Comparison of autogenous shrinkage measurements by different methods in case of fast-hardening mortar

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Abstract. Autogenous shrinkage in the volume of cementitious materials results from changes in the microstructure and environmental conditions. These deformations can be sufficient to cause premature cracking of structures, especially the fast hardening materials or thin products with large exchange surfaces, such as paving, screeds and cement-glass composite. The appearance of cracks influences the quality and aesthetics of the works. The dimensional variations can be observed immediately after the cement and the water have been brought into contact during mixing. In this research, the endogenous shrinkages of a fast hardening mortar based on ettringite binder were studied with different methods. In this mortar, there is not only the shrinkage phenomenon but also the swelling relating to the early ettringite formation. Therefore, the understanding of the dimensional variation with different measurement methods is very important. The results indicate that the endogenous shrinkage measured by linear methods and volumetric methods are in good agreement. All measurement method well recorded both a quick shrinkage and a swelling phenomenon in the mortar.

1. Introduction

Autogenous shrinkage is a topic attracting many researcher' concerns about construction materials, especially about concretes and mortars. Autogenous shrinkage introduces deformations in materials using cement at early ages [1,2]. When preventing the free shrinkage or expansion, the stresses will be built up and causing cracks in materials. For materials with fast hardening process, the risk of cracking due to shrinkage is even higher [3,4]. Different testing methods for autogenous shrinkage measurement can be found in literature [5]. There are two groups of measurements: linear measurements and volumetric measurements.

In linear measurements, methods of determination of endogenous deformations generally consist of measuring the change in length by the installation of a transducer at the end of the sample. The cement paste, mortar, or concrete specimens will be cast in a rigid steel mold. The length change of these samples will be recorded by sensors at one end or both ends of the specimens [6-9]. Two types of linear measurements can be distinguished: vertical and horizontal measurements.

For vertical measurements: Some researchers used vertical specimens in their measurements with dial gauge or sensors placed vertically. The fresh mortar or concrete is cast into a vertical tube. Linear vertical shrinkage measurements can start immediately after casting, by means of LVDT-transducers. The free deformation of the specimen can be ensured by embedded perpendicular thermocouple and sensors [1,10,11].
For Horizontal measurements: Jensen and Hansen [12,13] have developed a device, which allows the linear deformations of the sample to be measured just after casting. This device consists of a dilatometer, which has flexibility, can transform volume deformations into linear deformations before setting. The horizontal displacement of the mortar and concrete start soon after the settlement is complete and internal pressure in mortars and concretes begins to develop. The other main method has the measuring gauges placed through the mold’s sidewalls. These methods are limited to measurements beginning after the setting time and there is a risk of friction between the gauge plug and the mold walls [5, 14].

Linear measurements of endogenous deformations are very sensitive to the direction of the measurement and the two test configurations (vertical or horizontal) show a disagreement between their results at least in the period before setting. This phenomenon is explained by a loss of homogeneity before setting in the case of vertical measurement following the sedimentation of the material.

In case of volumetric measurement methods, the most popular is membrane method (or buoyancy method). This method is based on the change in buoyancy of the specimen in a liquid. After filling with fresh cement paste, a plastic membrane (or rubber) bag is sealed and immersed into a liquid immediately. Autogenous shrinkage is assessed by recording the weight change of the plastic membrane over time [15]. Another method can be found in literature is capillary tube method which is normally used for measuring chemical shrinkage by Le Chatelier contraction [6]. Some researches shown that the autogenous shrinkage measured with volumetric methods is significantly higher than that from linear measurements [16]. Autogenous shrinkage can be estimated by indirect measurement of porosity and change in relative humidity. Results from indirect methods are consistent with those from direct ones [15,16].

Most of the studies in literature are especially for Portland cement. In the case of fast hardening mortar based on ettringite binders, the researches are still few. In these new materials, there is not only the shrinkage phenomenon but also the swelling relating to the early ettringite formation. Therefore, the understanding of the dimensional variation with different measurement methods is required.

2. Materials and test methods

2.1. Materials

The binder used in this research consists of 67% by weight of the calcium aluminate cement, 23% by weight of hemihydrate CaSO₄·0.5H₂O and 10% by weight of Portland cement CEM I. The amount of CA and CA₂ in CAC was 57.2% and 37.5% by weight respectively, which were determined by the Rietveld quantitative phase analysis. The fine aggregate used for fast-hardening mortar composes of quartz sand, carbonate powder and ground granulated furnace slag. The sand to binder ratio is fixed of 1:1. This mortar has a water/solid ratio of 0.33. Some adjuvants (superplasticizer, viscosity modified agent and shrinkage resistance agent) were used with the content of 15% by weight of binder. To control the hardening of mortar, an accelerator and a retarder were added to the mortar with the total content of 0.66% by weight of binder. After mixing, the setting time by Vicat penetration method according to EN 196-3 was determined. The result indicates that the initial setting and final setting time of fast hardening mortar are 40 minutes and 60 minutes respectively.

2.2. Test methods

2.2.1. Horizontal linear measurement

The principle of this method is the measurement of the uniaxial deformation of a bar of fast-hardening mortar (Figure 1). The device consists of a rectangular steel mold 16 cm long, 4 cm wide and 1 cm high. Anchors are placed mid-thickness at each end of the specimens. One end is fixed to the frame; the other is free to move. The measurements are taken automatically every 5 minutes, up to 24 hours when the stabilization of the deformation curves can be observed. The resolution of this measurement is ± 2 μm/m.
In order to measure the deformations as soon as possible after casting, the side faces are removed as soon as the bar has enough rigidity (do not to flow down under its own weight). Demolding is carried out shortly before the initial setting time of the mortar. To limit friction between the mortar and the mold, the walls and the bottom of the mold are covered with petroleum jelly and a stretch film. As the sidewalls are removed during the initialization of the measurements, the friction is only located between the lower part of the bar and the bottom of the mold. To ensure the endogenous condition of the sample, the stretch plastic is covered around the sample before starting the measurement. All measurements were carried out under endogenous conditions at 20°C.

2.2.2. Vertical linear measurement

This technique is called “Cone shrinkage” [17]. Indeed, with this technique, the volume shrinkage of a matrix cast in a cone can be measured. Under an isotropic shrinkage (or swelling), the radius and height \( h \) of the cone decrease or increase by the same percentage. The principle of this technique is as follows: the glass cone is filled with the mortar, a reflector is placed on the surface, a laser measures the variations in height of the cone. The measurements can be carried out in endogenous condition with a plastic covered on top of mortar to avoid evaporation of the water. The measurements can be initialized as soon as the mortar is poured in the cone.

![Device for vertical shrinkage](image)

**Figure 2.** Device for vertical shrinkage [17]

2.2.3. Volumetric shrinkage measurement

The volumetric shrinkage of the mortar was measured as described in detail in [18]. The device used for measuring the endogenous volumetric shrinkage is shown in Figure 3. After mixing, the mortar is poured into a membrane. After a vibration for 1 minute in order to evacuate the air bubbles, the membrane is then tied with a glass wire and to determine the initial mass. The specimen is then placed on a basket submerged in water. This basket is hung under an electronic balance, which is connected to a computer allowing data acquisition. The mass measurement is carried out every minute. The change of volume of the mortar was measured by the amount of liquid displaced by the immersed sample, typically by measuring its weight change.
In order to be able to compare the results obtained by the linear method with that obtained by the volumetric method, it is supposed that the endogenous strain is an isotropic strain. Therefore

$$\frac{\Delta L}{L} = \frac{\Delta V}{3V}$$

Where:

- $\Delta L/L$: Linear deformation of the sample
- $\Delta V/V$: Volume deformation of the sample

3. Results and discussion

3.1. Evolution of dimensional variation of fast hardening mortar with time

The results of dimensional variation of fast hardening mortar with time are presented in Figure 4:

![Figure 4. Evolution of dimensional variation of fast hardening mortar with time](image-url)
The results in Figure 4 indicate the fast hardening mortar begins to shrink quickly until reaching the setting stage; there is a phenomenon of swelling just one hour after mixing. The maximum value of horizontal linear shrinkage is about 0.16mm/m. The evolution of the vertical linear shrinkage by glass cone also agrees with the results of the horizontal shrinkage but shows much more shrinkage than the horizontal linear measurement with the maximum shrinkage value of 1.2mm/m. The difference in the measurement results of these two methods also is due to the different moment of measurement. With horizontal measurement, the data only was recorded at initial setting time, a large part of the deformations at early-age is therefore not measured. While vertical linear shrinkage is recorded after casting.

In case of volumetric shrinkage, it can be seen that the evolution of the endogenous volume deformation is also in agreement with the results obtained for the linear measurements. After the shrinkage phase, the mortar begins to swell very quickly. Comparing to linear method, the volumetric measurement method (converted to linear measurement) give the highest the shrinkage value achieved. The mortar can shrink up to 1.8mm/m. An explanation of the phenomenon will be linked to the pressures exerted by the immersion liquid and by the membrane, which compress the hydrates formed in the microstructure at a very young age. This leads to a possible overestimation of the recorded withdrawal.

In general, the curves of the endogenous shrinkage measurements have the same profile: The swelling after the shrinkage at 0.8h after mixing. The swelling could be related to the fast formation of massive ettringite crystals (E) which is clarified in the Figure 5:

![Figure 5. SEM of fast-hardening mortars after 2 hours of mixing](image)

The expansion of the ettringite binder by the theory of growth of ettringite crystals was proposed by Cohen [19] and confirmed by Evju [20]. They proposed that the formation of ettringite and expansion could be divided into two theories: the theory of crystal growth and the theory of swelling. According to the first theory, expansion is caused by the growth of ettringite crystals that form on the surfaces of the particles or in the solution. The growth of these crystals is responsible for the crystallization pressure and, therefore, the expansive force. Cohen [19] also proposed that the expansion is caused by the swelling of colloidal-size ettringite particles. These particles are commonly designated as a gel with a large specific surface. They consume water to produce expansion by swelling.
3.2. Comparison of the linear and volumetric shrinkage shifted from the initial set

As mentioned above, it is necessary that the mortar must reach certain rigidity in order to receive the results more reliable and comparable between the different measurements. The values of the deformations obtained were shifted from the time of setting to clarify the influence of the three measurement methods. The comparison results are shown in the Figure 6:

![Image of Figure 6: Comparison of endogenous shrinkage measures shifted from the initial setting time](image)

**Figure 6.** Comparison of endogenous shrinkage measures shifted from the initial setting time

The results in the Figure 6 give the interesting information. In 2 cases of linear measurement, the vertical linear measurement shows less shrinkage than the horizontal linear measurement. The smallest deformation recorded when using the vertical measurement can be explained by the influence of friction between the mortars and the wall of the cone that prevents dimensional change. In addition, a possible artifact may be the evaporation of water. When shifted to the moment of initial setting time, the period of evaporation of free water on the surface of mortar in «cone» which causing overestimation the measuring value has been eliminated.

The results indicate the shrinkage value for volumetric measurement is the smallest. This is probably due to the fact that after the beginning of the setting, the mortar formed a relatively rigid skeleton. Therefore, the mortar will expand freely without any obstructions related to the water pressure around the sample. In addition, the friction does not influence the volume measurement method as the 2 linear measurements above, so the degree of volume expansion is also higher.

4. Conclusion

Based on the research results, some main conclusions are drawn as follows:

The evolution of the endogenous deformation of fast-hardening mortar measured by linear methods and volumetric method are in agreement. The mortar begins shrink quickly as soon as recording data, then followed by a swelling phenomenon just one hour after mixing when the mortar begins to set.
When comparing the amplitude of expansion of the mortar. The expansion amplitude in this case of volumetric method is the largest, while the value measuring by vertical linear method is the smallest.

Volumetric method is an easy implementing method. It is suitable in the case of researching the evolution of dimensional measurement as soon as possible with the purpose of hydration kinetic study.

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