Mechanical influences of drying: experimental analysis on a mortar

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ABSTRACT: The main purpose of this study concerns the characterization of the coupled effect between drying shrinkage and damage for a cementious material. An experimental study on a normalized mortar is then presented in order to characterize the damage effect, induced by drying and desiccation shrinkage on the multiaxial compression behavior. Uniaxial and triaxial compression tests are carried out at different times of drying. The observed increase in uniaxial and deviatoric strengths and decrease of Young's modulus and Poisson ratio are related to the loss in mass of specimens. These results are commented through the damage processes of material since drying phenomenon causes microcracking.

1 INTRODUCTION

The long term behavior of cementious materials depends on mechanical, hydrous, physical and chemical degradation mechanisms and their coupling. Durable concrete has to maintain, over a long period of time, its main properties face to these solicitations. Despite numerous studies regarding evaluation of deformations due to concrete shrinkages (see in general Bažant & Wittmann 1982, Ulm *et al.* 2001), only few results relative to drying shrinkage effect on concrete behavior can be found in the literature. Thus, to evaluate this drying effect, a wide experimental program has been undertaken by our laboratory. The first results of this study have demonstrated significant influences of drying shrinkage on mechanical behavior which become essential to be included in a reliable modeling. In fact, cementious material behavior is strongly influenced either by uniform or non-uniform drying (Wittmann 1982, Popovics 1986, Bartlett & MacGregor 1994). Moisture gradient (from material body to its external surface) induces deformations prevented by differential contraction; as a result the cementious matrix is subjected to tensile stresses which induce microcracks if tensile strength is exceeded. Furthermore, uniform drying is going with increase in capillary pressure and surface tensions which play an important role since mechanical behavior of material during its drying has to be identified. However, matrix deformations are prevented by aggregates leading to a diffuse cracking in cement paste (Hearn 1999, Bisschop & Van Mier 2001, Bisschop *at al.* 2001). Hence, the induced microcracking due to these effects will have an influence on elastic property, damaging process and failure stress of material. Determination and evolution of elastic properties are important as they play an important role in numerous concrete structure calculations, as well as in valuation of the delayed strains.

This experimental study aims to evaluate the coupled effect between drying shrinkage and multiaxial mechanical behavior of a mortar. In this objective, a standard mortar (French norm) with a W/C ratio of 0.5 was cast and immerged in water during 6 months in order to obtain a highly mature mortar with negligible autogeneous and thermal shrinkage effects. Several standard uniaxial and triaxial compression tests with loading-unloading cycles were carried out on cylindrical samples (ϕ37x74 mm^3) at different drying times. Furthermore, the drying shrinkage of the same mortar was measured on prismatic samples (40x40x160 mm^3). Increases of uniaxial and deviatoric strengths and decreases of Young's modulus and Poisson's ratio were observed. These results have to be interpreted through the different mechanisms induced by drying process. Indeed, the latter leads to strengthening of mortar by creating uniform and non uniform moisture gradients through the sample. Microcracks of mortar are also induced if tensile strength is exceeded. Thus, these effects have an influence on variation of elastic properties and damaging process of cementious material, which have to be taken into account in a reliable modeling. In a first part, the setting up of the experimental program and the necessary requirements (the studied material and the experimental process) are described. In a second part, the obtained results are presented in order to underline the mechanical behavior evolution of a mortar, under uniaxial and triaxial compression stresses, in relation with the drying process.

2 EXPERIMENTAL PROGRAM

2.1 *Stating of the problem*

Total shrinkage of mortar and concrete comes from several shrinkages (Acker 1988): endogenous (including "Le Châtelier" contraction and self-desiccation shrinkage), thermal and desiccation shrinkage which is the object of this study. Further shrinkage, known as carbonation shrinkage, can take place for samples preserved, during a long period of time, in a highly charged atmosphere with CO_2. Since drying shrinkage was assumed to have prevailed within the present study, carbonation shrinkage was not measured. The main cause inducing drying shrinkage is commonly assumed to be the loss of free water (Wittmann 1982, Acker 1988). Thus, moisture gradient takes place from the heart to external sides of the sample, which, coupled with a low material permeability, will cause a differential drying shrinkage leading to tensile stresses at the outer surface. As a result, there are initiation and propagation of microcracks whether tensile strength is exceeded. In parallel, the cementing matrix contraction will arise around aggregates which are there like rigid inclusions. From this, a diffuse cracking may result depending on aggregate sizes (Bisschop & Van Mier 2001, Bisshop *et al.* 2001). In this work, influences of the drying shrinkage on the damageable elastic-plastic behavior of a mortar are studied under uniaxial and triaxial compression. For that purpose, a particular experimental procedure was designed.

2.2 *Composition of mortar and samples conservation*

To carry out this study, a normalized mortar of classical composition (see Table 1) was used and compound with a normalized sand (maximum grain size of 2 mm, European norm EN196-1). Such mortar has the advantage to be easily reproduced by other laboratories (Yurtdas *et al.* 2004a).

The necessary amount of mortar to achieve the whole study was cast at the same time in a beam formwork (4 m length, 150x150 mm^2 section) whose surface in contact with room atmosphere (Temperature (T) = 21°C ± 1°C, Relative Humidity (Hr) = 60% ± 5%) was protected by a plastic cover in order to prevent a local desiccation. Five days later, the beam was immersed for 6 month in water regulated at 20°C. At the end of this period, effects of thermal and endogenous shrinkages are thus negligible while maturation of mortar is almost achieved. Samples – 37 mm diameter, 74 mm length – were cored and cut from the beam then carefully rectified to obtain a perfect geometry. Sample dimensions were chosen to measure the relevant parameters within a reasonable period of time. After 6 months of immersion, samples were classified in 3 different series:

- protected samples from desiccation by two layers of adhesive aluminum, mentioned further as "saturated samples",
- samples submitted to desiccation in a controlled atmosphere (T = 21°C ± 1°C, Hr = 45% ± 5%), mentioned further as "desiccation samples",
- oven dried samples at 60°C until constant weight and protected from re-saturation by 2 layers of aluminum, mentioned further as "dried samples".

The experimental program is scheduled as follows (all the presented tests are performed according to the drying process and the conservation mode):

- ✓ measurements of endogenous and drying shrinkages on prisms (40x40x160 mm^3), these prisms were made up and preserved under the same previously described conditions,
- ✓ uniaxial compression tests and triaxial compression tests on cylinders (ϕ37 mm x 74 mm),
- ✓ measurements of loss of water of prisms (40x40x160 mm^3) and cylinders (ϕ 37x74 mm).

Components	*Quantity*
Standard sand (EN 196 – 1)	1350 kg/m^3
Cement CEM II/B 32.5 R	450 kg/m^3
Water	225 kg/m^3
Water/Cement ratio	0.5

Table 1. Composition of the standard mortar.

2.3 *Experimental devices and measurements*

Various tests were thus performed with this mortar: uniaxial compression and classical triaxial compression tests with unloading - reloading cycles and desiccation shrinkage.

Mechanical tests were carried out using a triaxial cell, a confining pump (Gilson© 307) to ensure oil injection until the required pressure level and a hydraulic press (Instron® 500 kN capacity). A prescribed displacement mode was used, the axial strain velocity being of 2 $\mu m.s^{-1}$ for the axial and the deviatoric loading rates (Fig. 1). The axial stress, applied on sample, was deduced from the machine load measurement cell. The longitudinal and transversal strains were measured with 4 gauges: 2 longitudinal and 2 transversal located at the middle of the sample (Fig. 2). In order to carry out a perfect uniaxial stress state (without significant bending effect), a special hinged loading platen was designed (Fig. 1, 2) and placed between the superior press platen and the sample. Imperfections due to a possible parallelism defect between the two sample surfaces were thus minimized.

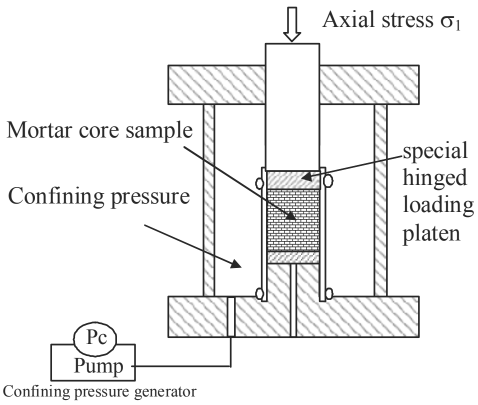

Figure 1. Principle of the triaxial compression test.

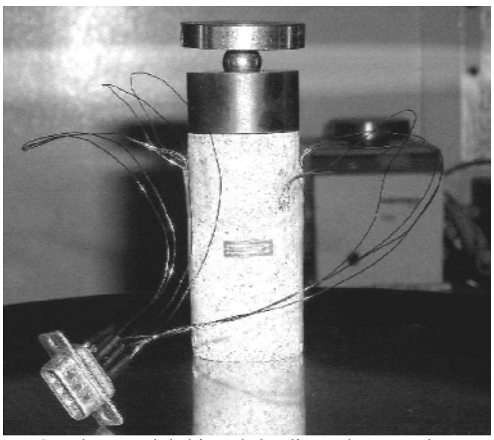

Figure 2. The special hinged loading platen and a mortar sample.

Finally, the shrinkage measurements on prisms were achieved by classical device (using a “retractometer”), corresponding to the variation of the prism length (base 160 mm).

3 EXPERIMENTAL RESULTS: UNIAXIAL AND TRIAXIAL COMPRESSION TESTS

3.1 *Desiccation shrinkage measurements*

An example of drying shrinkage measurement performed on prismatic sample submitted to desiccation is depicted in Figure 3. One can notice that endogenous shrinkage, measured on samples immerged 6 months in water and protected from desiccation, is negligible compared to drying shrinkage.

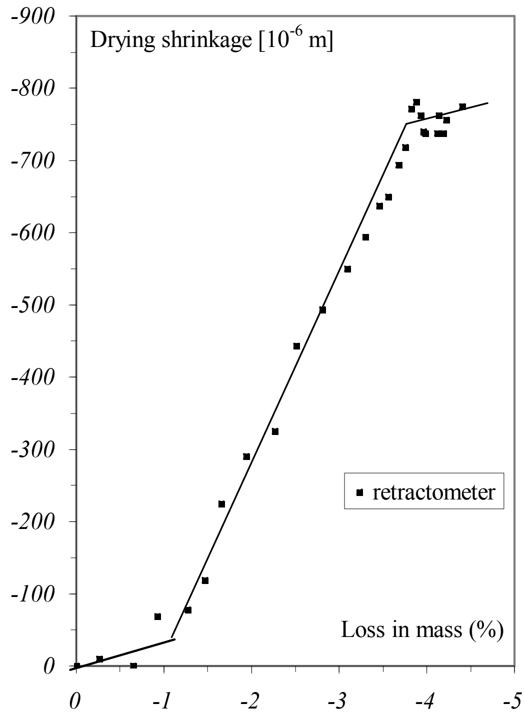

Figure 3. Drying shrinkage versus loss in mass for standard mortar.

The result is classical as 3 characteristic phases are present (Granger 1994): the first phase, corresponding to the weight loss with only weak shrinkage measurement, comes from rapid evaporation of surfacic water coupled with an induced microcracking which counterbalances prism shrinkage ; in the second phase, drying shrinkage is a linear function of loss of water : this is due to solid skeleton contraction induced by capillary depression (Acker 1988, Burlion 2000), variation in surface energy (Wittmann 1982) and disjoining pressure (Bažant & Wittmann 1982): we will consider that the dominant mechanism is the capillary suction ; finally, the third phase shows a weight loss evolution without additional shrinkage. This last phase can be explained either by the fact that contraction of cement matrix becomes low by lack of free water, by a non-linear drying and desiccation shrinkage relation, for example due to induced microcracking, or by a non-linear mechanical behaviour of mortar (Meftah *et al.* 2000).

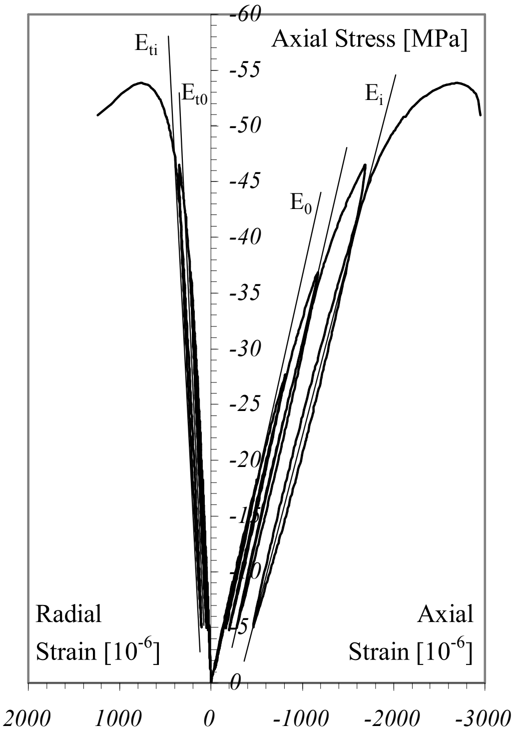

Figure 4. Uniaxial compression test: measurement of elastic parameters of mortar.

3.2 *Uniaxial compression results*

Obtained results from uniaxial compression tests are presented in Figure 4 where compression stress is plotted versus axial and lateral strains. The strain values, reported there, were calculated by averaging the two corresponding gauge measurements as preliminary tests showed they were virtually identical. Material behavior exhibits hysteretic loops which are due to material viscosity. Notice that their opening decreases with drying. Results obtained in terms of mechanical damage in uniaxial compression are very similar to those presented in the literature on this classical mortar.

Then the analysis of uniaxial compression tests can be performed taking into account the drying time of mortar. For each considered time of drying, 3 cyclic uniaxial compression tests were carried out the same day. To verify the complete maturity of the mortar and the reliability of the results, compression tests were also performed on 3 saturated samples at different times (for more details see Yurtdas et al. 2004a). Finally, three dried samples were tested with the purpose to simulate complete drying – i.e. no more free water into the material.

The results of uniaxial compression tests versus loss in mass clearly demonstrate the desiccation effect on compression strength (Fig. 5): the latter increases (about 20 %) from the initial value of saturated samples to final value of dried samples. No more variation of failure strength can be observed after a loss in weight of about 2.5%, corresponding to 30 days of drying. Furthermore, the saturated samples strength within this period of time is virtually constant; this could be the evidence that no maturity effect is to be noticed after 6 months in water.

The increase in strength of "desiccation and dried samples" compared to saturated has also been reported in literature (Pihlajavaara 1974, Popovics 1986, Bartlett & MacGregor 1994). However, the observed strength evolution according to drying is actually different from the evolution mentioned by Pihlajaavara (1974). Pihlajaavara's mortar samples were tested under a constant relative humidity. Moreover, Bartlett and MacGregor (1994) or Popovics (1986) obtained similar results to those presented in this paper. An increase, about 20% of strength for "desiccation samples" compared to the strength reached for water saturated samples, was also reported by Gilkey (1937). The influence of moisture gradient was then highlighted.

This increase of mortar strength is assumed to come from two concomitant phenomena: the first is capillary suction effect leading to an almost isotropic compression of solid skeleton. As a result, material behaves like a prestressed mortar of higher strength. This phenomenon, commonly observed for rocks, is combined with an increase of compression strength, whatever the moisture gradient is present or not. The second phenomenon is linked to moisture gradients which are taking place and involving a contraction of the external part of the sample as well as a confinement of sample inside body. This "confining lateral pressure" will then induce an increase of strength in the perpendicular direction: the sample is self-reinforced. In addition, water saturated sample of low permeability will bring about interstitial fluid pressure increase. Locally, and by coupling effect, this interstitial overpressure may have an amplifying effect on the propagation and opening of microcracks due to the mechanical axial load.

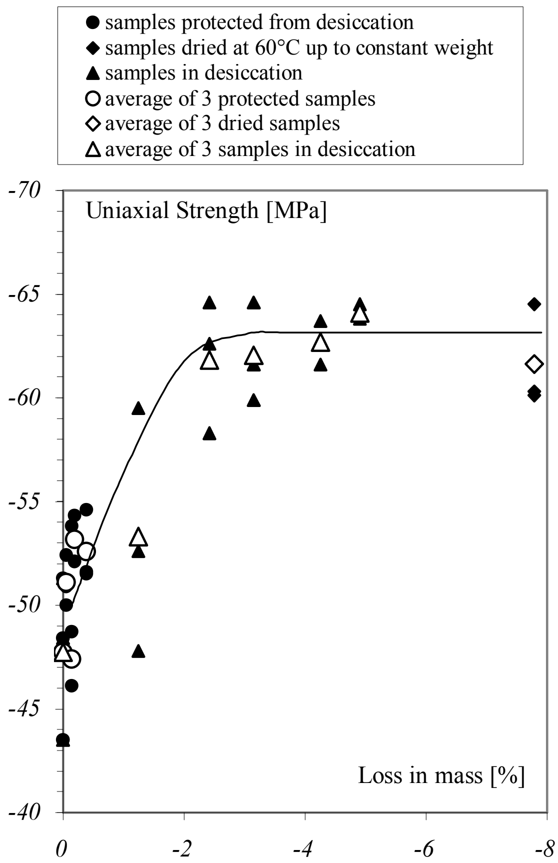

Figure 5. Mortar uniaxial strength versus weight loss.

3.3 *Triaxial compression results (P_c = 15 MPa)*

3.3.1 *Triaxial compression strength evolution*

Triaxial compression result can be analysed in relation to the drying time of mortar. For each considered time of drying, 2 cyclic triaxial compression tests were carried out on the same day. To verify the complete maturity of the mortar and the reliability of the results, triaxial compression tests were also performed on 2 saturated samples at different times (Fig. 5). Finally, 2 dried samples were tested with the purpose to simulate complete drying – i.e. no more free water into the material (more details are given in (Yurtdas *et al.* 2004b).

Authors showed that the desiccation increased cementitious material's strength (Pihlajaraava 1974, Popovics 1986, Bartlett & MacGregor 1994, Burlion et al. 2000, Yurtdas et al. 2004a) and decreased mortar's elastic characteristics under uniaxial compression (Yurtdas et al. 2004a). Results of triaxial compression tests according to the loss in mass (Fig. 6) clearly display the effect of desiccation on the maximal deviatoric strength: an increase of about 29 % (this increase was about 21 % for uniaxial compression strength, Figure 5) from the value obtained for saturated samples to those obtained on dried specimens. In order to verify that no maturation effect occurs during the experimental campaign, triaxial compression tests on samples preserved from desiccation were made periodically. The dried specimens (point ◆) exhibit a higher strength compared to the samples protected from desiccation, whereas specimens left in natural desiccation (point ▲) have a deviatoric strength which evolves, during drying, from saturated samples values towards dried samples values of strength. One can notice that desiccation samples do not reach the strength of dried samples, which was not the case when measured in uniaxial compression. This comes from an amount of free water evaporated, from specimens during natural desiccation, smaller than for dried samples at 60°C. Therefore, the lower the suction effect is, the lower the increase of deviatoric strength will be.

Besides the effect of confining pressure, mortars' deviatoric strength increase can be attributed to two concomitant phenomena. The first is the capillary suction effect, leading to a compression of the solid skeleton, similar to a "prestressing" of mortar, which will be, as a result, more resistant. Thus, there will be an increase of the triaxial compression strength, with hydrous pressure gradient or not. This capillary suction may be considered as isotropic, and could partially justify the more important strength increase (29 %) observed under multiaxial compression loading (the suction is "active" in a multiaxial way) compared to uniaxial compression (21 %). The second phenomenon is linked to the hydrous pressure gradients, present in the sample during drying. The induced contraction of the external part of the sample leads, first, to a microcracking and also to a confining effect on the "non-retracting" central part. This phenomenon, obviously observed for “desiccation sample”, brings about an over-confining effect which is not to be active for oven dried sample of uniform humidity content. Moreover, when these low permeability samples are tested closed to complete saturation, the mean compressive stress increase may induce an interstitial overpressure known as Skempton effect (under undrained conditions). This effect would amplify the opening and propagation of microcracks previously induced by drying.

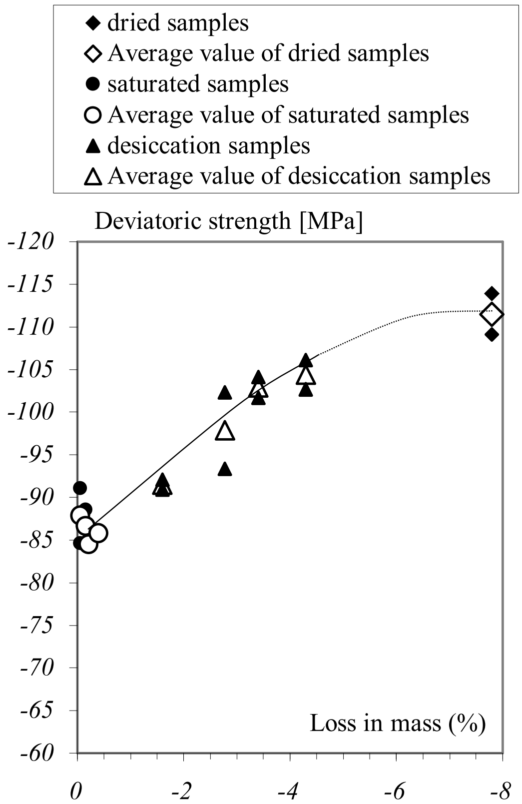

Figure 6: Deviatoric strength versus time of drying

On the other hand, strength increase under triaxial compression (29 %) is higher than increase of uniaxial compression strength (21 %) during complete drying: this phenomenon may be due to the fact that interstitial pressure is initially higher in triaxial case. Hence, induced microcrackings, which play an important role in failure process, would be more pronounced under deviatoric loading, when sample is closed to complete saturation. When failure occurs, macrocracks and shearing band dividing the sample into two or three parts can be observed. Under low confining pressure conditions, this type of failure is frequently reported in the literature (for example, see Sfer *et al.* 2002).

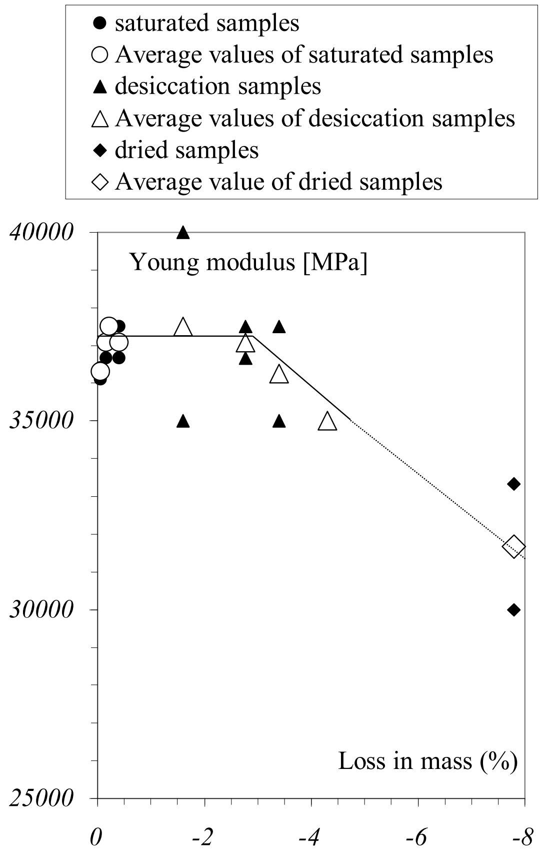

Figure 7: Young modulus versus loss in mass

3.3.2 *Measurements of Young modulus and Poisson’s ratio under triaxial loading*

Young modulus and Poisson’s ratio evolutions, versus loss in mass during drying, are respectively plotted on Figures 7 and 8. Both modulus and Poisson’s ratio vary between two limit values: an upper one (that of saturated samples) and a lower one (that of dried samples). Inside this range, Young modulus value of desiccation samples remains constant in a first stage before an almost 15 % decrease to eventually reach the dried sample values. Poisson ratio variations are quite similar with a decrease around 25 %. The loss in mass threshold, from which elastic parameters begin their drop, is closed to 3 % - i.e. forty drying days.

Two different effects can be attributed to moisture gradient, as they are coming along with increase of capillary suction: microcracking (induced by desiccation) and previously mentioned structural effect causing mortar sample prestressing. From the latter, the measured Young modulus can be considered as an apparent stiffness. One can mention there, that, under intermediate saturation state, the humidity content can not be considered to be uniform through the sample. As a consequence of a possible structural effect, elastic properties measurements and strength determinations have to be carefully used.

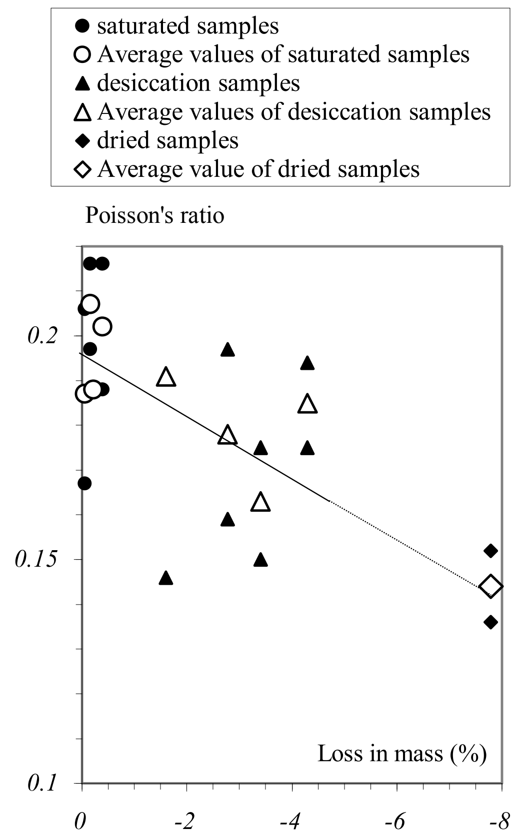

Figure 8: Poisson's ratio versus loss in mass

Microfissuration involved with drying must logically cause a Young modulus decrease; this assertion is thus consistent with the final values of the latter for desiccation samples and the decrease of elastic stiffness observed after a significant amount of lost free water. The loss in mass threshold, from which elastic parameters begin to decrease, is also the state from which no more drying shrinkage is observed (phase 3, Fig. 3). At this stage, the sample presstressing should not counterbalance the microcracking growing, leading hereby to visible hydrous damage phenomena.

4 CONCLUDING REMARKS

This experimental study has put in light the influence of drying and desiccation shrinkage on mechanical behaviour of a normalised mortar submitted to uniaxial and triaxial compressive loading. An increase of mortar uniaxial strength (21%) and deviatoric strength (29 %) is undoubtedly linked to the desiccation while, for elastic parameters, a contrary variation is observed. The Young modulus and Poisson ratio decrease was respectively about 15 and 25 % for the studied mortar, from saturated to dried conditions. These opposite phenomena come not only from capillary depression generated by drying, but also from the microcracking induced by the differential contraction between external and internal part of the samples and by the presence of aggregates. A drying damage is then obtained without any mechanical loading. Such a drying effect has to be involved in a modelling of the coupling effect of desiccation as regards mechanical behaviour of concrete. Because of an initial balance between capillary suction and microcracking evolution effects, the decrease of elastic properties is observed after 3 % loss in mass only. It is of interest to emphasize there, that these 3 % loss in mass are closed to the threshold beyond which no more desiccation shrinkage is measured during drying.

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