Strength Behaviour of a High-Performance Concrete Under Drying

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Abstract Cement-based materials usually undergo drying which influences their mechanical behaviour. This study investigates the evolution of mechanical properties of a high-performance self-compacting concrete subjected to drying at an early age and after long-term maturation. Uniaxial compression and bending tests are performed at different drying times. The evolution of the mechanical properties obtained is controlled by a competitive effect between material strengthening (due to capillary depression, disjoining pressure, hygral gradients, and hydration if it still occurs) and drying-induced micro-cracking (due to material heterogeneity and differential shrinkage). The competitive effect shows a great dependence on maturation level. Such couplings have to be taken into account for a reliable durability analysis.

Keywords High-performance concrete · Maturation · Drying · Micro-cracking · Mechanical properties

1 Introduction

Concrete structures are subjected to drying due to the hygral imbalance between the early age concrete and environmental conditions. Shrinkage is a macroscopic consequence of drying and is induced by variation of capillary depression, disjoining pressure and surface tension [1, 2]. The drying which is non-uniform because of the low permeability of concrete and structure geometry creates hygral gradients that lead to a differential shrinkage producing tensile stress and surface micro-cracks as soon as the tensile strength is reached [1–6]. Micro-cracking also occurs at the interface of the hydrated cement paste/stiff inclusion because of a retracting matrix

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and inclusions [7–9]. Moreover, drying at an early age generates hydration gradients in the material [10]. The earlier the drying the stronger the hydration gradients become. Therefore, the interaction between drying, hydration and mechanical behaviour will greatly influence the durability of concrete structures. The previous studies on cement-based materials [3, 5, 11, 12] showed the occurrence of a competitive effect between strengthening of material and induced micro-cracking during drying. The strengthening of material is due to a variation in capillary suction, disjoining pressure and surface tension which create an isotropic pre-stressing in the material. This strengthening is amplified by hygral gradients [1–6] which lead to the confinement of the sample's core. The drying-induced micro-cracking comes from the heterogeneities of the material and differential shrinkage. However, if the hydration has not yet reached stabilisation, the strength increase due to the hydration process (which slows down and then stops in time from the outside to the inside of the material because of drying) has also to be considered in this competitive effect.

In an earlier work [13], the effect of drying on the evolution of the mechanical behaviour of a high-performance concrete has been investigated after a long-term maturation period. The objective of the present work is to perform a comparative study between the effects of drying at early age and after long-term maturation on the evolution of strength behaviour. This behaviour is evaluated by means of uniaxial compression and bending tests carried out at different times. These two tests also made it possible to show which is more sensitive to drying-induced micro-cracking. In the first part, the setting up of the experimental investigation is described. In the second part, the results obtained are presented and analysed by putting forward the coupling effects between drying, hydration and mechanical properties.

2 Experimental Investigation

The experimental study was set up to follow the evolution of the hygro-mechanical behaviour immediately after material casting. A high performance self-compacting concrete was used to perform the study (Table 1). The gravel (4/10 mm) was crushed while the sand (0/4 mm) was rolled, the two aggregates being silicocalcareous.

Table 1 Composition of concrete

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

Cement CEM I 52.5 N CP2 and limestone filler were used to manufacture the high performance self-compacting concrete. The high range water reducer admixture was a polycarboxylate modified superplasticizer. Cylindrical (Ø160 × h320 mm^3) and prismatic (40 × 40 × 160 mm^3) samples were manufactured to conduct the investigation.

One day after casting, the samples were separated into two series: the first series were stored in lime-saturated water at 21 °C while the second series were submitted to air-drying in a controlled environment with temperature = 21 ± 1 °C and relative humidity = 60 ± 5%. The comparison of the strength behaviour of these two series made it possible to evaluate the effect of air-drying at an early age with regard to water maturation. The testing programme was composed as follows:

- uniaxial compression tests on cylindrical samples (Ø160 × h320 mm^3),
- three-point bending tests on prismatic samples (40 × 40 × 160 mm^3) and uniaxial compression tests on cubic samples (40 × 40 × 40 mm^3) by using the half-prisms obtained after the bending tests,
- measurement of the loss in mass of samples with time,
- determination of porosity.

The effect of air-drying on strength behaviour was also tracked 75 days after casting. After this long-term maturation period in lime-saturated water, the effect of hydration on strength [12, 13] and endogenous shrinkage [14] can be considered as slight. The tests carried out on prismatic samples of the first series at different times of drying enabled comparison of the effect of drying at an early age with that occurring after an optimal maturity.

The compression tests on cylindrical samples (Ø160 × h320 mm^3) were performed with a loading velocity of 10 kN/s (EN 12390-3). To ensure a perfect transmission of the load and thus to minimise the bending effect, all the samples were surfaced and a rotating plate system was used. Three-point bending tests were carried out on prismatic samples (40 × 40 × 160 mm^3) with a loading velocity of 0.05 kN/s (EN 196-1). After the failure of the sample in the flexural test, the two parts of each prism were subjected to compressive stress with the help of a device consisting of two steel plates 40 mm wide, with a loading velocity of 2.4 kN/s (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 type of test and conditioning, at least two samples were tested. However, only the average values will be presented for reasons of clarity.

3 Results

3.1 Effect of Drying at Early Age

Figure 1 presents the evolution of the uniaxial compressive strength of cylindrical samples and cubic samples (previously tested in flexion) as a function of time and conditioning mode. The air-drying begins one day after casting. The strength of water-stored samples increases in time due to hydration, the rate of increase being higher up to 14 days. Then, it tends towards a stabilisation for large cylindrical samples but continues to increase slightly for small cubic samples. The increase in strength reaches 55% and 72% for large cylindrical samples and small cubic samples respectively. The porosity was also determined on water-stored samples at different times of mechanical tests by the difference between saturated and dried (at 60 °C) state. The porosity obtained between 4 and 75 days of maturation varies between 12.2 and 12.8%. This variation is non-significant and means that the microstructure is well formed after 4 days of casting. It does not enable the variation in compressive strength to be captured.

The compressive strength of air-dried samples also increases in the same proportion as that of saturated samples and then begins to decrease but remains clearly higher than the one day compressive strength (non-dried samples): the increase reaches 40 and 57% at 14 days then drops to attain 36 and 40% at 75 days for large cylindrical samples and small cubic samples respectively compared to the strength after one day.

The increase in compressive strength of the air-dried samples can be attributed to the hydration which slows down in time by faster drying and to the beneficial effect of capillary depression and disjoining pressure. The decrease in strength that follows shows the harmful effect of drying-induced micro-cracking which prevails

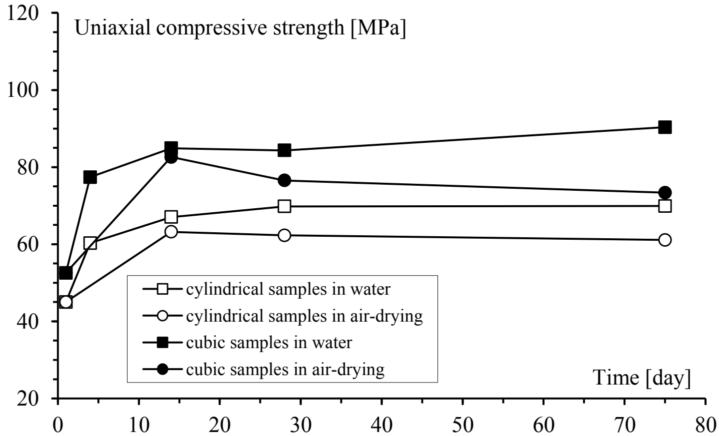

Fig. 1 Uniaxial compressive strength of cylindrical (Ø160 × h320 mm^3) and cubic (40 × 40 × 40 mm^3) samples versus time and conditioning mode

over the strengthening effect. This evolution is similar to that shown by the results of Price [12] on an ordinary strength concrete. Moreover, compared to large cylindrical samples, the increase then the decrease in the compressive strength of small cubic samples with time of drying with regard to one day strength is more pronounced. This could be caused by their faster drying which also leads to a smaller degree of hydration from the outside to the inside of the material.

Figure 1 also highlights the influence of a scale (size) effect on uniaxial compressive strength. Indeed, the compressive strength of cubic samples is higher than that of cylindrical samples for the two conditioning modes. Various reasons could explain this difference in strength: length-to-width (*l/w*) ratio whose effect decreases with the increase of material strength, 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 10mm in a line to span the sample) thus inducing a more marked opposing force of aggregates to the mechanical loading compared to cylindrical samples, probable effect of the difference between the loading rate of cubic (1.5 MPa/s) and cylindrical (0.5 MPa/s) samples.

Figure 2 shows the evolution of the bending strength of prismatic samples as a function of time and conditioning mode. As indicated previously, the air-drying begins one day after casting. The bending strength of the saturated samples is again higher than for the air-dried samples. The increase in bending strength of the air-dried samples due to hydration and variation of capillary depression and disjoining pressure is countered by drying-induced micro-cracking which reduces the bending strength although this still remains slightly higher than the one day strength.

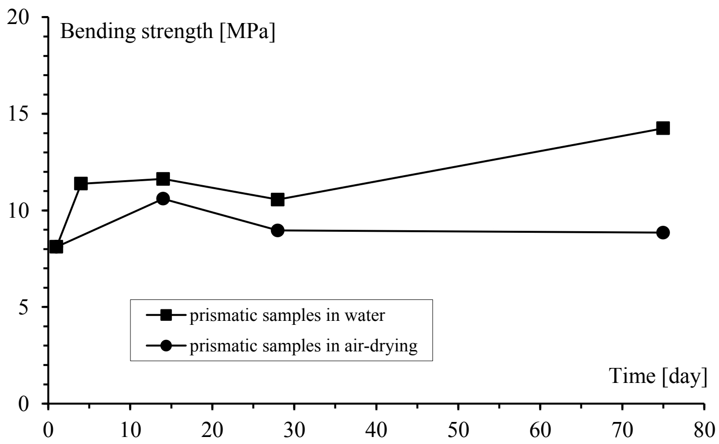

Fig. 2 Bending strength of prismatic samples (40 × 40 × 160 mm^3) versus time and conditioning mode

3.2 Effect of Drying After Long-Term Maturation

Figure 3 shows the evolution of the compressive strength of cubic samples versus time of drying one day and 75 days after casting. Time 0 corresponds to the beginning of drying process. Figure 4 gives the same evolution versus loss in mass. Note that the tests performed on saturated samples after 75 days of maturation did not show significant variation of strength due to continuation of hydration [13]. Therefore, any strength evolution after this long-term maturation can be attributed mainly to the effect of drying unlike the strength evolution of air-dried samples one day after casting.

The strength of mature samples increases with time of drying by about 22% and does not show a decrease, contrary to the case of early age drying for which strength first rises by 57% then decreases to about 44% compared to non-dried samples. Therefore, for mature material, the strengthening effect is dominant compared to the effect of drying-induced micro-cracking. Such an increase in strength has also been reported by other authors for cement-based materials whether or not the sample drying was homogeneous [3, 5, 11, 15, 16]. However, it has also been observed that the effect of drying-induced micro-cracking can become preponderant after sufficient air-drying generating a slight strength decrease following an initial higher increase [12].

Note that when the samples of low permeability, like those of the present study, are tested close to saturation, this will bring about an interstitial over-pressure which amplifies opening and propagation of micro-cracks. The presence of water also has a lubricating effect. The influence of these two effects decreases with drying.

Figure 5 displays the evolution of the bending strength of prismatic samples versus time of drying one day and 75 days after casting. Time 0 corresponds to the beginning

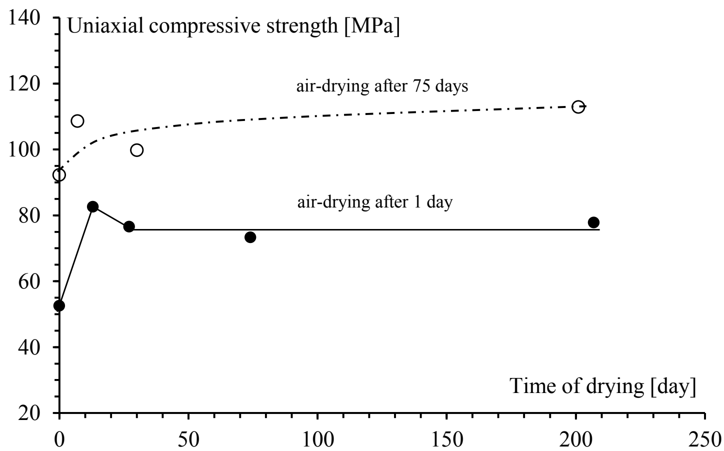

Fig. 3 Uniaxial compressive strength of cubic samples (40 × 40 × 40 mm^3) versus time of drying

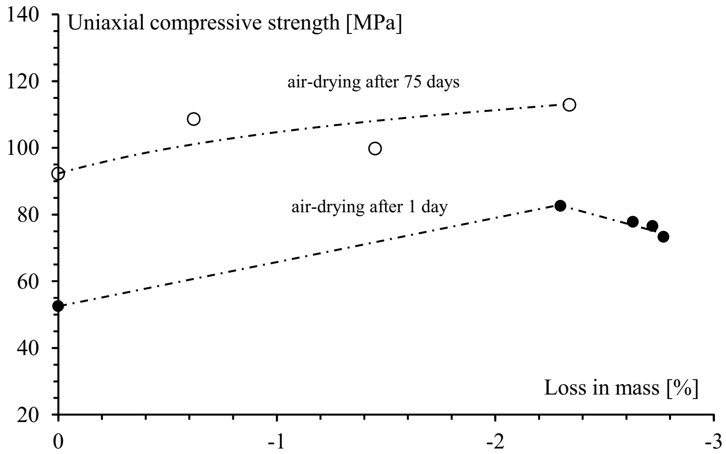

Fig. 4 Uniaxial compressive strength of cubic samples (40 × 40 × 40 mm^3) versus loss in mass

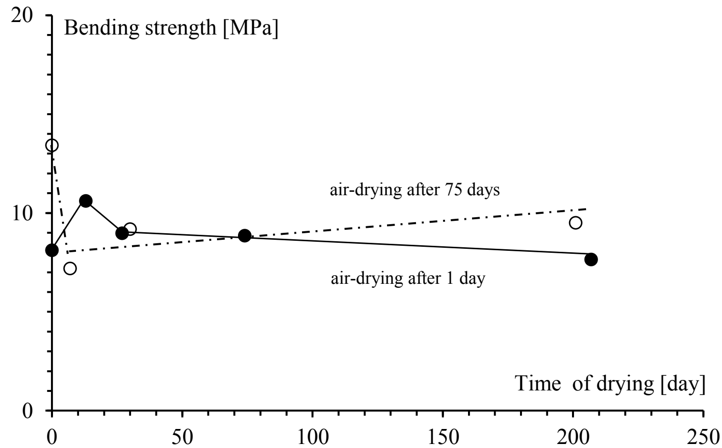

Fig. 5 Bending strength of prismatic samples (40 × 40 × 160 mm^3) versus time of drying

of the drying process. Figure 6 gives the same evolution versus loss in mass. Air-drying of mature samples provokes a drastic decrease of 44% in bending strength at the beginning of drying. Then, the bending strength begins to increase with drying to have a final net decrease of 31%. This evolution of bending strength occurs under the same above cited competitive effect between material strengthening and drying-induced micro-cracking. Thus, after a significant reduction due to drying-induced micro-cracking, the bending strength increases gradually without reaching the value of the water saturated samples. This increase illustrates the effect of capillary suction and disjoining pressure on the evolution of bending strength. However, the bending strength of the air-dried samples one day after casting increases by 31%. Then, it

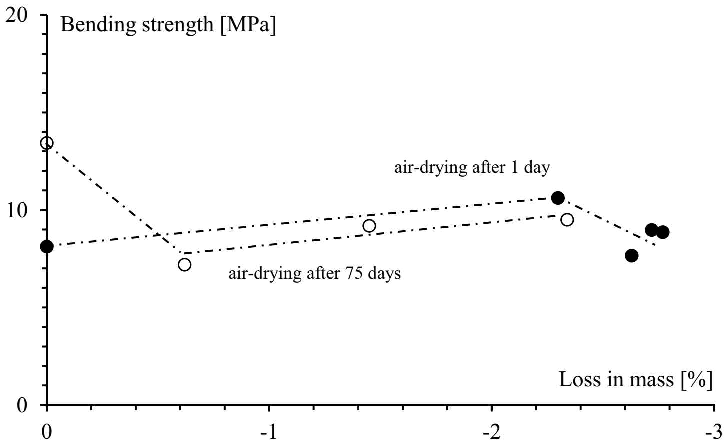

Fig. 6 Bending strength of prismatic samples ($40 \times 40 \times 160$ mm^3) versus loss in mass

decreases due to drying-induced micro-cracking and reaches a final drop of 6% compared to non-dried samples. Notice that the creep of matrix which depends on maturity level would contribute to the evolution of bending strength as it reduces the shrinkage stresses in aggregate/cement paste interfacial zone and then the occurrence of supplementary micro-cracks [6, 9]. The results obtained also highlight that the drying-induced micro-cracking is more easily detected by the measurement of the bending strength. Indeed, in the flexural tensile test, the external zone (outer fibre of the beam) weakened by the induced micro-cracking is directly subjected to the loading contrary to a uniaxial compression test.

The bending strength evolution reported here is comparable to that obtained by Walker and Bloem [17] who carried out their tests under non uniform drying conditions on mature concretes with w/c = 0.42 and 0.45 and containing air-entraining admixture. They note first a decrease of the bending strength that can reach 40% after 4 days of drying then register a gradual increase of the bending strength up to the end of their study, i.e. 32 days, which results in a drop of 19% compared to the bending strength of non-dried samples. Moreover, Kanna et al. [18] report an increase of 6% in bending strength of a mortar with w/c = 0.45 cured 7 days in water then subjected to 21 days of drying at 50% of relative humidity. Okajima et al. [15] who tested a mature mortar with w/c = 0.65 at various uniform internal humidities do not observe any significant bending strength variation at 60% relative humidity compared to saturated case. However, the bending strength increases for more severe conditions of drying. Moreover, the results of Pihlajavaara [16] who tested a mature mortar with w/c = 0.50 at various uniform internal humidities show an increase of about 28% at 60% relative humidity. All these results illustrate the importance of the competitive effect in the evolution of mechanical properties with drying.

4 Conclusions

This experimental study highlights the effect of drying at an early age (one day) and after long-term maturation (75 days) on mechanical properties of a high-performance self-compacting concrete. The evolution of mechanical properties depends on the competitive effect between material strengthening due to capillary depression, disjoining pressure, hygral gradients and hydration (if it still takes place), and drying-induced micro-cracking due to material heterogeneity and differential shrinkage. Thus, in the case of early age drying during which hydration still occurs, the uniaxial compressive strength and bending strength increase due to the strengthening of the material. However, these strengths begin to decrease when the drying-induced micro-cracking effect overcomes the material strengthening effect. After long-term maturation, the uniaxial compressive strength shows only an increase with air-drying whereas the bending strength drastically decreases at the beginning of drying then slightly increases. Therefore, the drying-induced micro-cracking effect is very quickly detected on the bending strength of a mature material, the subsequent limited strength increase showing the beneficial strengthening effect. The results obtained clearly show the effect of maturation in the evolution of mechanical properties with drying, which has to be considered in durability analysis.

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