particularly adapted for the production of prefabricated elements with very high mechanical performances (Qian *et al.*, 2003; Kuder *et al.*, 2007b; Perrot *et al.*, 2007).

In this context, the present study is devoted to the development of extrudable RPC (ERPC), especially designed for the manufacture of tubular elements adapted to chemically aggressive environments. To this end, various RPC were prepared with varying dosages of polycarboxylate superplasticizer, silica fume and crushed quartz to obtain extrudable mixtures. Alongside their microstructural analysis by X-ray diffraction and scanning electron microscopy (Courtial *et al.*, 2011), the materials were characterized at fresh state (extrudability), at early age (hydration rate and autogenous shrinkage) and at longer term (mechanical strength, porosity and mass transfer parameters). The article proposes a cross-analysis of the ERPC properties measured before extrusion, and a comparative cost/benefits ratio analysis including other types of concretes.

2. Experimental procedures

2.1. *Materials and mixtures*

The ERPC studied were prepared with Portland cement (CEM I 52.5N, produced by Lafarge in Le Havre's plant), silica fume (commercialized by Condensil), crushed quartz powder (Millisil C500, Sibelco), siliceous sand (CV32, Sibelco), superplasticizer, noted SP (Cimfluid 2002, Axim) and water. The cement contained 3.30% of gypsum and its Bogue composition was 67.50% of C_3S, 10.70% of C_2S, 2.64% of C_3A, 12.80% of C_4AF. The chemical composition of the solid components of ERPC is provided in Table 1. Their density and fineness are given in Table 2. The SP used was a modified-polycarboxylate high-range water-reducing superplasticizer in liquid form with 35% of dry matter. The dosages of SP, indicated in Table 3, correspond to the mass ratio between the SP dry matter and the cement content.

The ERPC were manufactured by mixing the solid compounds with tap water in a 20-L mixer. The water-to-cement (W/C) ratio was equal to 0.16 for all the ERPC. The same mixing procedure, schematized in Figure 1, was rigorously applied for each batch. The total time of mixing was 25 min. The composition of the five ERPC mixtures investigated is given in Table 3.

It is important to note that all the tests presented in the following sections were performed on non-extruded ERPC samples.

Table 1. *Chemical composition (mass percentage) of the solid components of ERPC*

Constituents	Portland cement	Silica fume	Sand	Crushed quartz
CaO	64.58	-	< 0.023	< 300 ppm
SiO_2	21.39	93.50	> 98.7	> 98.9
Al_2O_3	3.66	6.10	< 0.6	< 8000 ppm
Fe_2O_3	4.25		< 0.045	< 800 ppm
MgO	0.96		-	-
K_2O	0.28		< 0.460	< 6000 ppm
SO_3	2.63		-	-
Na_2O	0.10	0.15	-	-

Table 2. *Fineness and density of the solid components of ERPC*

Materials	Portland cement	Silica fume	Crushed quartz	Sand
Specific surface area (m^2/kg)	382	14 000	1030	12.6

Unit weight (kg/m^3)	3200	2200	2650	2650

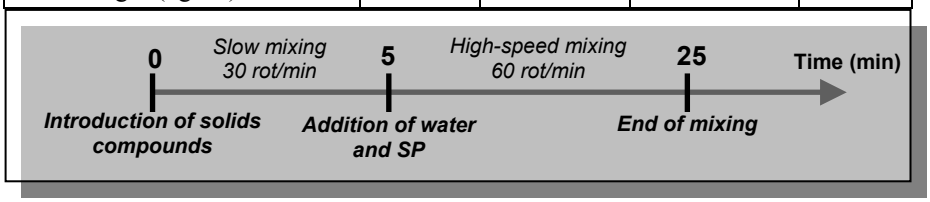

Figure 1. *Mixing procedure of ERPC*

Table 3. *Composition of ERPC (mass proportion)*

Mixtures	Portland cement	Sand	Silica fume	Crushed quartz	SP*	Water
ERPC_1	1	1.1	0.25	0	0.5%	0.16
ERPC_2	1	1.1	0.25	0	1.0%	0.16
RPC_3	1	1.1	0.25	0	1.8%	0.16
ERPC_4	1	1.1	0.25 × 3/4	0.25 × 1/4	1.8%	0.16
ERPC_5	1	1.1	0.25 × 3/4	0.25 × 1/4	2.0%	0.16

*: Superplasticizer

2.2. *Test procedures*

In order to control the test conditions, the experimental devices were placed in a temperature-controlled room at 20±1°C.

2.2.1. *Extrusion tests*

The extrusion tests were carried out with a ram extruder (home-made device) placed on a 50-kN compression test machine. The diameter and the length of the circular die were 1.2 cm and 3 cm, respectively. The experimental system is presented in Figure 2. Before each test, the sample was put under vacuum for 5 minutes, to de-aerate the material without losing significant amounts of water by evaporation. The barrel of the extruder was then completely filled with freshly-mixed material.

A pre-compression phase enabled to obtain a similar initial state of the various ERPC before extrusion. Then the extrusion started, and the ram drove down at a selected constant speed. During the test, the force exerted by the piston and its displacement were recorded. Different extrusion rates were applied to measure the effect of this parameter on the extrudability of the RPC.

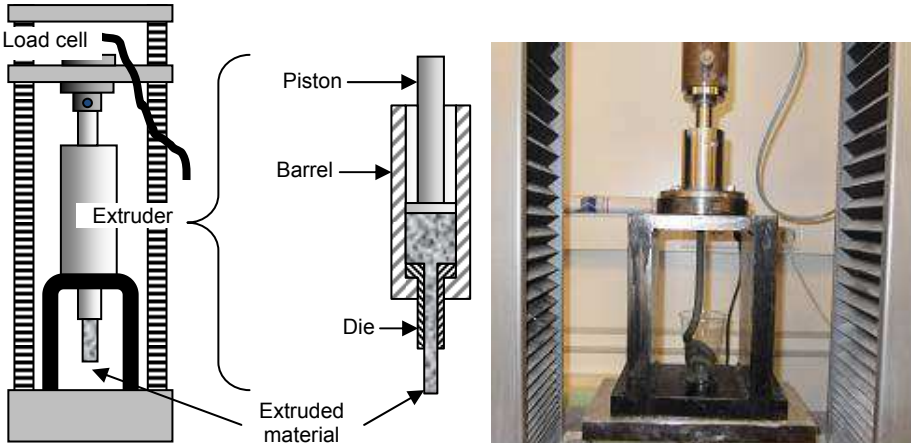

Figure 2. *Extrusion test device*

2.2.2. *Hydration rate*

Isothermal microcalorimetry (TAM Air apparatus) was used to compare the early-age hydration rate of the different ERPC. For each mix, two samples of about 4 g were taken from the same batch and placed into flasks immediately after mixing. The flasks were then loaded in the apparatus and the heat flow produced by the hydration reactions was recorded during the first six days at 20°C. The average curves from two samples of each mix were used for analysis.

2.2.3. *Autogenous strain*

Early-age autogenous strains of ERPC in free conditions were measured with a specific experimental system presented in previous articles (Bouasker *et al.*, 2008; Mounanga *et al.*, 2011a). It was a horizontal linear experimental system (Figure 3) inspired by the works of Laplante and Boulay (Laplante *et al.*, 1994) and Jensen and Hansen (Jensen *et al.*, 1995). The fresh material was cast in a molded, tight and very flexible PVC membrane and immersed in a thermostated water bath at 20±1°C. Waterproof contactless sensors were used to measure the longitudinal specimen displacements, which were automatically recorded by a data logging system connected to the sensors. This method made it possible to follow the deformations of the sample from its very early age.

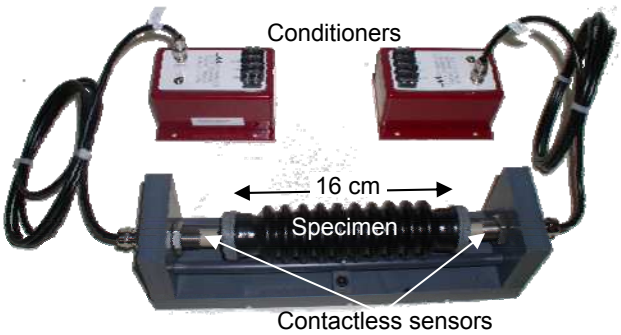

Figure 3. *Free linear autogenous shrinkage test device*

2.2.4. *Mechanical properties*

The 28-day mechanical properties of ERPC were determined on 40×40×16-mm prismatic specimens kept in autogenous conditions at 20±1°C until testing. The dynamic Young's modulus E_{dyn} was measured via impulse excitation tests with a Grindosonic® device. The mean value of three readings of the flexural resonant frequencies was adopted to determine the dynamic Young's modulus (Spinner *et al.*, 1961). The flexural strength R_F was obtained from the results of three-point flexural tests and the compressive strength R_C was determined on both parts of each specimen used for flexural tests. Each test was repeated at least three times and the results were used to calculate an average value of the mechanical performances.

2.2.5. *Porosity and transfer properties*

The gas permeability K_V, the water-accessible porosity n and the chloride diffusion coefficient D_e were measured on ERPC discs of 11-cm diameter and 5-cm thickness, aged of more than 90 days, oven-dried at 80°C for several weeks, until constant mass (± 0.01 g) and cooled during 48h in a desiccator at 20 ± 1°C.

The intrinsic gas permeability was determined using a Cembureau permeameter with nitrogen as the neutral percolating gas. The test method consisted in applying various differential pressures to the concrete disc and in measuring the steady flow of gas passing through the specimen (Picandet *et al.*, 2001). The intrinsic coefficient of permeability, as defined by Klinkenberg (Klinkenberg 1941), was then calculated assuming a laminar flow, compressible fluid and steady state of flow in the specimens.

The volume percentage of water-accessible porosity in ERPC specimens was estimated by successively measuring the mass of the ERPC discs in dry state, in saturated state and in hydrostatic conditions (saturated and submerged in water), according to the procedure proposed by the AFPC-AFREM (AFPC-AFREM 1997).

After the gas permeability and porosity tests, each ERPC disc was placed between two chambers containing solutions of NaOH (0.025 mol/L) and KOH (0.083 mol/L). NaCl (0.513 mol/L) was added in the upstream solution and a 12-V potential difference was applied between the two parallel sides of the concrete sample. The chloride concentration in the downstream tank was determined by means of potentiometric titration with a Metrohm SA CH- 9101 Herisau automatic titrator, with 0.05 molar silver nitrate ($AgNO_3$) titrant (Djerbi *et al.*, 2008).

3. Results and discussion

3.1. *Extrudability*

The extrusion tests were performed at various ram speeds (10, 20 and 40 mm/min) on the five RPC. Figure 4 presents an extrusion test and the "force-displacement" curves obtained on ERPC_1 and ERPC_2. At the die exit of the extrusion system, the self-supporting material left in a continuous manner and without cracks. In addition, the ERPC did not exhibit visible phase migration or separation of phases after extrusion. These observations prove the extrusion capacity of the ERPC. The "force-displacement" curves recorded during the extrusion tests could be segmented into three main parts (Aouadja *et al.*, 1997; Perrot 2006):

– The first part of the curves (Zone 1) was relative to a phase of non stationary flow due to the placing and the settling of the material into the barrel. The duration of this phase was particularly influenced by changes in the SP dosage: considering the other mix parameters as constant, we observed that an increase in the dosage of superplasticizer caused an extension of the Zone 1 (Figures 4.A and 4.B).

– The second part (Zone 2) corresponded to a zone of steady flow, showing the establishment of a permanent flow of the ERPC for a relatively constant extrusion force. At this moment, the material reached its plasticity threshold (Perrot 2006). The extrusion force, whose intensity corresponded to the horizontal stage of the curves, increased when the ram speed increased and decreased as the dosage of superplasticizer increased, for given dosages in solid constituents,

– The third phase (Zone 3) indicated the end of the test. It appeared when the piston approached the entry die. It was characterized by rapid changes in force for a small displacement of the piston. This phase corresponded to the compression of the dead zone of the extruder and the complete emptying of the die. The maximum capacity of the extruder system was then reached and the extrusion was stopped.

During these tests, only RPC_3 appeared as not extrudable because too fluid. Besides, the introduction of crushed quartz, coarser than silica fume, in the mix composition enabled to increase the viscosity of the mixture and to obtain extrudable concretes, even for high dosages of SP (ERPC_4 and ERPC_5). This result shows that the optimization of both dosages of crushed quartz and SP could allow to minimize the force needed for the extrusion of ERPC.

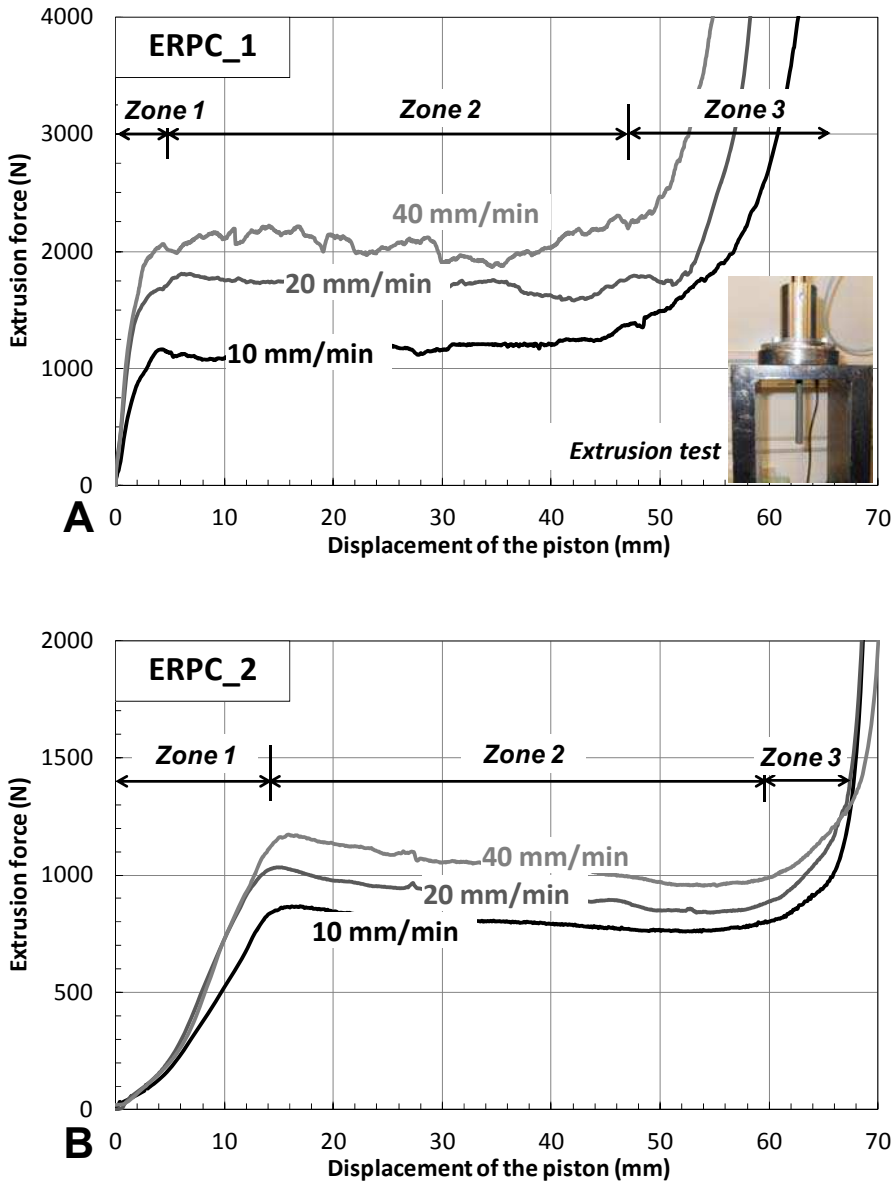

Figure 4. *Extrusion test results of ERPC_1 (A) and ERPC_2 (B) at three different ram speeds*

3.2. *Hydration rate*

Figure 5 presents the evolution of the heat flow of hydration monitored by isothermal microcalorimetry. Each curve is characterized by a dormant period with a very low evolution of the heat flow, followed by a peak marking a period of intense chemical activity. This early-age chemical activity of ERPC may be mainly attributed to Portland cement hydration, since it was shown that, at 20°C, the pozzolanic reactions of silica fume remained weak during several days (Mansoutre *et al.*, 1996; Loukili *et al.*, 1999), and even nil for crushed quartz (Zanni *et al.*, 1996). The peak of heat flow could therefore be associated with the hydration of C_3S, the major phase of Portland cement (Taylor 1990; Odler 1998). It occurred at 25.2, 40.7, 59.7, 55.4 and 58.6 h for ERPC_1, ERPC_2, RPC_3, ERPC_4 and ERPC_5 mixtures, respectively. The appearance of this peak was considerably delayed when comparing with the hydration rate of an ordinary Portland cement mortar, whose hydration peak usually developed within the first 12 h of hydration (Mounanga *et al.*, 2011b). This delay was caused by the high dosage of SP in ERPC, which induced an extension of the dormant period of the hydration reactions. This slowing down was particularly high for RPC_3 and also resulted in a significant decrease of the hydration peak intensity, as shown in Figure 5. This secondary effect of SP on cement hydration is well-known and explained by the adsorption of the polymers on cement grains, and also by possible reactions of the Ca^{2+} ions with polymer anions (Mollah *et al.*, 2000), which generate a global retardation of hydration.

The presence of crushed quartz enabled to partially limit the retardation effect of SP on hydration rate: indeed, the hydration peak of the ERPC_4-curve developed about 4 h before that of the RPC_3 curve, for identical SP dosage. The peak magnitude was also higher for ERPC_4, as compared with RPC_3, indicating a greater chemical activity at early age. This positive influence of crushed quartz on the advancement of reactions may be caused by an effect of nucleation site on the development of hydrates: Indeed, Cyr *et al.* (Cyr *et al.*, 2006) highlighted that the presence of very fine particles (with specific surface area higher than 100 m^2/kg) could activate the cement hydration by heterogeneous nucleation. This physical process is related to the nucleation of hydrates on foreign mineral particles and causes an acceleration of the early-age cement hydration and setting.

Several studies have shown that silica fume also has the ability to accelerate early-age cement reactions by nucleation and growth site effect (Cheng *et al.*, 1985; Lilkov *et al.*, 1997; Zelić *et al.*, 2000, for example). Some of these studies revealed that this accelerating effect depended on both the initial water content and the dosage of silica fume (Langan *et al.*, 2002; Kadri *et al.*, 2009). It seems that, for the ERPC investigated and the powder dosage considered here, crushed quartz was more efficient than silica fume in increasing early-age cement hydration rate.

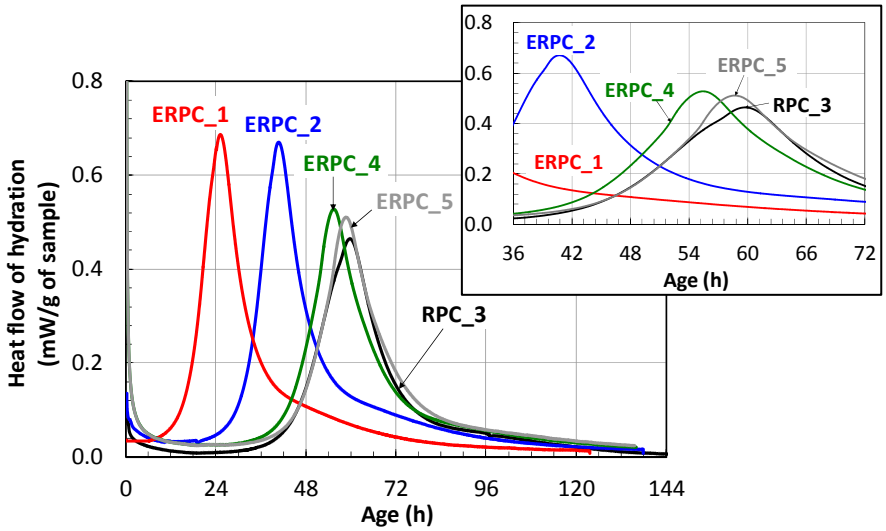

Figure 5. *Isothermal calorimetry curves of the ERPC*

3.3. *Early-age autogenous shrinkage*

Figure 6 shows the results of free linear autogenous shrinkage of ERPC at 20°C. As the deformations were monitored from the very first minutes after mixing, the autogenous strain measured was a combination of chemical shrinkage and self-desiccation shrinkage. Chemical shrinkage, also called Le Chatelier's contraction, develops before the setting of the matrix: it mainly corresponds to the dissolution of clinker minerals, hydration of anhydrite and precipitation of ettringite (Beltzung *et al.*, 2000), and to the negative balance between the absolute density of hydrates and those of the binder and water (Powers *et al.*, 1948; Mounanga *et al.*, 2004). The setting and the progressive water desaturation of the porous network leads to a second type of deformation, called self-desiccation shrinkage. Self-desiccation is directly linked to the initial water content of the cement-based material, a lower water-to-binder ratio giving higher self-desiccation shrinkage (Baroghel-Bouny *et al.*, 2006). The transition between chemical shrinkage and self-desiccation shrinkage is generally marked by the flattening of the autogenous shrinkage curve (Justnes *et al.*, 1996).

In our case, considering identical dosages of cement and water and low reactivity of the supplementary cementing materials at early-age, the gap between the autogenous shrinkage curves of the different ERPC may be due to both the varying SP content and the partial substitution of silica fume with crushed quartz. The hydration retardation induced by the SP, highlighted in the previous section, led to a delay of setting and an extension of the deformation phase dominated by chemical shrinkage. The development of the chemical shrinkage of the ERPC was particularly high during the first hours, while the main peak of hydration has not yet

appeared (Figure 5). This discrepancy between the relatively low heat release of the ERPC and the significant very early-age volume changes was closely related to the dosage in SP of the ERPC: indeed, RPC_3 (SP dosage = 1.8%) exhibited higher autogenous shrinkage values than ERPC_2 (SP dosage = 1.0%), whose autogenous shrinkage was higher than that of ERPC_1 (SP dosage = 0.5%). The flattening of the curves, which indicates the transition from chemical to self-desiccation shrinkage, also appeared later when the SP content increased. All other mix parameters being kept constant, the partial substitution of silica fume with crushed quartz induced a decrease of the autogenous shrinkage of ERPC_4, when compared to that of RPC_3 (Figure 6). This positive effect of crushed quartz on early-age autogenous strain can be linked to its acceleration effect on cement hydration rate (see section 3.2): it may be supposed that the presence of crushed quartz attenuated the SP retardation effect on the setting time of ERPC. Therefore, the material hardened more rapidly and resisted more efficiently to the strain imposed by Le Chatelier's contraction and the water desaturation of the porous network. Crushed quartz probably also led to a better particle packing and, consequently, to a re-organization of the porous network of the cementitious matrix: as the pore distribution is one of the major parameters controlling the evolution of self-desiccation (Jiang *et al.*, 2005), this effect of crushed quartz on the mitigation of early-age ERPC autogenous shrinkage, should be investigated more deeply. A third complementary explanation to the lower autogenous strain of ERPC_4 was the higher Young's modulus value of this mixture (Table 4): submitted to an identical internal capillary tension, it will shrink less than the other ERPC.

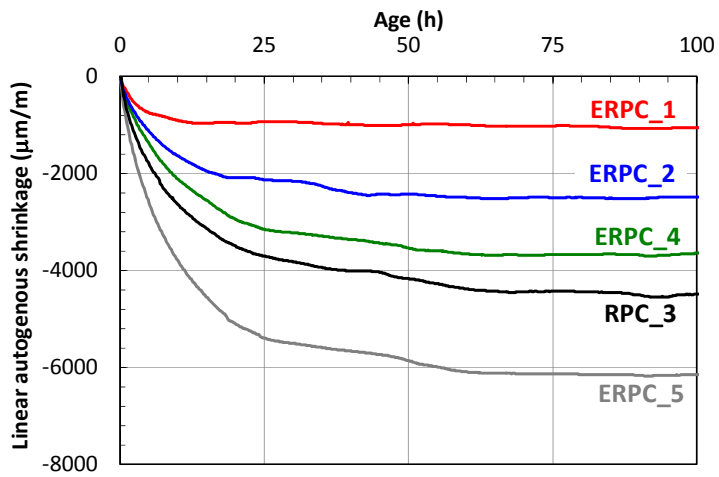

Figure 6. *Early-age linear autogenous shrinkage of the ERPC*

3.4. *Mechanical and transfer properties*

Table 4 provides the 28-day mechanical performances of ERPC, ordinary and high-performance concretes, for comparison. The ERPC compressive strength values were in the same range than those given by Richard and Cheyrezy (Richard *et al.*, 1995), for a RPC200 without fibers, cured at 20°C, and more recently by Yazici (Yazici 2007).

The increase of SP content resulted in a significant decrease of compressive strength and a simultaneous increase of Young's modulus. Indeed, the addition of SP generates a more homogeneous microstructure, promoting a better distribution of hydrates around the sand grains. This would prevent the phenomena of rigidification and locking created by contacts between solid grains. The SP may also play the role of a lubricant around some solid particles that are not in contact with the hydrates. The effect of SP content was less significant on flexural strength.

The partial replacement of silica fume with crushed quartz appeared to significantly improve the mechanical properties of ERPC: it led to an increase of 25% of the compressive strength, 20% of the flexural strength and 16% of the dynamic Young's modulus, for a constant SP content (Table 4). This improvement of mechanical performances could be explained by a better hydration of cement in presence of crushed quartz, as already observed on microcalorimetry curves (Figure 4) and by a better granular packing of the ERPC in presence of crushed quartz, which presents a particle size distribution intermediate between the cement and silica fume used (Cherkaoui *et al.*, 2010). Indeed, the optimization of the particle packing is the main way to obtain denser cement-based matrices and therefore greater mechanical performances (Richard *et al.*, 1995; Scrivener *et al.*, 2008)

The water-accessible porosity, the gas permeability and the chloride diffusion coefficient measured on ERPC specimens aged of more than 90 days are presented in Figures 7.a, 7.b and 7.c, respectively, and compared with bibliographical data on ordinary and high-performance concretes (Djerbi 2007). Because of the very low porosity of the ERPC, the measurement of their mass transfer properties was not an easy task. The gas permeability of the ERPC_4 and ERPC_5 mixes were too low to be detectable with the Cembureau permeameter. Moreover, the chloride migration test results highlighted the difficulties in saturating the ERPC porosity with conventional procedures (AFPC-AFREM 1997). The possible hydration of anhydrous cement, which is present in large proportion in RPC, and the potential interactions between cement and chlorides further complicated the result analysis. As expected, the water-accessible porosity was very low (Figure 7.a). The values obtained were close to those presented in previous studies: for example, Resplendino and Petitjean indicated water-accessible porosity values of RPC between 1.5 and 5% (Resplendino *et al.*, 2003). The absolute differences recorded between the porosity of the five ERPC were not high enough to conclude on a particular effect of SP or crushed quartz content. The gas permeability values of the

ERPC_1, ERPC_2 and RPC_3 specimens were 3.75×10^{-19} m^2, 1.62×10^{-19} m^2 and 2.56×10^{-19} m^2, respectively. The chloride diffusion coefficients of ERPC lay between 0.88 and 1.38×10^{-13} m^2/s. These results could be compared to those presented by Resplendino and Petitjean, who gave an oxygen permeability value lower than 10^{-19} m^2 and a chloride-ion diffusion factor equal to 2×10^{-14} m^2/s for an ultra-high performance concrete (Resplendino *et al.*, 2003).

Table 4. *28-day mechanical properties of ERPC. Comparison with an ordinary concrete (OC) and a high-performance concrete (HPC)*

Concretes	W/C ratio	E_{dyn} (GPa)	R_C (MPa)	R_F (MPa)	References
OC	0.49	42.0	46	-	Djerbi 2007
HPC	0.38	46.0	83	-	
ERPC_1	0.16	54.0	155	19.2	*Present study*
ERPC_2		59.1	150	18.6	
RPC_3		60.0	140	18.6	
ERPC_4		69.4	175	22.3	
ERPC_5		65.3	170	20.6	

4. Comparative cost/benefits analysis

The composition of RPC, rich in cement, silica fume and superplasticizer, makes them much more expensive than conventional concretes. Indeed, for the ERPC investigated, the dosages of cement, silica fume and superplasticizer range between 962 and 976 kg/m^3, 183 and 242 kg/m^3 and 13 and 56 L/m^3, respectively. The particularly high cost of RPC is one of the main obstacles to a wider use of these concretes, but this aspect is generally not addressed in the articles dealing with RPC. In 1999, Blais and Couture noted that, because of its cost, RPC will not replace conventional concrete where the ordinary concrete can economically meet performance criteria. RPC should rather be seen as a competitor with steel. Blais and Couture also underlined that the cost of RPC dropped one-third between 1997 (the year of the completion of the Sherbrooke pedestrian/bikeway bridge, the world's first major structure to be built with RPC) and 1999. When the Sherbrooke Footbridge was built, the cost of a 200-MPa RPC could be estimated at nearly $ 1,000 US/m^3 (Aïtcin 2003), about 870 €/m^3. In 2003, Aïtcin indicated that the same RPC could be made for $ 750 US/m^3 (650 €/m^3) and in the near future, it should be possible to produce it for $ 600 to $ 650 US/m^3 (520 to 570 €/m^3). Aïtcin also analyzed that even at $ 1,000 US/m^3, that is to say $ 400 US/ton (350 €/ton), for specific applications where durability and compressive strength were key factors, RPC could compete with structure steel that cost $ 1200 to $ 1500 US/t (1,040 to 1,300 €/ton in 2003).

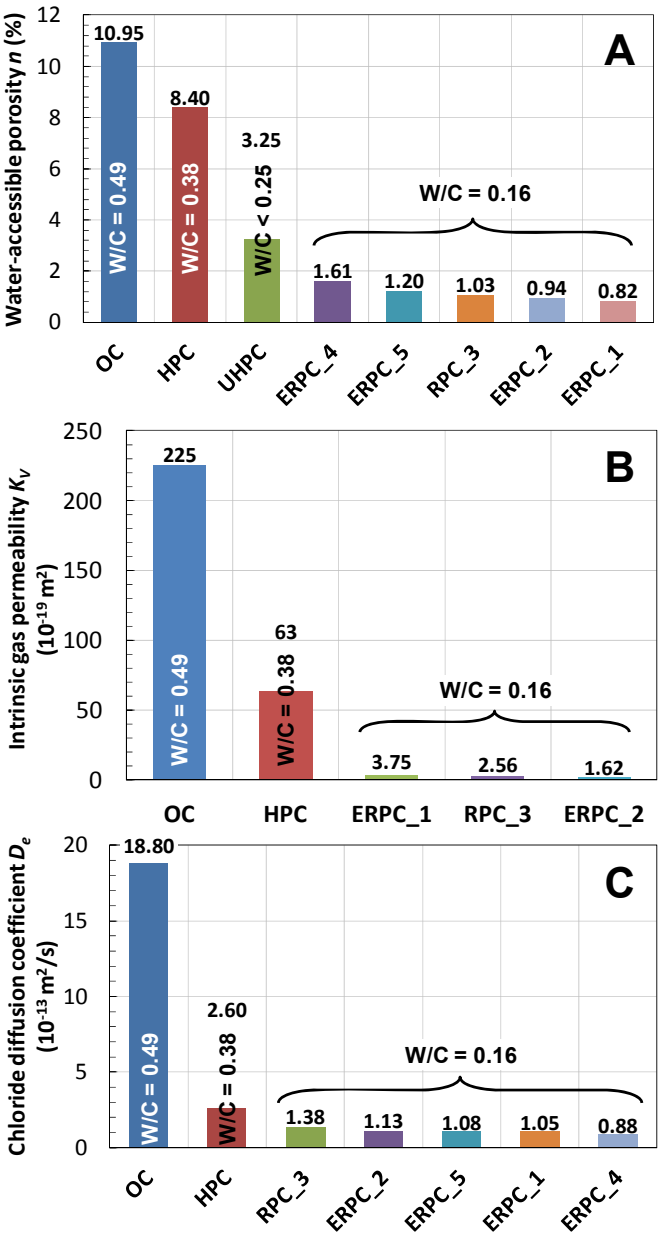

Figure 7. *Mass transfer properties of ERPC measured after 90 days of hydration. A: Water-accessible porosity; B: Intrinsic gas permeability; C: Chloride diffusion coefficient. Comparison with an ordinary concrete (OC), a high-performance concrete (HPC) (Djerbi 2007)*

To complete this analysis, the last part of the article is devoted to an estimation of the cost of the ERPC and a comparison of their cost/benefits ratio with those of an ordinary concrete (OC) and a high-performance concrete (HPC) whose properties were taken from the literature (Djerbi 2007). It is worth noting that the approach proposed is only estimative, since the concrete cost and the cost/benefits ratios do not only depend on the cost of the concrete constituents but also on the manufacture process of concrete.

The average costs of each component of concrete are recapitulated in Table 5. The most expensive constituents are the SP and the silica fume. For the latter, the cost is very dependent on the quality and the treatment applied to the material: it can vary from 500 €/ton for the grey silica fume to 2,000 €/ton for the white silica fume. These data were used to estimate the cost of the ERPC investigated. The high dosage of cement, silica fume and SP in ERPC results in a material cost up to 15 times higher than those of the ordinary concrete and high-performance concrete considered (Table 6).

However, the cost per m^3 of ERPC should be analyzed in terms of gain of performances. The performance ratios between each concrete and the ordinary concrete were calculated for the compressive strength R_C, the gas permeability K_V, the water-accessible porosity n and the chloride diffusion coefficient D_e (Table 6). Considering the mechanical properties, the HPC had the best cost/benefits ratio: the ratio between the cost of HPC and OC was about the same that the ratio between their compressive strength. For the ERPC, the cost ratio with OC ranged from 12.7 to 14.7, whereas their mechanical strength was multiplied only by a factor comprised between 3.0 and 3.8. The real benefits of ERPC appeared on their potential of durability: indeed, the performance ratios between ERPC and OC reached 140 for the intrinsic gas permeability, 13 for the water-accessible porosity and 21 for the chloride diffusion coefficient, far from the durability performance ratios between HPC and OC.

Table 5. *Average costs of main components of concrete, excluding transport*

Constituents	Cost (€/ton)	References
Cement	110	(SESSI 2007)
Silica fume	500 to 2000	Manufacturer's data (2011)
Crushed quartz	150	Manufacturer's data (2011)
Fine sand for RPC	80	Manufacturer's data (2011)
Aggregates	7	(Bodet 2003)
Superplasticizer (SP)	1640	Manufacturer's data (2011)

Table 6. *Comparative data of the cost and performances of concretes (the indicated costs are based on the cost of the concrete constituents and do not take into account the cost of manufacturing, transportation, and implementation of concrete)*

Concrete	Estimated cost		Performance ratios as compared with ordinary concrete (OC)			
	(€/m^3)	Ratio with the cost of ordinary concrete	$\frac{R_C}{R_C(\text{OC})}$	$\frac{K_V}{K_V(\text{OC})}$	$\frac{n}{n(\text{OC})}$	$\frac{D_e}{D_e(\text{OC})}$
OC	52	1	1	1	1	1
HPC	90	1.7	1.8	3.6	1.3	7.2
ERPC_1	696	13.4	3.4	60.0	13.4	17.9
ERPC_2	727	14.0	3.3	138.9	11.6	16.6
RPC_3	764	14.7	3.0	87.9	10.6	13.6
ERPC_4	660	12.7	3.8	> 140	6.8	21.3
ERPC_5	669	12.9	3.7	> 140	9.1	17.4

5. Conclusions

This research work focused on the development and the characterization of the fresh, the early-age and the durability performances of five reactive powder concretes (RPC), prepared with various dosages of superplasticizer and a partial replacement of silica fume with crushed quartz. The analysis of the results highlighted the following key points:

- Among the five RPC manufactured, four of them exhibited properties of extrudability. The extrusion tests, conducted at different ram speeds, gave a homogeneous, continuous and visible crack-free extrudate of these concretes;
- The replacement of 25% of silica fume with crushed quartz showed significant positive effects on the hydration rate, the development of early-age autogenous shrinkage, the 28-day mechanical performances and the long-term mass transfer properties of the extrudable reactive powder concretes (ERPC);
- The cost/performances ratio analysis of the ERPC underlined that the major advantage of these concretes lies in their exceptional potential of durability rather than in their mechanical strength, when comparing with conventional and high-performance concretes.

This work was conducted to optimize the composition of the ERPC matrix, free of fibers. The study of both the effect of fibers on the behavior of ERPC and the feasibility of extruding tubular pieces will be the next steps of this research work.

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