Cement & Concrete Composites 33 (2011) 380–388

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Evolution of the mechanical behaviour of a high performance self-compacting concrete under drying

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ARTICLE INFO

Article history:
Received 19 January 2010
Received in revised form 3 December 2010
Accepted 7 December 2010
Available online 15 December 2010

Keywords:
High-performance concrete
Drying
Uniaxial compression
Bending strength
Micro-cracking

ABSTRACT

Mechanical behaviour of cement-based materials is strongly influenced by drying. In order to evaluate only drying effects on mechanical behaviour, it is necessary to conduct the studies on mature materials, i.e. materials for which the strength increase due to hydration has already reached stabilization with an adequate curing regime. Previous studies on two mature mortars with large water-to-cement (w/c) ratios of 0.5 and 0.8 showed that, during drying, there is the occurrence of a competitive effect which controls the evolution of the mechanical behaviour. The competitive effect occurs between the increase in material strengthening due to capillary suction and hygral gradients and drying induced micro-cracking due to material heterogeneities and differential shrinkage. This effect depends on the quality of the binder paste. Therefore, a high performance self-compacting concrete, i.e. a high performance material, with water-to-binder (w/b) ratio of 0.41 is cast to study the evolution of the mechanical behaviour under drying conditions. Uniaxial compression and bending tests are carried out on samples subjected to air-drying (21 ± 1 °C and 60 ± 5% R.H.) and/or oven-drying (60 °C and 10% R.H.). The results reveal that the competitive effect also has a great influence on the mechanical behaviour of high performance materials. The uniaxial compressive strength of the high performance self-compacting concrete increases while its bending strength decreases with air-drying. This shows the higher sensitivity of bending strength to the drying induced micro-cracking. In the case of accelerated drying in the oven, the drying induced micro-cracking strongly affects the uniaxial compressive strength, Young's modulus and bending strength in spite of a higher paste quality leading to lower porosity. The maximum size of the aggregates seems to play an important role in this deterioration of mechanical properties, especially in the case of accelerated drying. Drying induced micro-cracking is made clearly visible by hydraulic oil impregnation.

1. Introduction

Mechanical behaviour of cement-based materials depends greatly on their hygral state which evolves under environmental conditions. Due to the hygral imbalance between early-age concrete and ambient conditions, concrete structures are subjected to drying that can affect their durability. Steep hygral gradients are created because of the low permeability of concrete and structure geometry [1–9]. Shrinkage is a macroscopic consequence of drying. However, drying shrinkage is prevented by structural and local effects. These restraints of shrinkage produce stress that can exceed the tensile strength, leading to the appearance of surface micro-cracks [1–4,7,9]. Micro-cracking also occurs at the interface of the hydrated cement paste/stiff inclusions [10,11], and seems to be dominant [12]. The induced micro-cracking appears in any concrete structure [3,13,14]. It increases the permeability [10,15] and modifies the elastic properties and the failure process of the material. The coupling between the mechanical behaviour and the various effects of drying will then have a direct impact on the durability of concrete structures.

In the context of the present work, the evolution of the mechanical behaviour of solely mature cement-based materials during drying is under discussion. Previous studies on the compressive behaviour of concretes [5,6,8,16] and mortars [17–19] showed the occurrence of a competitive effect during drying. Indeed, there is an increase in isotropic capillary pressure (suction) with drying [4,8]. This capillary suction acts on the material as an isotropic pre-stressing and leads to an increase in material rigidity. This phenomenon is amplified by hygral gradients [4–6,8] which result in a confining effect of the sample's core, leading to higher mechanical properties. The strengthening effect due to capillary suction and hygral gradients is countered simultaneously by the drying induced micro-cracking due to material heterogeneities and

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doi:10.1016/j.cemconcomp.2010.12.002

differential shrinkage [1–4,7,9–12]. Therefore, the mechanical behaviour evolves under the competitive effect between strengthening of material and induced micro-cracking during drying. The same competitive effect is also at the origin of the elastic modulus decrease [9,15–22] that occurs during significant drying induced micro-cracking. On the other hand, the flexural behaviour of mortars [21,23,24] and concretes [25,26] is also influenced by drying induced complex phenomena that depend on the composition of the material and its curing/maintenance. All of the above cited research works were performed on ordinary strength cement-based materials. Moreover, our previous studies performed on two mature mortars with large w/c ratios of 0.5 and 0.8 showed that the aforementioned competitive effect depends on cement paste quality: the strengthening effect is dominant for materials with good paste quality (i.e., lower porosity which generally signifies lower permeability and higher tensile strength) while materials with low paste quality are more sensitive to drying induced micro-cracking (see [17,19] for more details).

For high performance materials, which generally have high paste quality, the effects of drying on the mechanical behaviour have not received adequate attention, even though there is a large amount of results on drying shrinkage of such materials. Thus, the main objective of this work is to understand the effects of drying on the hygro-mechanical behaviour of a high performance material. Is there always a variation of mechanical properties under the above cited competitive effect? And if so, what factors could explain it? The proposed experimental study is performed on a high performance self-compacting concrete (HPSCC). The experimental study investigates the variation of mechanical properties under the aforementioned competitive effect, and what are the primary factors. Compared to two mortars studied previously [17,19], HPSCC has a lower water-to-binder (w/b) ratio, a higher cement strength class, a higher paste quality, and also contains coarse aggregates. The mechanical behaviour is evaluated from saturated state to dried state, and by means of uniaxial compressive strength, Young's modulus and bending strength. Uniaxial compression and bending tests also made it possible to show which is more sensitive to drying induced micro-cracking. The presence of the drying induced micro-cracking is shown by hydraulic oil impregnation. On the other hand, two types of conditioning, i.e. air-drying (21 ± 1 °C and 60 ± 5% R.H.) and rapid oven-drying under moderate temperature (60 °C and 10% R.H.), are applied on test samples to compare the effects of natural and accelerated drying on the evolution of mechanical properties.

2. Experimental investigation

The experiments were set up so as to be able to follow the evolution of the hygro-mechanical behaviour immediately after material casting. The material composition is given in Table 1. The gravel (4/10 mm) was crushed while the sand (0/4 mm) was rolled, the two aggregates being silicocalcareous. Cement CEM I 52.5 N CP2 and limestone filler were used to manufacture the high performance self-compacting concrete according to the AFGC (Association Française de Génie Civil) recommendations [27]. The high range water reducer admixture was a polycarboxylate modified superplasticizer. Cylindrical ($Ø160 \times h320\,mm^3$) and prismatic ($40 \times 40 \times 160\,mm^3$) samples were manufactured to conduct the study. Two contradictory reasons led us to choose this material. Indeed, as this study aimed to evaluate only drying effects on a high performance material, it was necessary that all variations due to hydration process, i.e. strength increase due to hydration and endogenous shrinkage, reach stabilization before looking at the influences of drying. If not, the hydration and the drying processes will occur simultaneously and it will be very difficult to clearly distinguish the effects of drying alone on mechanical properties. However, the high performance materials have a w/b ratio lower than 0.5. But the lower the w/b (or the w/c) ratio is below 0.5 the longer the curing period is to obtain a material with no further variation of strength due to hydration [28,29] and no further variation of endogenous shrinkage [14]. The chosen material ($w/b = 0.41$) was thus an acceptable compromise. Indeed, this material made it possible to obtain high strength with a low capillary porosity and a very high hydration level in a short timescale with an adequate curing regime. Samples were stored 1 day after casting in lime water at 21 °C for an optimal maturation, i.e. a material for which the increase in strength due to hydration reaches stabilization. After this curing period (maturation period) in water, the variation of endogenous shrinkage can also be considered as weak, even negligible, due to a high hydration level [14]. Uniaxial compression and bending tests were carried out on samples during the curing period in water. These tests were accompanied by porosity measurements (the porosity was determined by the knowledge of the saturated and oven-dried mass of each sample. The dried mass was obtained after drying saturated samples in an oven at 60 °C until constant weight. The apparent volume of each sample was determined using a pycnometer). As can be seen on Figs. 4 and 8 (curves of samples in water), a curing period of about 75 days in water can be considered as sufficient because the compressive and bending strengths become almost constant. At this stage, the porosity is already well formed (see Figs. 2 and 3). This means that, after this curing period in water, there will be no further hydration and endogenous shrinkage effects at the macroscopic level on strength and elastic modulus evolutions with drying. Therefore, the study of the drying influence on the mechanical behaviour was only carried out after 75 days of storage of samples in water (from which the samples can be easily considered as saturated) by conditioning samples in the following ways (see also Fig. 1):

- a part of the prismatic samples was removed from water after 75 days and left in drying in a controlled atmosphere with temperature = 21 ± 1 °C and relative humidity = 60 ± 5% (air-dried samples),
- another part of the prismatic samples and cylindrical samples were submitted to rapid drying in an oven at a moderate temperature of 60 °C until constant weight after 75 days water maturation, the relative humidity measured in the oven being equal to a maximum of 10 % for those samples (oven-dried samples). This moderate temperature makes it possible to obtain a satisfactory drying of the porous network without removing chemically linked water of samples [7].

This last conditioning enabled comparison of the drying effects due to a natural process with the drying effects due to an accelerated drying. To carry out this comparison in a reasonable time, small prismatic moulds of $40 \times 40 \times 160\,mm^3$ were used to obtain samples. Indeed, the process of drying is slow. This slow speed is accentuated by a high level of maturity leading to low permeabil-

Table 1
Composition of the high performance self-compacting concrete.

Component	HPSCC (kg/m^3)
Gravel (4/10)	793.9
Sand (0/4)	980.5
Cement CEM I 52.5N CP2	397.0
Limestone filler	109.2
Superplasticizer	6.4
Water	170.2
Water/binder (w/b)	0.41

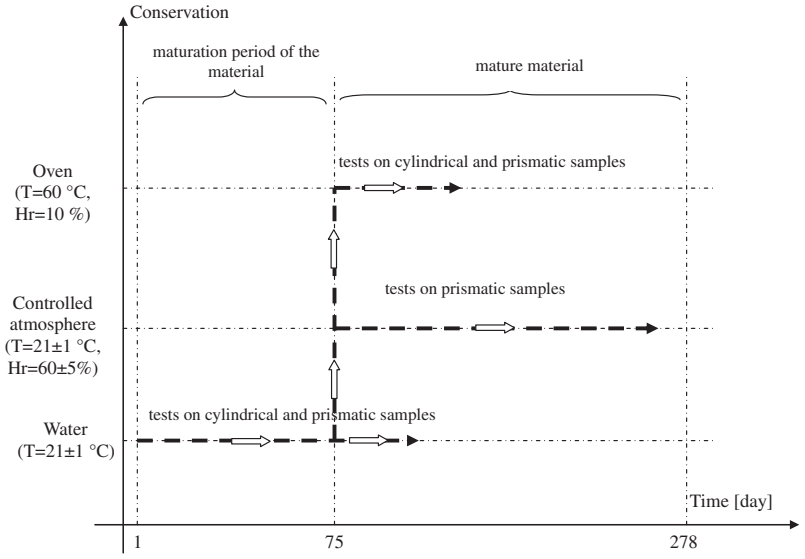

Fig. 1. Schematic representation of the experimental campaign sequences.

ity. A rapid drying process was also necessary for the large sample sizes in order to obtain the necessary parameters to characterise the mechanical behaviour in a reasonable time (for example, 10 years of drying would be necessary to obtain hygral equilibrium of a Ø160 × *h*320 mm^3 cylindrical sample within surrounding ambient air [4]). Moreover, conditioning at a temperature of 60 °C enabled the mechanical behaviour evolution to be characterised from a saturated state to a dry state (for example, there is no further variation of mass).

The study was carried out with the following tests and measurements according to the two conditioning modes cited above:

- uniaxial compression tests on cylindrical samples (Ø160 × *h*320 mm^3) with measurement of elastic modulus,
- three-point bending tests on prismatic samples (40 × 40 × 160 mm^3),
- uniaxial compression tests on cubic samples (40 × 40 × 40 mm^3) by using the half-prisms obtained after bending tests,
- measurement of weight loss of samples with time.

A hydraulic press with a capacity of 3000 kN was used to carry out the compression tests on cylindrical samples (Ø160 × *h*320 mm^3), in accordance with the European Standard EN 12390-1, with a loading velocity of 10 kN/s (European Standard EN 12390-3). During those tests, Young's modulus was also measured, at the third cycle of loading (10 MPa) in order to avoid any unstable response of the samples at the beginning of test [16]. To ensure a perfect transmission of the load and thus to reduce to minimum the bending effect, all the samples were surfaced and a rotating plate system was used.

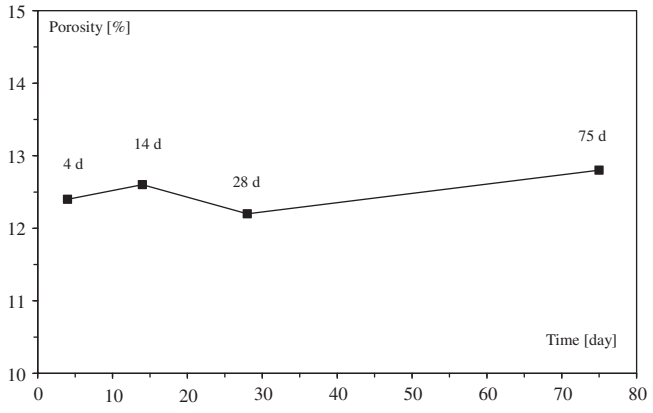

Fig. 2. Average porosity of samples (40 × 40 × 80 mm^3) stored in water versus time.

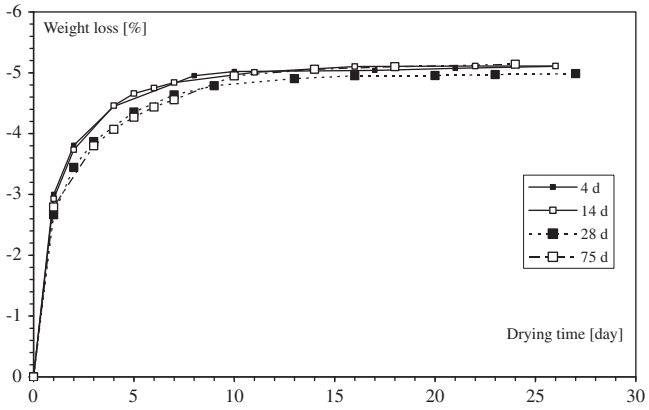

Fig. 3. Average weight loss of samples (40 × 40 × 80 mm^3) versus drying time in the oven at 60 °C after 4, 14, 28 and 75 days stored in water.

Three-point bending tests were carried out using a classical machine, with a capacity of 6 kN, on prismatic samples (40 × 40 × 160 mm^3) with a loading velocity of 0.05 kN/s ± 0.01 kN/s (European Standard EN 196-1). After the failure of the sample in flexural test, the two parts of each prism were subjected to compressive stress with the help of a device consisting of two steel plates of 40 mm width, with a loading velocity of 2.4 kN/s ± 0.2 kN/s (European Standard EN 196-1). The top of the device is equipped with a rotating plate while the bottom of the device is fixed. The loaded fraction of the half-prism sample is a cube of 40 × 40 × 40 mm^3.

For each conditioning, two prismatic samples for the bending test (which means four prismatic samples for the compression test) and two cylindrical samples for the compression test were used. However, only the average values will be presented for reasons of clarity.

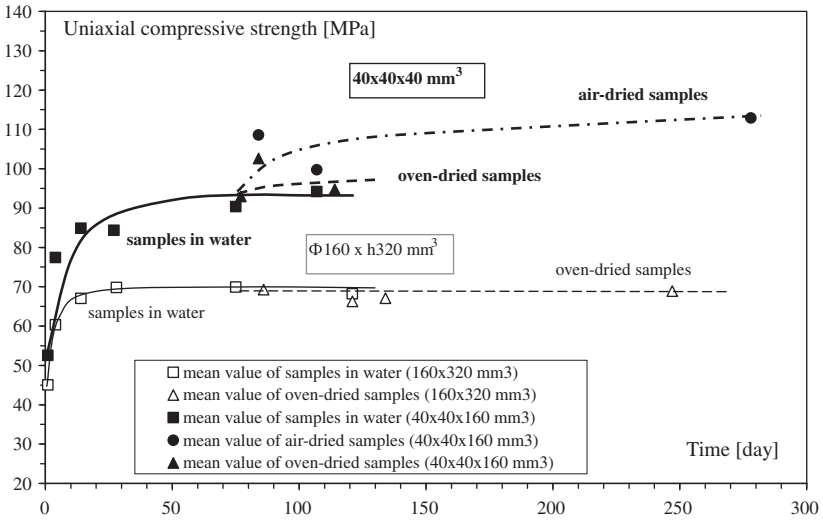

Fig. 4. Uniaxial compressive strength of the cubic ($40 \times 40 \times 40$ mm^3) and cylindrical samples ($Ø160 \times h320$ mm^3) versus time for different conditioning modes. The air-drying and oven-drying of samples begin after 75 days of maturation in water.

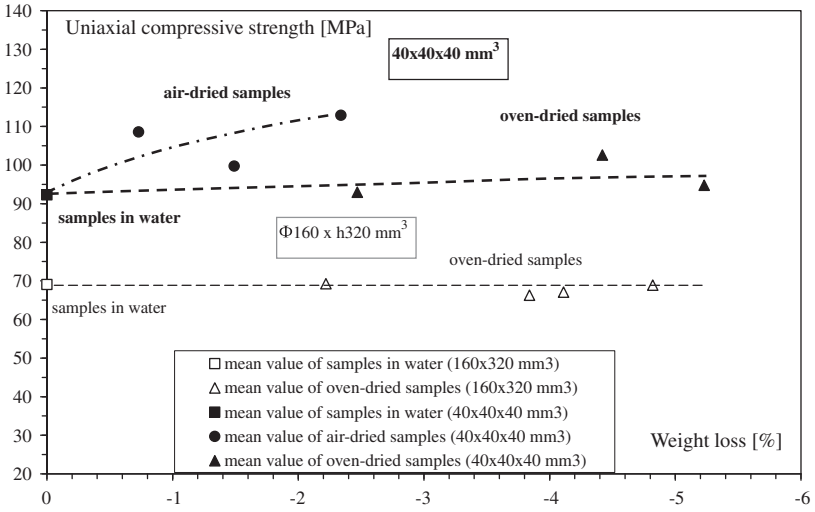

Fig. 5. Uniaxial compressive strength of the cubic ($40 \times 40 \times 40$ mm^3) and cylindrical samples ($Ø160 \times h320$ mm^3) versus weight loss, after 75 days of maturation in water.

3. Results

3.1. Evolution of porosity during maturation process

Fig. 2 shows the evolution of average porosity of prismatic samples ($40 \times 40 \times 80$ mm^3) at different maturation time in lime water, from 4 to 75 days. There is no important evolution of porosity with time: the maximum and minimum values of porosity measured between 4 and 75 days are respectively 12.8% and 12.2%. This porosity is constituted principally of capillary porosity and C–S–H "gel" porosity. Notice that according to Powers et al. [30], just 3 days are sufficient to obtain the interruption of the capillary porosity connectivity of a cement paste with $w/c = 0.40$ (during the oven-drying process to obtain dried state, rapid hydration would take place in samples, especially at early ages that would reduce the porosity. This can explain why the porosity at 4 days is lower than at 14 days). Therefore, we can assume that the microstructure is well formed 4 days after casting. This is confirmed by Fig. 3 where the weight loss of samples used to determine porosity is plotted versus time during oven-drying. It can be seen that the longer the sample is kept in water, the more the kinetics of drying decreases at the beginning of drying. However, after about 15 days, all the samples have very similar weight loss. This means that the porosity does not change but becomes finer with hydration. The average porosity of the mature HPSCC is equal to 12.5%. According to previous studies conducted on concretes, a large part of this porosity is due to that of the C–S–H "gel" [31].

3.2. Drying effects on compressive and flexural mechanical behaviours

3.2.1. Uniaxial compressive mechanical behaviour

Fig. 4 shows the strength evolution of the cylindrical ($Ø160 \times h320$ mm^3) and cubic samples ($40 \times 40 \times 40$ mm^3) for different conditioning modes and drying time. All the compression tests on the air-dried and oven-dried samples are carried out after 75 days of maturation in water. For the cylindrical samples, rapid drying in the oven (Δ) does not lead to variation of the strength, which follows the same evolution as that of the samples in water (□). For the cubic samples, strengths of the samples subjected to drying increase, in particular for the air-dried samples (●) com-

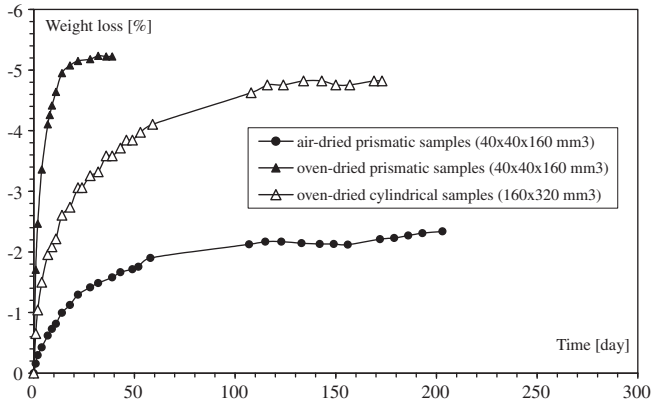

Fig. 6. Average weight loss of the air-dried and oven-dried prismatic samples ($40 \times 40 \times 160\ mm^3$) and of the oven-dried cylindrical samples ($Ø160 \times h320\ mm^3$) versus time, after 75 days of maturation in water.

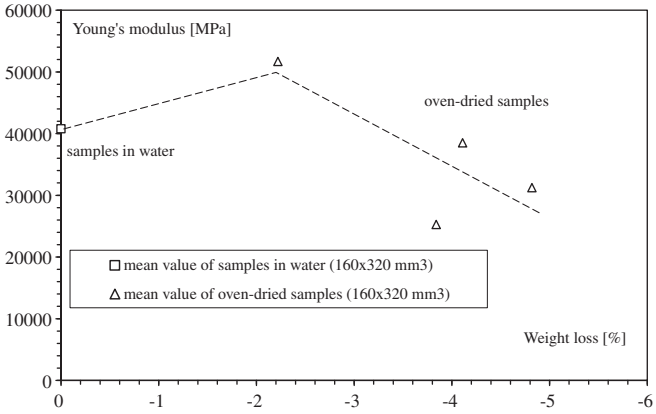

Fig. 7. Young's modulus of the cylindrical samples ($Ø160 \times h320\ mm^3$) versus weight loss, after 75 days of maturation in water.

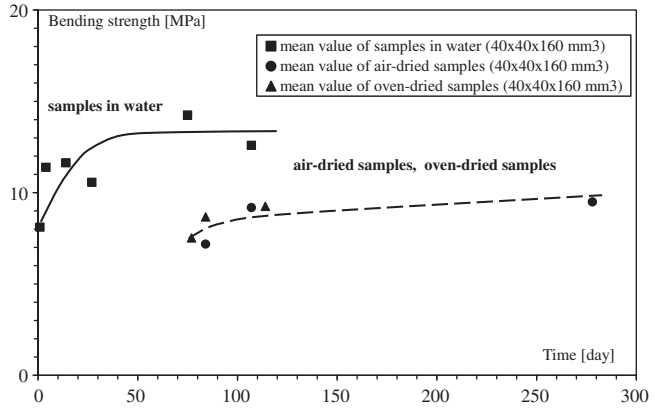

Fig. 8. Bending strength of the prismatic samples ($40 \times 40 \times 160\ mm^3$) versus time for different conditioning modes. The air-drying and oven-drying of samples begin after 75 days of maturation in water.

pared to the saturated ones (■). Notice that the tests performed on water stored samples after 75 days of maturation (the last point of saturated curves ■ and □) do not show any substantial variation of strength due to possible continuation of hydration.

Fig. 5 gives the strength evolutions of the two types of samples versus weight loss after 75 days of maturation. In this figure, a weight loss of 0% corresponds to the saturated state, and the strength value of water stored samples (■ and □) corresponds to the mean value of the tests carried out from 75 days and more. The weight loss of the prismatic and cylindrical samples with time according to conditioning mode is plotted on Fig. 6. Oven-drying accelerates the drying process: a weight loss more than twice higher is obtained for the prismatic samples after oven-drying during a short time. Moreover, the weight losses of the oven-dried prismatic and cylindrical samples are close, with however, longer drying time for the cylindrical samples. Fig. 5 shows that the increase in strength of air-dried cubic samples ($40 \times 40 \times 40\ mm^3$) is about 22% from the value obtained for samples in water. This increase is only about 5% after oven-drying of samples. Moreover, for the same weight loss, the oven-dried samples have lower strength than the air-dried samples. As previously pointed out, there is no significant strength variation for the oven-dried cylindrical samples ($Ø160 \times h320\ mm^3$). Moreover, Figs. 4 and 5 highlight the influence of two size (scale) effects on uniaxial strength (see Section 4.1). The first is that the compressive strength of cubic samples is higher than that of cylindrical samples for any samples' conditioning mode. The second is linked to the fact that the strength of cubic samples slightly increases with oven-drying whereas that of cylindrical samples does not change.

Fig. 7 shows the evolution of Young's modulus of the cylindrical samples versus weight loss. Young's modulus value of samples in water corresponds to the mean value of the tests carried out from 75 days and above. After a first increase, about 23%, Young's modulus decreases with weight loss, by approximately 31% in comparison with the value of samples in water.

3.2.2. Bending strength

Fig. 8 gives the evolution of the bending strength for different conditioning modes and time. Drying, in the controlled ambient air or in the oven, leads to an important decrease in strength, of approximately 44%. However, after this first stage, the bending strength begins to increase with drying to have a final net decrease of 31%. This is clearly shown on Fig. 9, which illustrates the evolution of the bending strength versus weight loss. Furthermore, for the same weight loss (between 2% and 2.5%), the oven-dried samples have lower bending strength than the air-dried samples as was the case for uniaxial compressive strength. Notice that the variation of bending strength occurs between the same upper (strength value of water stored samples) and lower limits (strength value of air-dried or oven-dried samples).

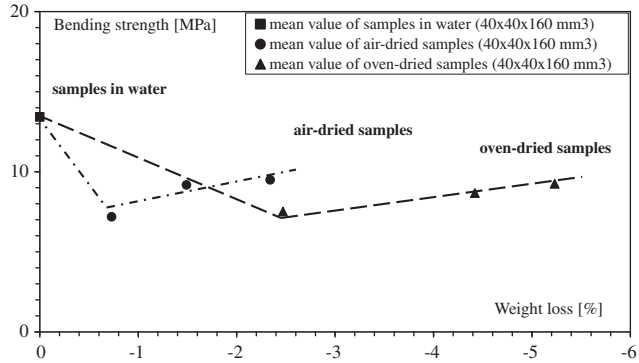

Fig. 9. Bending strength of the prismatic samples ($40 \times 40 \times 160\ mm^3$) versus weight loss, after 75 days of maturation in water.

4. Discussion on the influences of drying on the mechanical behaviour

4.1. Uniaxial compressive strength

The higher increase in strength of cubic samples with air-drying compared to oven-drying, 22% versus 5% (Figs. 4 and 5), would be explained by the kinetics of drying under the two conditioning modes. Indeed, drying in the ambient air being slow (Fig. 6), the capillary suction and the hygral gradients develop slowly. As the intensity of these two phenomena is low compared to that under rapid drying in the oven, the stress induced by drying shrinkage can be more relaxed by creep [32] and induced micro-cracks remain weak. Therefore, a higher increase in the compressive strength of the air-dried samples is measured. Rapid drying in the oven prevents the relaxation of stress due to drying shrinkage by creep [32]. This leads to the immediate creation and propagation of the micro-cracks which counterbalances the increase in strength due to capillary suction. A part of these micro-cracks can also be due to the thermal gradients at the temperature of 60 °C and come to be added to the previous ones. As a consequence, a slight increase of the compressive strength is observed (5%). The fact that the oven-dried samples have lower strength than the air-dried samples for a given weight loss (see Fig. 5) confirms the presence of more drying induced micro-cracks in the oven-dried samples. As for oven-dried cylindrical samples, as they are larger than the cubic samples (size effect), the hygral gradients remain longer in samples, creating thus more micro-cracks. This is why the strength does not increase.

The occurrence of drying induced micro-cracking is put in evidence by the following experiment. After the maturation period, samples were cut and their surfaces polished then they were subjected to oven-drying at 60 °C. After reaching constant weight, they were cooled for 24 h to be at ambient temperature. Then, the polished and non-polished surfaces were impregnated with hydraulic oil in order to visualize the possible induced cracks. Fig. 10a–c shows the cross section of a prismatic sample before drying, after drying, and after drying and impregnation with hydraulic oil, respectively. Fig. 10c illustrates drying-induced cracks which propagate between and sometimes around aggregates, as shown by

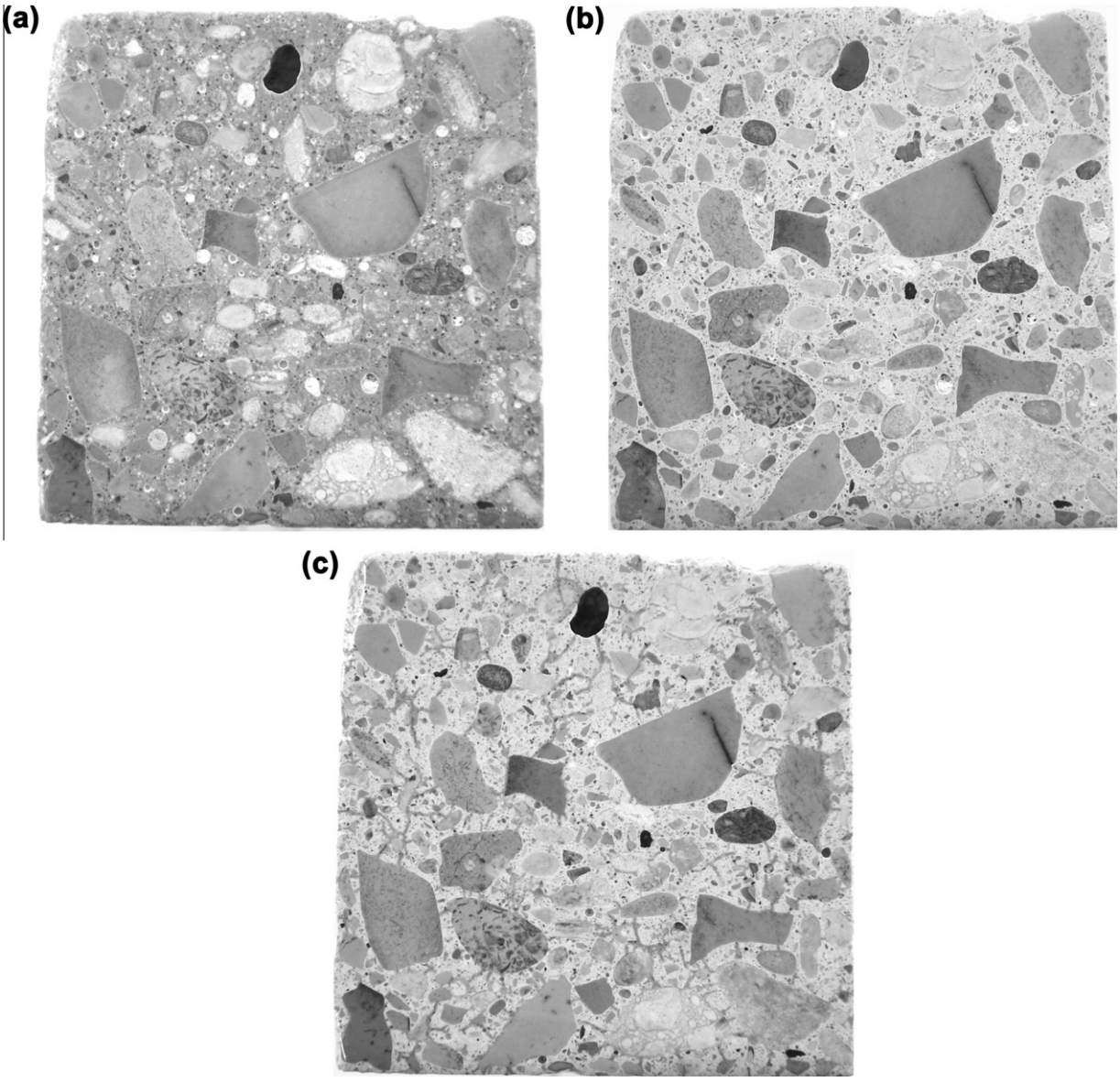

Fig. 10. Evolution of the cross section and lateral surface of a prismatic sample ($40 \times 40 \times 160\ mm^3$) with drying: (a) cross section before drying, (b) cross section after drying, (c) cross section after drying and impregnation, (d) lateral surface after drying, and (e) lateral surface after drying and impregnation.

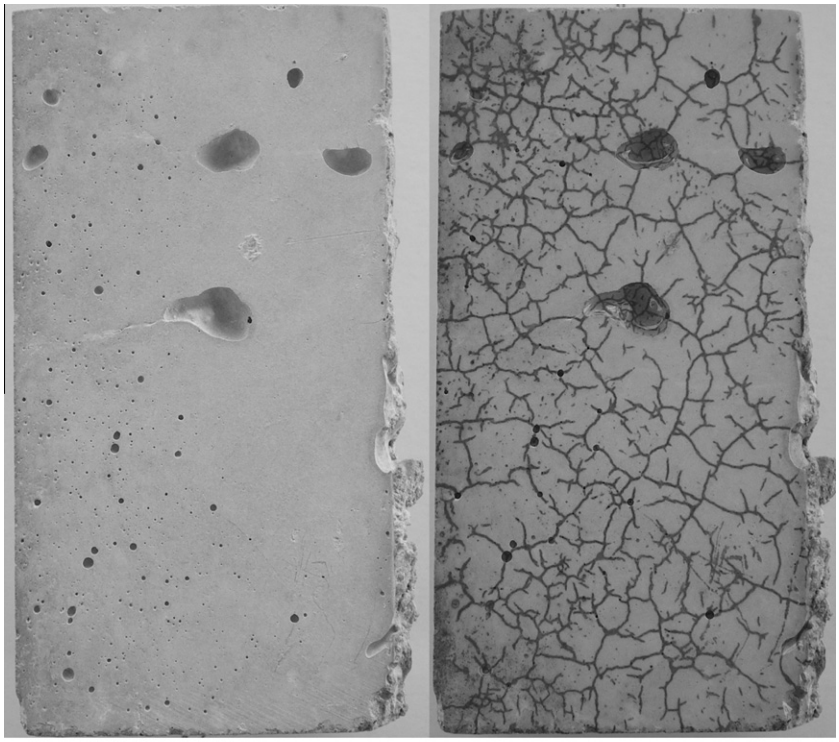

Fig. 10 (*continued*)

Bisschop et al. for glass balls [11]. This is the evidence that drying leads to the reduction of the strength between aggregates and binder paste by inducing micro-cracks. As Fig. 10d and e shows, this induced cracking, observed on all surfaces of the sample, is much more visible on non-polished lateral surfaces. This is due to more elevated matrix presence at lateral surfaces. Of course, the same phenomena are observed from a cross section of cylindrical samples.

The increase of mortar and concrete uniaxial compressive strength with air-drying similar to that of the HPSCC is also reported in literature whether the drying of samples is homogenous [21,24] or not [16–19,28]. Price [29] has even found on concrete samples ($w/c = 0.51$) a slight decrease in strength after sufficient air-drying following an initial increase. When samples are oven-dried up to constant weight, uniaxial strength either decreases very slightly [17,18] or increases [21,24] compared to the final air-dried samples' strength. As the composition, conservation and conditioning of tested materials are different, it is very difficult to compare these results from literature. However, as we have already studied a mature mortar with $w/c = 0.5$ to analyse the drying effects (for more detail see [17–19]), and some of this mortar's samples have been tested under the same oven-drying conditions as those HPSCC, it is possible and useful to make a comparison of the obtained results. The principal parameters of the two materials are recapped in Table 2. The HPSCC has a better paste quality and a little more aggregates in comparison to the mortar. For the mortar the difference between the strengths of air-dried and oven-dried samples is very small and they increase respectively by 24% and 22% compared to water saturated samples. For the HPSCC this increase is 22% for air-dried cubic samples and 5% for oven-dried cubic samples respectively. Moreover, no strength variation is measured for oven-dried cylindrical samples compared to water saturated samples. As the paste quality of the HPSCC is better than that of the mortar, the drop of the HPSCC strength under oven-drying comes mainly from the presence of large aggregates. On the other hand, more aggregates in HPSCC cannot explain the decrease in strength. It is the maximum size of the aggregates which plays an important role in the strength evolution (10 mm for HPSCC versus 2 mm for mortar): the higher the maximum size of the aggregates the more these aggregates can prevent the paste from shrinking. This reveals the great influence of the big size aggregates on the induced micro-cracking development. Indeed, in spite of a higher paste quality, the strength of HPSCC is more influenced by oven-drying induced micro-cracking. Notice that Bisschop et al. [11] have already pointed out the effect of aggregate size on the induced micro-cracking development, but these authors only studied drying induced micro-cracking in composite materials made using the same size of glass balls.

Notice that when the samples of low permeability, like those of HPSCC, are tested close to complete saturation, the pore water pressure increases during uniaxial compressive mechanical loading. This induced over-pressure amplifies opening and propagation of micro-cracks. A particular study carried out on the mortar with $w/c = 0.5$ demonstrated that there is a direct effect of the interstitial over-pressure on the failure strength (see [22] for more

Table 2
Comparison of uniaxial compressive strengths (f_c) and Young's moduli (E) of the HPSCC with $w/b = 0.41$ and the mortar with $w/c = 0.5$ according to conditioning modes.

Material	Sample dimension (mm)	w/b	P (%)*	A (%)*	$\frac{f_{c\_airdried}}{f_{c\_saturated}}$	$\frac{f_{c\_ovendried}}{f_{c\_saturated}}$	$\frac{E_{ovendried}}{E_{saturated}}$
Mortar	$\Phi 37 \times h74$	0.50	42	58	1.24	1.22	0.85
HPSCC	$40 \times 40 \times 40$	0.41	33	67	1.22	1.05	–
	$\Phi 160 \times h320$				–	1.00	0.69

* P and A correspond respectively to the quantity of the paste and aggregates in % of unit volume.

details). Therefore, the interstitial over-pressure should also influence the strength evolution of HPSSC. Of course, this influence decreases with drying.

As previously mentioned, the compressive strength of the cubic samples is higher than that of the cylindrical samples (Figs. 4 and 5). Various reasons can explain this difference in strength. The first is linked to the samples size: due to different length-to-width (l/w) ratios, the cubic samples ($l/w = 1$) have higher strength than that of the cylindrical samples ($l/w = 2$). However, this strength difference of the two types of samples depends on the material's strength and decreases with the increase of material strength [32]. The second reason would come from the smaller critical dimension of the prismatic samples which is conducive to contact between the coarse aggregates (it would take only four aggregates with a maximum size of 10 mm in a line to span the sample). For the cylindrical samples, as they have a critical length four times greater than the prismatic samples, it is much less likely that aggregate chains span the cylinders. Therefore, the aggregates' opposing force to the mechanical loading would be more marked for the cubic samples hence a higher uniaxial compressive strength. Moreover, the loading rate being 1.5 MPa/s for the cubic samples and of 0.5 MPa/s for the cylindrical samples in accordance with the European Standard (see Section 2), a part of this increase could also come from difference of loading velocity. Notice that the cubic samples are loaded perpendicularly to the casting direction contrary to the cylindrical samples. It seems however that casting direction has no significant influence on compressive failure strength of homogenous concrete without segregation [32].

4.2. Young's modulus

The evolution of Young's modulus versus weight loss is also dependent on the competitive effect between material strengthening and drying induced micro-cracking. As the capillary suction is first dominating, the elastic modulus increases with drying, by about 23%. The induced micro-cracking overcomes the material strengthening effect after a sufficient drying time leading to a drop of 31% compared to the value of samples in water. The decrease was 15 % for the mortar with $w/c = 0.5$ [17–19] (see also Table 2). Again, the more important decrease of the HPSCC's elastic modulus would come mainly from its coarsest aggregate size (10 mm) compared to the mortar's one (2 mm).

The decrease of Young's modulus is also reported by other authors. For instance, Okajima et al. [21] who carried out tests on a mortar with $w/c = 0.65$ at homogenous internal humidity register a decrease of 9% when the relative humidity pass from 100% to 20%, and 20% when the relative humidity is close to 0%. Kanna et al. [23] observe a drop of 36% after oven-drying at 105 °C. A decrease of 25% on the samples of an ordinary concrete with $w/c = 0.63$ preserved in an environment with 60 ± 5% relative humidity is also reported [16].

4.3. Bending strength

The bending strength's relationship with drying also comes from above cited competitive effect. Moreover, the results obtained (Figs. 8 and 9) indicate that the drying induced micro-cracking is more easily detected by the measurement of the bending strength. Indeed, for a flexural tensile test, the external zone (outer fiber of beam) weakened by the induced micro-cracking (see Fig. 10e) is directly subjected to the loading contrary to a uniaxial compression test or splitting tensile test. This is why the drying induced micro-cracking effect can be easily seen by bending strength measurement (Figs. 8 and 9) while uniaxial compressive strength of cubic samples continues to increase (Figs. 4 and 5). The fact that the oven-dried samples have lower strength than the air-dried samples for a given weight loss (in this study between 2% and 2.5%) comes from a supplementary micro-cracking under rapid drying at 60 °C. Indeed, hygral gradients become large in a short time under this conditioning in comparison with the hygral gradients at controlled ambient atmosphere, and leads to more micro-cracks. On the other hand, thermal origin micro-cracking can also occur. After this immediate micro-cracking with oven-drying, the bending strength increases gradually without reaching the value of the water saturated samples. This increase in bending strength shows the capillary suction effect on bending strength evolution. In addition, creep of matrix would reduce, especially for air-dried samples, the shrinkage stresses in aggregate/cement paste interfacial zone and then the occurrence of supplementary micro-cracks [12,32,33].

The bending strength evolution observed here differs from those obtained by Pihlajavaara [24] and Okajima et al. [21] who tested respectively the mortars with $w/c = 0.5$ and 0.65 after obtaining a good maturity. They performed their bending tests at uniform internal humidity, and register increases of 58% and 36% respectively. Kanna et al. [23] reported an increase of 39% in bending strength of a mortar with $w/c = 0.45$ after 6 days of oven-drying at 105 °C. However, Walker and Bloem [26], who carried out their tests under non uniform drying conditions on ordinary mature concretes with $w/c = 0.42$ and 0.45 (measurements carried out without reaching hygral equilibrium), observed an evolution of bending strength comparable to that presented in this paper. For their two concretes that have similar evolution, they note first a decrease of the bending strength that can reach 40% after 4 days of drying. Then they register a gradual increase of the bending strength up to the end of the study, i.e. 32 days, which results in a drop of 19% compared to the bending strength of non dried samples. Mills [25] also reported a drastic decrease, 42%, in bending strength of a concrete with $w/c = 0.5$ after oven-drying at 110 °C during 1 day. On the other hand, Pihlajavaara [24] also observed a decrease of bending strength after oven-drying at 105 °C up to constant weight, and the above cited increase of 58% becomes 21%. All these results confirm the important roles of drying induced micro-cracking and capillary suction in the evolution of mechanical behaviours of SCCs under drying.

5. Conclusions

The mechanical behaviour of ordinary strength mature cement-based materials evolves, during drying, under a competitive effect that occurs between capillary suction and hygral gradients leading to material strengthening and induced micro-cracking due to material heterogeneities and differential shrinkage. However, as this competitive effect depends on the quality of the binder paste (that is linked to the water-to-binder ratio, strength class of cement used and presence of mineral admixture), the purpose of the present experimental study is to highlight the influence of drying on the mechanical behaviour of a high performance material (a high performance self-compacting concrete is used in this study). Compared to the ordinary strength cement-based material, this material has a higher binder paste quality which implies a lower porosity (or capillary porosity). After casting, all the samples are stored in lime water at 21 ± 1 °C for 75 days, they are then submitted to air-drying (21 ± 1 °C and 60 ± 5% R.H.) and/or oven-drying (60 °C and 10% R.H.). The following drying effects can be deduced from this investigation:

- The strength of small cubic samples ($40 \times 40 \times 40\ mm^3$) submitted to air-drying increases approximately by 22%. However, when the samples are subjected to oven-drying, there is only an increase of about 5% for small cubic samples ($40 \times 40 \times$

40 mm^3), and no strength variation for the bigger cylindrical samples (Ø160 × h320 mm^3). Thus, in the case of air-drying of small cubic samples, the material strengthening prevails over micro-cracking. In the case of oven-drying of small cubic samples and big cylindrical samples, the effect of the first is countered by the second depending on the sample's size; this is why there is only a slight compressive strength increase for the small cubic samples and no compressive strength variation for the big cylindrical samples. Notice that the presence of the drying induced micro-cracking is shown by application of hydraulic oil on the samples previously oven-dried.

- Young's modulus of cylindrical samples subjected to oven-drying first increases approximately by 23% corresponding to 2.2% of weight loss. This increase comes from the beneficial effects of capillary suction and hygral gradients (material strengthening). Afterwards, Young's modulus begins to decrease as the drying induced micro-cracking overcomes material strengthening. The final decrease after maximal weight loss (4.8%) is about 31% compared to the Young's modulus of water saturated samples.
- The bending strength of prismatic samples subjected to air-drying and oven-drying first decreases by about 44% corresponding to 0.7% and 2.5% of weight loss for air-dried and oven-dried samples respectively. Then the bending strength increases to reach a final drop of 31% compared to the bending strength of water saturated samples, after maximal weight loss (2.3% for air-dried samples and 5.2% for oven-dried samples). As in the case of the flexural tensile test, the external zone weakened by the drying induced micro-cracking is directly loaded contrary to uniaxial compression test, the drying induced micro-cracking effect is observed very quickly on the bending strength evolution. Therefore, the bending strength decreases at the beginning of drying. Afterwards, there is a limited increase in bending strength due to the beneficial effect of capillary suction and hygral gradients (material strengthening). Notice that the oven-dried samples have lower bending strength than the air-dried samples for a given weight loss as was the case for uniaxial compressive strength.
- The bending strength is more sensitive to the drying induced micro-cracking (under air or oven-drying conditions) compared to the uniaxial compressive strength. The higher sensitivity of bending strength to the drying induced micro-cracking is known for ordinary concrete.
- It is observed that the mechanical properties (uniaxial compressive strength, Young's modulus) of the high performance self-compacting concrete (w/b = 0.41) with 10 mm maximum aggregate size are more affected than those of a previously studied mortar (w/c = 0.5) with 2 mm maximum aggregate size under the same oven-drying condition. This shows that the maximum size of the aggregates can play an important role in the drying induced micro-cracking process, especially in the case of accelerated drying.

Thus, the experimental investigation clearly highlights that the mechanical behaviour of high performance materials is also greatly influenced by the aforementioned competitive effect during drying. It shows that even if the paste is of higher quality (lower porosity), the drying induced micro-cracking strongly affects, especially under accelerated drying conditions, the mechanical properties of high performance materials. The maximum aggregate size seems to play an important role in this deterioration of the mechanical properties. The results obtained are relevant with respect to the importance of the drying process in the durability study of high-performance concrete structures.

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