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On the measurement of free deformation of early age cement paste and concrete

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Abstract

Autogenous deformation and thermal dilation produce stresses, which may lead to cracking in early age concrete subjected to external restraint. To quantify the two types of "free deformation" by measurements is a prerequisite to fundamental understanding, as well as to formulate numerical models for use in stress calculations. However, results reported in the literature reveal large deviations and also inconsistencies between different measuring methods. The present paper discusses free deformation measurements and show that different types of measuring errors are involved, where, for instance, reabsorption of bleed water is an important one, and a standard test procedure should therefore describe how to handle the effect of bleeding. Furthermore, it is possible to obtain fairly good reproducibility within one laboratory using the same test rig, whereas a Round-Robin test program showed that it is far more difficult to produce similar results from different laboratories measuring on the same concrete. The implication is that measuring errors were present. Hence, there is a need for more calibration work and better control of test rig behavior.

Keywords: Early age cement paste and concrete; Free deformation measurements; Measuring error; Bleed water reabsorption; Round-Robin test program

1. Introduction

Increasing use of high performance concrete (HPC) has revealed an increased early age crack sensitivity compared to more "normal" concrete qualities, presumably caused by increased *thermal dilation* as well as *autogenous shrinkage*. This is due to high amounts of reactive material (cement and pozzolanes) and low water-to-binder (w/b) ratios in HPC causing both high maximum curing temperatures (i.e. high thermal dilation) and significant self-desiccation (i.e. high autogenous shrinkage). To quantify the two types of "free deformation" by measurements is a prerequisite to fundamental understanding, as well as to formulate numerical models for use in stress calculations.

Research on free deformation in early age concrete is taking place today in many countries, with particular focus on autogenous shrinkage. This has led to numerous publications during recent years and with several conferences exclusively devoted to this subject. It is a trend that each publication presents new results and discusses and interprets these, often with little regard for other sets of results. However, as pointed out in state-of-the-art reviews, [1–4], autogenous shrinkage as presented in different publications varies enormously, both in direction, i.e. from contraction to expansion, and magnitude. And, as importantly, the influence of temperature on autogenous shrinkage varies even more—which is particularly unsatisfactory since varying temperature always is involved in practical situations.

The fact that autogenous shrinkage may occur also as expansion, suggests that the term *autogenous deformation* is a more correct one. This term is used in the present paper.

Another finding from the literature is that the development of the coefficient of thermal expansion (CTE) in early age concrete is rather uncertain since the amount of work reported is very limited. This is clearly unsatisfactory because thermal dilation in most cases is the main contributor to early age stresses. The development of early age CTE is discussed by Bjøntegaard and Sellevold [3–5].

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The inconsistencies present in the literature are clearly related to the fact that autogenous deformation and thermal dilation are complicated phenomena, as well as being a product of different types of measuring errors. The present paper focuses on the latter. Results are presented and, as will be demonstrated, the effects of bleeding must be paid special attention.

A comprehensive Round-Robin test program performed as a part of the BriteEuram project *IPACS* (concluded in June 2001) clearly illustrated the difficulties in free deformation measurements [6]. Some of the results will be discussed in Section 4.

The paper also deals with the inconsistencies that are present between volumetric and linear measurements of cement paste and between linear measurements in cement paste and concrete, which are important aspects in terms of both fundamental understanding and model formulations.

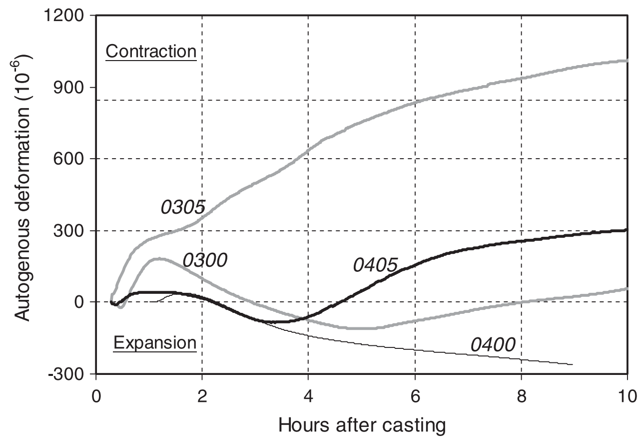

Fig. 1. Effect of w/b-ratio and silica fume addition on autogenous deformation during very early age. 20 °C isothermal tests [9].

2. Volumetric and linear measurements of paste

Autogenous deformation of pure cement pastes and binders can be measured both by volumetric and linear methods. A review of measuring techniques is presented by Hammer [7]. In the *volumetric* one the paste sample is cast in a rubber bag, which is placed in a water bath. Autogenous deformation is then registered as the change in buoyancy. During such tests the effect of bleed water collected on the top of the sample is an important source of error. After setting, the bleed water will be reabsorbed into the paste and recorded directly as an extra contraction. Along with water loss from the top (observed contraction) there will be a swelling of the paste itself, but it has never been observed since the former effect is much larger. Hence, the presence of bleed water strongly overestimates autogenous shrinkage when measured volumetrically. In order to avoid the bleeding, the rubber bag may be placed on rollers to be rotated until final set. The effect of rotation is discussed by Justnes et al. [8]. Another measure to avoid bleeding is of course to use cement paste with no bleeding.

During *linear horizontal* measurements the effect of bleeding is opposite that during the volumetric measurements. In the linear case, the bleed water will be reabsorbed into the sample after setting, but in this case only the swelling of the paste is recorded.

Hammer [9] has measured autogenous deformation (horizontally) from about 30 minutes in cement pastes with w/b-ratios of 0.3 and 0.4, and with 0 and 5% silica fume, respectively, see Fig. 1. Note that no water reducing agent was used and setting occurred after less than 2 h. The results show that the 0.4 cement paste ("0400") expands both during and after setting, whereas the 0.4 paste with 5% silica fume ("0405") expands only a few hours initially before it starts to shrink. The pattern is the same for the 0.3 pastes, but here the expansion phase is totally gone when 5% silica fume is added ("0305"). Note that the pure 0.4 cement paste has most bleeding whereas the 0.3 paste with 5% silica fume has none.

Ettringite formation has been widely discussed as a potential early swelling mechanism (but not proven by experiments), thus there may be underlying swelling mechanism(s) related to chemical reactions. However, considering Fig. 1 (and the Figs. 4 and 5, discussed later) the influence of bleeding reabsorption on the "autogenous swelling" during the first hours after setting appears to be the dominating swelling mechanism in these tests.

Note that vertical measurements (not shown here) on the same cement pastes showed large settlement the first hours or two (which is quite expected since the paste is fluid), but after that (i.e. after setting) the results were quite similar to Fig. 1. Hence, the expansions seen in Fig. 1 occur in all directions.

Investigations have shown that there is an inconsistent relation between autogenous shrinkage measured volumetrically and linearly in the period after setting, Barcelo et al. [10]. In parallel measurements, the volumetric method (transferred to linear deformation, i.e. the volumetric deformation is divided by three) gives generally much higher values (approximately three times the linear one) even if the bleeding effect is non-existing. Several plausible explanations have been suggested, but the origin of the inconsistency is not resolved today. One important thing is that the rubber bags (condom) used are not waterproof, and thus allow water to penetrate, Hammer et al. [1]. The influence is insignificant in the initial phase and shortly after because there is no self-desiccation yet to drive the water through the rubber bag. In the period beyond some days, the effect is however significant.

3. Linear measurements on concrete

3.1. General

Several types of systems for measuring the length change of beams, slabs or cylinders are referred in the literature. Roughly we can divide them into horizontal and vertical systems. Hammer et al. [1] has discussed different set-ups in detail. Length change measurements are performed on specimens with different geometry using numerous techniques, such as: "cast in nails" through end plates, moveable endplates with "plugs", horizontal transverse cast in bars, cast in strain gauge, vertical cast in bars in a concrete slab, metal plates placed on top of a vertical specimen, etc. The movement has been measured using inductive displacement transducers (IDT) or linear variable differential transformers (LVDT). But also "non-contact" transducers like reflection of electronic pulses or laser against a metal chip on the concrete have been used. Different sources of errors are probably associated with the different test set-ups and measuring techniques, this is clearly illustrated in the following.

3.2. Test rig

A principle sketch of a test rig presently being used at NTNU/SINTEF is shown in Fig. 2. The rig allows recording of free length change vs. time for hardening mortar and concrete specimens of 500 mm length and a 100 mm × 100 mm cross section. The horizontally oriented specimen is surrounded by a fully temperature controlled mould. Temperature control is provided by water circulation in copper tubes that are fixed to copper plates forming the mould. The length change (ΔL) is measured at both sides of the specimen. The transducers are connected by an invar steel rod (not shown) to minimize the sensitivity to variations in the ambient air temperature, and the signals are recorded separately and added to obtain the total length change. The measuring bolts connecting the transducers with the specimen are put through holes that are made in the end plates of the mould and the bolts are made with a disc at the end extending 10–15 mm into the concrete sample; hence the "active" measuring length of the specimen is 470–480 mm. The end plates of the form are held in place during the early period when the concrete applies hydrostatic pressure. After setting, the end plates may be gently moved a few mm away from the specimen to allow the specimen to expand freely.

The mould is lined with two layers of plastic sheets with talcum powder in between in order to minimise the friction between the concrete and the mould. A thermocouple is put in the centre of the specimen. The top surface of the specimen is covered with a layer of aluminium foil that is tight against diffusion of water. This aluminium foil is wide enough to be bend down on both sides of the rig where it is fixed with tape. The 5 mm copper plate cover is then placed on top and weighted down to provide a seal against moisture loss. At each test the signals from the two IDT and the thermocouple are recorded continuously. The rig has demonstrated very good reproducibility for nominally identical mixes, Bjøntegaard [2].

3.3. Temperature control of the concrete

Autogenous deformation has proven to be more temperature dependent than most of other concrete properties, Bjøntegaard and Sellevold [2,5]. The hydration generated temperature rise in a specimen with a cross section of 100–150 mm in a mould surrounded by air of constant temperature may be up to more than 10 °C (dependent on material composition and the insulation given by mould walls). Thus, measuring the concrete temperature during such tests is a minimum requirement. For systematic tests, however, it is necessary also to have a temperature control facility in order to maintain a target isothermal temperature of the specimen through the whole test. For the test rig discussed in Section 3.2 this has been done by using moulds with copper tubes fixed on the outside (see Fig. 2), and

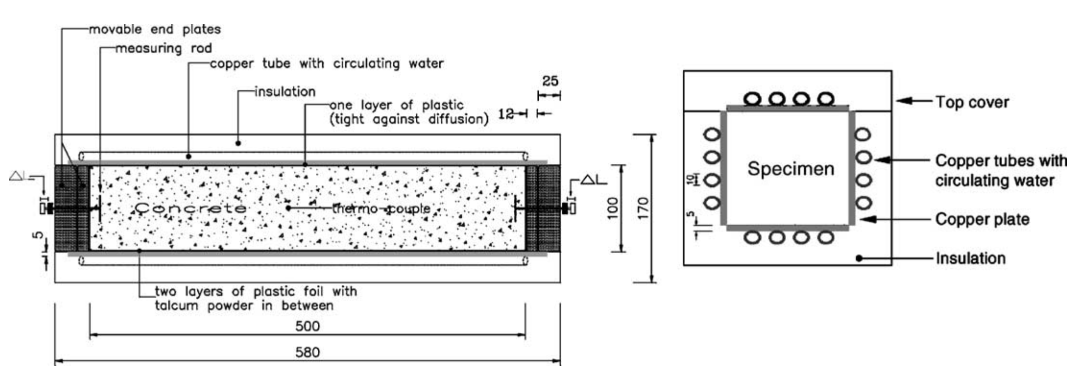

Fig. 2. Measuring system with "cast in nails" in a 500 mm long beam (left) and with a cross section of 100 × 100 mm (right) [2].

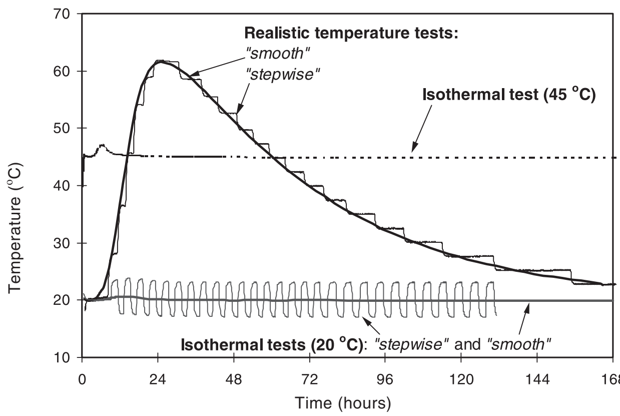

Fig. 3. Examples of measure temperatures during free deformation test (from test in the rig shown in Fig. 2) [2].

temperature controlled water is then circulated. Of course, other techniques to control temperature can also be used.

For the rig shown in Fig. 2, a large number of 20 °C isothermal tests (i.e. where the circulating water keeps a constant temperature of 20 °C) have shown that the temperature increase of the specimen is kept below 1 °C. Isothermal tests at other temperature levels, "stepwise" temperature developments as well as other temperature regimes are also easy to perform, see Fig. 3. Note that the stepwise temperature history shown in the figure is used to determine the development of both the CTE (calculated at each temperature step) and the autogenous deformation (measured directly during the isothermal periods) during realistic temperature histories. The motive behind and use of stepwise temperature histories is described by Bjøntegaard and Sellevold [2,5].

3.4. Sources of error

3.4.1. Bleeding and water in aggregate

The measurements of autogenous deformation can be influenced by *bleed water* collecting on the concrete surface during the fresh phase (i.e. before setting), similar to linear measurements of cement paste—as discussed earlier. After setting, this bleed water may be reabsorbed by the concrete as self-desiccation occurs, resulting in reduced autogenous shrinkage or even expansion (i.e. the reabsorption process provide a situation which is analogue to water curing/ponding), see below. In addition, other water sources such as absorbed water in the aggregates and internal bleeding (water trapped internally under aggregate particles) may also play a role, since very little water is required to "refill" the self-desiccation pores and thereby eliminate autogenous shrinkage.

The effect of the *water in the aggregate* on autogenous deformation was first demonstrated clearly by Hammer [11] for lightweight aggregate (LWA) concrete, and later explored systematically by several researchers [12–15]. The effect has yet not been demonstrated for normal aggregate concrete. Of course the effect will be smaller since normal aggregates contains less water than LWA. Still, we expect that the effect is significant and probably large enough to explain the fact that some results in the literature show low autogenous deformation the first few days.

Bjøntegaard [2] has investigated the effect of bleeding using the test rig described earlier (see Fig. 2). The tested concrete had $w/b = 0.40$ and 5% silica fume of cement weight, and it was added a fixed amount of a plasticiser and a superplasticiser. All concretes had a slump of 150–160 mm in. Fig. 4 shows the results from 20 °C isothermal tests (i.e. reflecting autogenous deformation directly) and Fig. 5 gives results from tests performed under a realistic temperature development with 40 °C temperature maximum after 20 h. (i.e. measured deformation reflects the sum of thermal dilation autogenous deformation).

In the isothermal test (Fig. 4) there is expansion for some hours after setting during standard testing, something that is shown in the three nominal identical tests marked "with bleeding" (i.e. no action done by the operator during the tests). The natural bleeding in this concrete has been measured several times giving an average of 1.2 l/m^3 concrete [2]. As can be seen, the reabsorption of (natural) bleed water gives an expansion of $30–40 \times 10^{-6}$ in the period between 7 and 12 h. In the test marked "bleeding removed" the bleed water was removed from the concrete surface just before setting, reducing the expansion to around 10×10^{-6}. The small expansion may be due to the fact that not all bleed water was successfully removed, or due to the fact that there is internal water available (i.e. from aggregate and/or bleed water trapped internally under aggregate particles). The latter means that the removal of external bleed water will not be enough to eliminate the entire expansion in this concrete. The presence of any expansive chemical

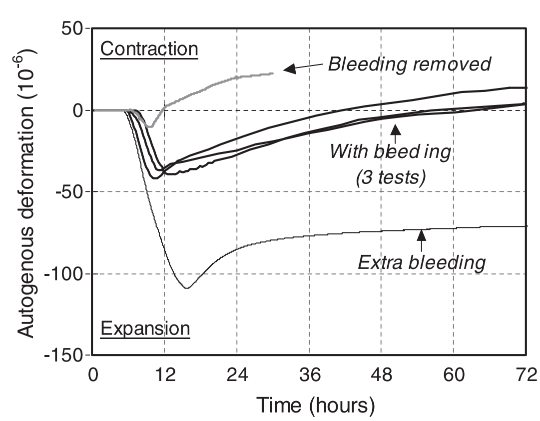

Fig. 4. Effect of bleed water reabsorption on autogenous deformation (from 7 h) during 20 °C isothermal tests [2].

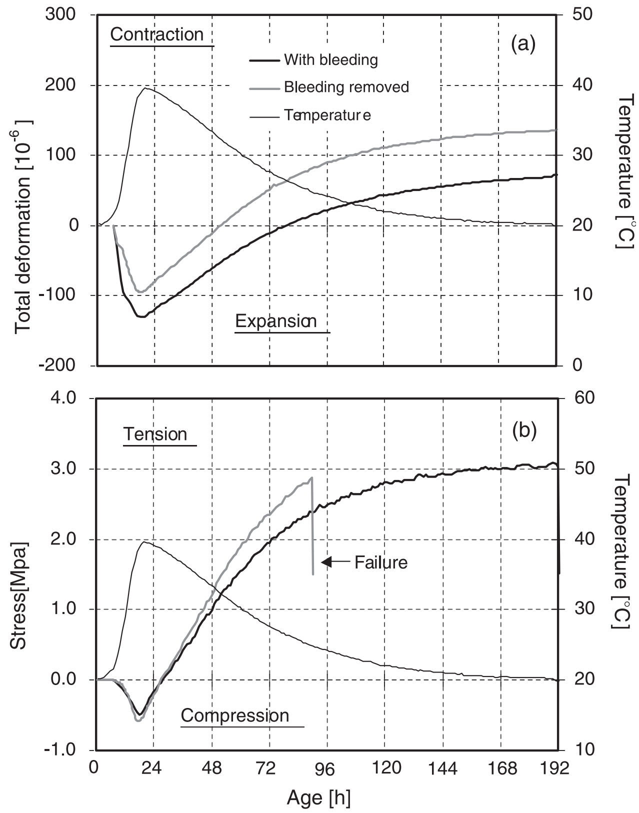

Fig. 5. Effect of bleed water reabsorption on measured total deformation (from 7 h) (a) and stress development (100% restraint) (b) during a realistic temperature development [2].

reaction may also contribute, as discussed earlier, but obviously the effect is very small for this concrete compared to the effect of bleeding reabsorption.

The test denoted "Extra bleeding" is somewhat special since extra water was added to the concrete surface just before setting (giving a total amount of bleed water of 4 l/m^3 concrete on the top surface), hence most of the bleeding was artificial. It is thinkable, however, that such high bleeding could occur also naturally, for instance, for higher superplasticiser dosages or if using a less filler-rich sand. In any case, the expansion now lasted up to 16 h and was totally as high as 110×10^{-6}. Hence, for the tested concrete there is an almost linear relationship between the amount of water collected on the surface before setting and the subsequent expansion of the concrete after setting.

Note that the autogenous *shrinkage* developments (after the initial expansion) are quite different among the three cases of bleeding, showing that initial reabsorption of small amount of surface water may also influence "long term" autogenous deformation. In the case with "natural bleeding" there will be a small reduction of the w/b-ratio (compared to the nominal ratio of 0.40) in the range of 0.005, whereas the subsequent reabsorption causes a permanent increase of the degree of saturation of the capillary pore system (a rough approximation gives a 1% increase (up from about 88–89%) in a mature $w/b = 0.40$ concrete). Hence, the autogenous deformation may also be affected even in the period after all the bleed water has been consumed due to an increased degree of saturation. The effect of reduced w/b-ratio and increased degree of saturation have probably opposite effects on "long term" autogenous deformation, but clearly the degree of saturation effect is the dominant.

The realistic temperature tests (Fig. 5) were supported by a parallel measurement in a "stress rig" (temperature-stress-testing-machine, TSTM) measuring stress development during 100% restraint. The TSTM apparatus is described in [2]. Initially (between 6 and 10 h) it can be seen that there was about 50×10^{-6} more expansion in the test "with bleeding" (Fig. 5a), probably due to reabsorption of bleed water and thus autogenous "swelling", which add to the thermal expansion caused by the heating. The concrete stiffness was, however, very low in this early period and the additional expansion was not measured in the TSTM-test as more compression (Fig. 5b). Significant stresses were measured in the TSTM from about 10 h, beyond which the expansion (i.e. from 10 to 20 h) was quite similar in the two tests.

Furthermore, during the cooling period between 20 and 90 h (Fig. 5a) there is about 30×10^{-6} more contraction in the test performed without bleeding ("bleeding removed"). The parallel stress developments (Fig. 5b) are quite coherent with this as there is more tension developed in the test run without bleeding (2.9 MPa vs. 2.5 MPa at 90 h), causing failure in tension after 90 h at 2.9 MPa. The deviation between the two tests of 0.4 MPa at this point is the largest seen between nominal identical tests in this particular TSTM apparatus [2], hence it is likely that the differences in Fig. 5b are induced by different bleeding reabsorption and the subsequent (permanent) difference in degree of saturation.

A third test series was performed similar to the realistic one described above, but with 62 °C as temperature maximum. In this series the effect of bleeding was not noticeable. Of course, both the free deformation and the stress measurements is relatively more influenced by temperature (i.e. thermal dilation) as the temperature maximum is increased and, subsequently, the influence of bleeding on autogenous deformation will be more difficult to detect.

It seems therefore quite clear that bleeding will disturb a fair comparison between different concretes having different bleeding characteristics. Also, when considering equal concretes, the bleeding is influenced by specimen size, degree of compaction, time between mixing and finishing, time before moisture protection, etc., which are points to keep in mind when comparing results from different laboratories. In addition, the CTE of concrete is also very sensitive to the degree of saturation [2,5], hence during realistic temperature histories both the autogenous deformation and the thermal dilation will be affected by bleeding.

3.4.2. Temperature effect on measuring bolts

When free deformation tests are performed with variable concrete temperature the measurement is influenced by the thermal movement of the cast-in bolts in a test set-up as shown in Fig. 2, since heat is transmitted from the concrete to the bolts. Hence, the measured length change (ΔL_m) during such tests is:

$$\Delta L_m = \Delta L_c + \Delta L_b \tag{1}$$

where ΔL_c is the length change of the concrete and ΔL_b is the length change of the bolts. The moveable parts of the measuring rig are indicated in Fig. 6.

Bjøntegaard [2] has measured bolt temperature during varying temperature developments, and thereby estimated bolt movements. Three thermocouples were fixed to one of the two measuring bolts (indicated in Fig. 6) in addition to the standard measurement of concrete temperature. Fig. 7 shows average bolt temperature plotted against the concrete temperature during temperature cycles between 5 and 60 °C. Two types of measuring bolts were studied—both with length of 70 mm (i.e. total length were $2 \times 70 = 140$ mm), whereas the diameters (D) and type of steel were different. Ambient air temperature was 22 ± 0.5 °C during the measurements.

As can be seen from Fig. 7, there is an approximately linear relationship between the concrete temperature and the temperature of the bolts within the applied temperature range. As indicated in the figure (trendline), as much as 54% of the temperature change in the concrete occurs as a (average) temperature change in the thinner bolt ($D = 3$ mm), whereas the percentage is 66% for the thicker bolt ($D = 7$ mm) due to higher volume/surface area. The smaller bolt was made of invar steel (CTE $= 1.65 \times 10^{-6}$/°C), while the larger one was made of ‘‘conventional’’ steel (CTE $= 10 \times 10^{-6}$/°C). In the case where the CTE of the concrete is, for instance, 10×10^{-6}/°C it is then easy to calculate that the measuring error caused by bolt deformation is 2.4% for the invar bolt and as large as 16.5% for the steel bolt. It is notable that the measuring error caused by bolt movements increases with decreasing CTE of the concrete.

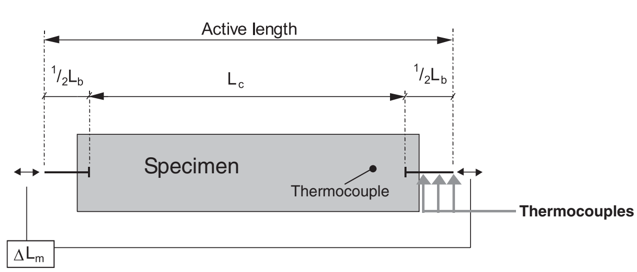

Fig. 6. The concrete (L_c) and the measuring bolts (L_b) deform when using a test set-up as shown in Fig. 2. The deformation of the bolt constitutes a measuring error [2].

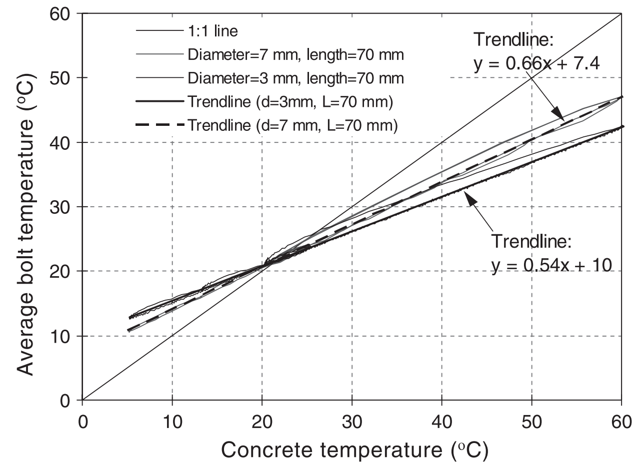

Fig. 7. Measured bolt temperatures vs. measured concrete temperatures for two types of measuring bolts. The measurements are done in the test rig shown in Fig. 2 [2].

It is therefore quite clear, and not very surprising, that the measuring error set-up by measuring cast-in bolts may be significant and, hence, the use of (thin) invar bolts are highly recommendable in order to reduce the error and the subsequent compensation. A point to consider is also the fact that some measuring devices (for instance, linear differential transformers, LVDT) may be sensitive to temperature. Thus, as little heat from the concrete as possible should be ‘‘allowed’’ to transmit.

3.4.3. Moisture protection

Usually, plastic or aluminium foils are used to cover the top of the specimen. Since the other sides are protected by the mould during testing and the testing time is relatively short, such foils will normally give sufficient sealing. However, considering the importance of any water loss, weight measurements at the start and the end of testing should be done.

3.4.4. Friction

Friction between specimen and mould should, of course, be as small as possible. Friction is probably much more important before setting than after. Experience with the rig described in Section 3.2 and with similar rigs [7] show that concrete should not be in direct contact with the mould, since the concrete develops underpressure soon after casting, Hammer [16,17], causing high friction. For instance, using two layers of plastic sheets with talcum powder in between has shown to perform well [2,10].

4. Round-Robin test results on free deformation of concrete

The test rig described in Section 3.2 was one of the rigs that took part in a Round-Robin test program within the EU-project *IPACS*. The full Round-Robin test program [6] involved laboratories from universities and research centres where many concrete properties were investigated. Here only the free deformation measurements are discussed. The measuring rigs that were used varied both in terms of geometry and measuring technique. The results from the test program illustrate the difficulties associated with free deformation tests, see below.

Prior to the Round-Robin tests, concrete part materials from one source were distributed to all participants together with target recipes and mixing instructions. The prescribed concrete had a w/b-ratio of 0.40 and 5% silica fume of cement weight.

Two test series were performed: One 20 °C isothermal test series (Fig. 8) and one test series where the concretes were subjected to a (target) temperature history with a temperature maximum of 40 °C after 20 h (Fig. 9). In the latter test series, of course, the measured deformations are the sum of thermal dilation and autogenous deformation. It can be seen, for both test series, that the measured specimen temperatures were quite close to the target temperature, hence the precondition for producing similar results in the different test rigs was present. But, as can also be seen, the measured deformations varied greatly. Particularly disappointing are perhaps the results during the cooling phase in Fig. 9, a period where the concrete is quite mature and has developed significant strength. For example, within the time period between 48 and 144 h it can be seen (Fig. 9a) that the measured cooling was 12–13 °C in all tests whereas the contractions (Fig. 9b) in the same time period vary between 55×10^{-6} and 180×10^{-6}—and with a smooth "distribution" of results between the extremes. This only proves that there are major faults with some measurement systems and/or procedures. When mixing concretes in different laboratories there is always a chance of doing something slightly different (despite of detailed instructions), but the deviating results, especially in Fig. 9b, are far to large to be explained by possible minor differences in mix composition or varying mixing procedures.

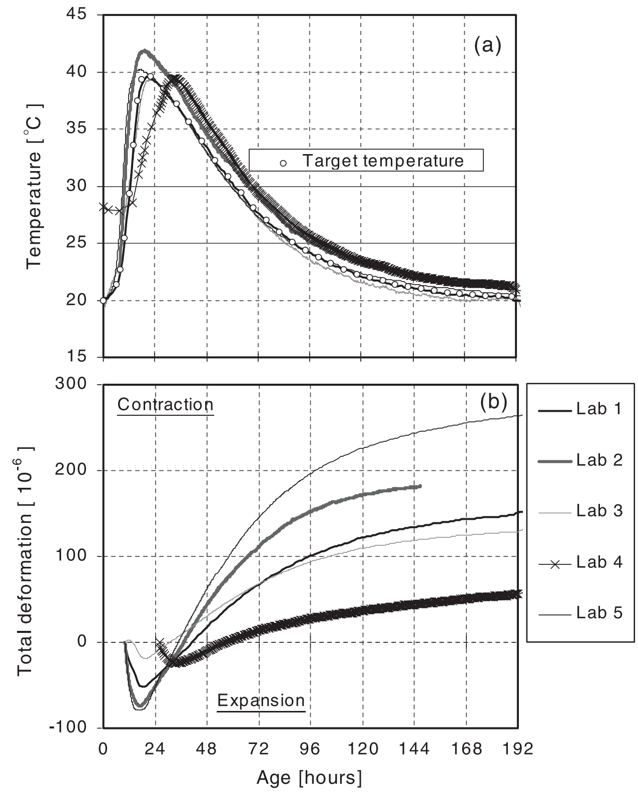

Fig. 9. Round-Robin test results: Measured temperatures (a) and total free deformation (from 10 h) (b) during tests performed with a realistic temperature development with target 40 °C maximum after 20 h [6].

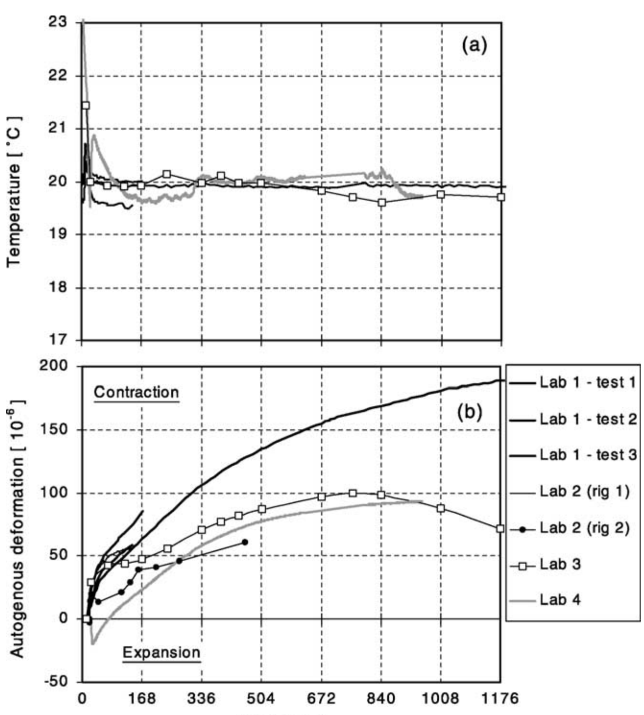

Fig. 8. Round-Robin test results: Measured temperatures (a) and autogenous deformation (from 12 h) (b) during 20 °C isothermal tests [6].

The results also show that it is possible to obtain fairly good test-to-test reproducibility within one laboratory when using the same test rig. But, of course, in principle it does not disprove the possibility that also measuring errors are reproduced.

Finally, the Round-Robin test results clearly show the difficulties associated with free deformation measurements, and it is likely that some of the measuring errors discussed previously have contributed to the deviations. There is clearly a need for more calibration work and better control of test rig behavior, before results are interpreted as concrete behavior.

5. Linear measurements of paste and concrete

Much research has been done on cement pastes and binders in order to study autogenous deformation. Such measurements are well suited for fundamental studies, but appear to be difficult to use in terms of predicting concrete behavior, see below.

Measurements of autogenous deformation at 20 °C on a concrete and the equivalent paste with $w/b = 0.40$ with 5% silica fume has been performed by Bjøntegaard [2], where both the concrete and cement paste were tested in the test rig shown in Fig. 2. To ensure good temperature control in the cement paste test, the cross section of the specimen was reduced to 50×50 mm (cross section of the test rig is 100×100 mm) by filling the mould with additional steel plates. The paste did not contain any plasticisers, while the concrete contained both a plasticiser with a retarding effect, and a superplasticiser.

As can be seen from the results in Fig. 10, the development during the first week is very different: The expansion of the concrete at the beginning is due to reabsorption of bleed water, as discussed earlier. The paste did not show any significant bleeding and also behaves fundamentally different as it starts with a rapid shrinkage. Furthermore, the slower development of the concrete in the first week is probably partly due to swelling of the paste as it absorbs water from the aggregates (absorbed water in the aggregates constitutes approximately 15 liter/m^3), and partly due to a restraining effect of the aggregates. However, from approximately two weeks there is no significant difference in the developments. This is a bit surprising since one should expect a slower rate in the concrete due to the restraining effect of the aggregates (it is also reasonable that water in the aggregate may contribute to a higher degree of hydration in the concrete, leading to progress of autogenous shrinkage over longer times).

The following parameters may then explain the inconsistency between autogenous deformation measured in cement paste and concrete:

(1) The concrete contains plastisicer/superplasticiser, as already stated, and the chemical influence on autogenous deformation is not clear, but it will certainly promote bleeding, which may be reabsorbed and thereby reduce autogenous deformation.
(2) In the concrete there will be water in the aggregate and internal bleeding will be available for the paste and thereby reduce autogenous deformation.
(3) In concrete there is restraint by the aggregate due to its high stiffness and physical/chemical bonding (varying with time) with the paste.

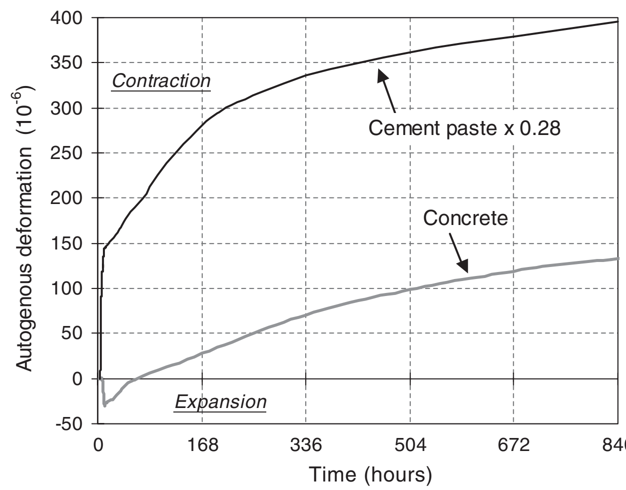

Fig. 10. Autogenous deformation in concrete ($w/b = 0.40$ and 5% silica fume) and an equivalent paste converted to its volume fraction (28%) in the concrete [2].

The implication of this is that autogenous deformation of concrete cannot be predicted from paste measurements using a simple composite model. For fundamental studies, however, cement paste tests are preferable, since concrete measurements are associated with "noise", as listed above.

6. Conclusions

Free deformation measurements are associated with different types of measuring errors, where, for instance, reabsorption of bleed water is an important one. A standard test procedure should describe how to handle the effect of bleeding.

Fundamental studies on autogenous deformation (and thermal dilation) should be performed on cement paste, since concrete measurements involve different types of disturbing water sources (external/internal bleeding, water in the aggregate and plasticisers). A consequence of this is, however, that the relation between autogenous deformation (and thermal dilation) from cement paste and concrete is not at all clear. Furthermore, systematic investigations on autogenous deformation and thermal dilation require strict control of concrete temperature, hence test rigs should be equipped with a temperature control facility.

The present inconsistencies that are seen between volumetric and linear measurements of cement paste are unsatisfactory—this issue should be investigated in future tests.

It is possible to obtain fairly good reproducibility within one laboratory using the same test rig. A Round-Robin test program measuring free deformation of concrete showed, however, large deviations. There is clearly a need for more calibration work and better control of test rig behavior before any meaningful evaluation of the varying results on autogenous deformation and CTE is possible.

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