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Discussion

On the measurement of free deformation of early age cement paste and concrete [Bjøntegaard Ø, Hammer TA, Sellevold EJ. Cement & Concrete Composites 2004;26:427–435]

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For more than 60 years, attempts to measure the autogenous deformation of cementitious systems have been based on either linear or volumetric methods. In the last three decades, researchers have debated about the disagreement between the two methods and pointed out some of their artefacts [1]. The paper by Bjøntegaard et al. [2] has the merit of participating in this most necessary debate on measurement techniques. However, we believe that some points in the paper need to be discussed. In the following we will address two of these: (1) the relationship between autogenous deformation of a concrete and of its cement paste and (2) the membrane permeability in the volumetric method.

1. Relationship between autogenous deformation of a concrete and of its cement paste

Bjøntegaard et al. mention a number of experimental observations relating to autogenous deformation of a specific concrete and its cement paste, see Fig. 10 in [2]. These include: (1) initial expansion of the concrete while the paste showed considerable initial shrinkage; (2) identical shrinkage rate for concrete and paste after 2 weeks.

Bjøntegaard et al. finally conclude that autogenous deformation of concrete *cannot* be predicted from paste measurements using a simple composite model.

It is our opinion that this conclusion cannot be drawn based on the experiments shown. One reason is that the paste examined by the authors does not relate well to the examined concrete. Water reducing agents, present in the concrete but not in the cement paste, may decrease the surface tension of the pore fluid [3] and thereby influence the autogenous deformation. Water reducing agents may also retard hydration and postpone setting, so that deformations of paste and concrete become kinetically incomparable.

Furthermore, Bjøntegaard et al. use a porous aggregate which can provide the hardening concrete with 15 l/m^3 of internal curing water. This amount is potentially enough to fully counteract self-desiccation of the concrete [4]; in the present case it may account for the observed differences in deformation behaviour between concrete and paste at early-age.

Finally, the choice of the model for calculating the autogenous deformation of concrete, $\varepsilon_{concrete}$, given the deformation of its cement paste, ε_{paste}, is inappropriate. Bjøntegaard et al. have used the following model:

$$\varepsilon_{concrete} = \phi_{paste} \cdot \varepsilon_{paste} \tag{1}$$

where ϕ_{paste} is the volumetric ratio of the cement paste in the concrete.

This formula suggests that the reduction of autogenous shrinkage due to the presence of aggregates is a sort of dilution effect. In contrast with this, it was demonstrated in 1939 by Carlson [5] that shrinkage of concrete with low-modulus aggregates is almost equal to shrinkage of the corresponding cement paste. According to a 2-phase composite model by Hobbs [6], the aggregates act as rigid, non-shrinking inclusions that restrain the deformation of the paste the more rigid they are and the less rigid is the cement paste. Consequently, a significant initial deformation of the paste will not

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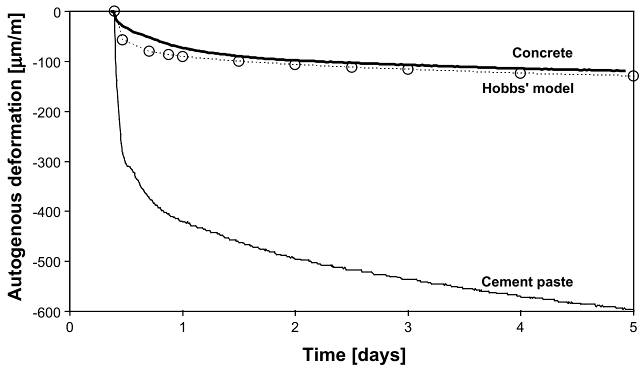

Fig. 1. Measured linear autogenous deformation from setting of concrete and its cement paste with w/c 0.37 and 5% silica fume addition; the paste fraction of the concrete was 0.33 [3]. The dotted curve shows predictions of autogenous deformation of concrete by Hobbs' model [6] based on autogenous deformation of cement paste. Shrinkage is plotted as negative.

result in an equivalent initial deformation of the concrete, since it occurs when the rigidity of the paste is low. Eq. (1) represents a particular case for Hobbs' model, when the aggregates have the same rigidity as the cement paste; notice that this is never the case for normal weight aggregates and furthermore that the modulus of the cement paste changes with hydration. Fig. 1 shows measurements of autogenous deformation of cement paste and concrete [3] together with autogenous deformation of concrete calculated with the simple composite model by Hobbs [6]. Measured and calculated autogenous deformation show the same slope, except from a deviation in the first hours which may be due to creep, microcracking or uncertainties in the determination of the cement paste modulus at early age [3]. Good predictions of autogenous deformation of concrete using Hobbs' model were also obtained by other authors that considered values after 28 days [7]. In synthesis, the model in Eq. (1) is conceptually wrong and gives especially bad predictions of autogenous deformation of concrete at early age.

2. Membrane permeability in the volumetric method

Volumetric measurement of autogenous deformation is frequently performed by placing the fresh cement paste in a rubber membrane immersed in water. The change in volume of the cement paste is measured by the amount of water displaced by the immersed sample, for example by measuring its weight change underwater. As mentioned by Bjøntegaard et al., one reason for the inconsistency between this type of volumetric technique and linear autogenous deformation measurements after setting is transport of water through the rubber membrane.

According to Bjøntegaard et al., the influence of the permeability of the membrane on the volumetric measurements is insignificant until self-desiccation occurs in the cement paste, a few days after casting. Self-desiccation would then cause a relative-humidity gradient across the membrane and drive water from the water bath into the sample. Penetrated water may partially fill the internal voids produced by chemical shrinkage, causing an increase in the submerged weight that is finally interpreted as volumetric shrinkage. On the other hand, water penetration will reduce the shrinkage of the sample or in extreme induce swelling.

We would like to emphasize that the change in immersed weight due to water absorption will completely override the buoyancy change due to deformation of the paste, which will be one order of magnitude lower.

However, we believe that water transport through the condom does not start some days after casting, but instead occurs right from the beginning. A difference in water activity across the membrane exist from the very start of the measurements due to dissolved salts in the pore fluid [1,3]. This difference in water activity constitutes a driving force for osmosis through the membrane, causing a transport of water into the paste.

The amount of water diffusing through the membrane due to osmosis is very significant. To examine this, we measured the water transport through standard latex condoms containing e.g. synthetic pore fluid, when immersed in distilled water. The experiments showed that water transport through the condoms was proportional to the solute concentration; in particular the mass of condoms filled with synthetic pore fluid increased by 0.26% per day.

Water transport into the sample due to osmosis is comparable to the one due to self-desiccation. In fact, high porosity and low tortuosity of the cement paste pore system at early age promote transport of water into the cement paste. Moreover, at early age the transport of water into the sample is entirely liquid based, instead of the slower, combined liquid-gas transport that occurs when pores in the cement paste have been partially emptied due to self-desiccation. As an example, weight measurements on condoms containing cement paste with water/cement ratio 0.35 immersed in a water bath showed a weight increase of 0.17% after 1 day and of 0.32% after 1 week. This artefact would lead to an error on the volumetric shrinkage measurements of about $3600 \times 10^{-6}\ m^3/m^3$ in the first day only, corresponding to a linear shrinkage of 1200 µm/m.

Besides the artefacts resulting from the measuring technique, absorption of water from the bath affects the curing conditions of the sample, which will not be autogenous any longer. To perform measurements of autogenous deformation, the cementitious system must be: (1) sealed, (2) kept at constant temperature, and

(3) not subjected to external forces [1]. Therefore, in the case of water penetrating the membrane the measured deformation is not autogenous deformation.

As a conclusion, water ingress due to osmosis through the membrane seems to compromise this type of measurements of volumetric autogenous deformation from the beginning and not only at later ages.

We are looking forward to continuing investigation and discussion on this subject. The last couple of years of debate in the scientific community suggest that a consensus on these matters will be reached. Research in this field is quite active at the moment: for example a RILEM committee on measuring techniques for autogenous deformation of concrete has been established recently. We are currently investigating measuring methods for autogenous deformation in a 3-year project founded by the Danish Technical Scientific Research Council (STVF).

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