Abstract
This paper is a summary of the most important points of the state-of-the-art report on the same subject written as a part of the RILEM TC EAS (Early Age Shrinkage Induced Stresses and Cracking in Cementitious Systems) overall report to be published in the near future.

1. Introduction
The stress generating deformation in concrete structures at early ages are the thermal dilation (TD) and autogenous deformation (AD). In order to utilize the commercially available computer programs for stress and cracking risk calculations, it is necessary to have mathematical models for these two properties for the relevant concrete composition under realistic temperature developments during the first 1 - 2 weeks. Such models are not available today, but based on a literature review and experimental work within the BriteEuram IPACS and Norwegian Research Council projects the current status is summarized and recommendations on how to proceed are given /1/-/4/. The following discussion and figures use, however, results from NTNU to show and exemplify some main features of the topic.

The work has demonstrated that the total deformation (TD + AD) may easily be determined using suitable equipment, but the two are interrelated, and consequently their separation depends on the experimental procedure used to achieve this goal. The recommended approach is to determine the thermal dilation coefficient periodically during the hydration process. Knowing the temperature development the TDC may be used to determine the TD. The TD is then subtracted from the total measured deformation, producing the AD component. This procedure is recommended since the other possibility to separate the two types of deformation, find AD and deduce TD, has been shown not to work.
2. Thermal Dilation

In most applications a fixed TDC-value near $10 \cdot 10^{-6}/\text{°C}$ is used. However experiments where sudden temperature steps have been imposed on a sample at periodic intervals have clearly demonstrated that the TDC varies with the degree of hydration at early age. Fig. 1 illustrates typical behavior for a concrete with water-to-binder-ratio of 0.40, 5% silica fume and 28 vol% binder. Results from different experiments are plotted together /1/. The TDC decreases strongly up to 10 - 12 hours, and then increases gradually over time. Fig. 2 demonstrates that self-desiccation is primarily responsible for this increase since a rewetting of the sample after 12 weeks reduced the TDC to almost the original minimum value. The change is about 35%, clearly a significant change with important consequences for stress calculations. The initial drop in TDC (Fig. 1) is believed to be caused by the transition from a liquid dominated state to one where a solid skeleton with not fully water filled pores controls the behavior.

The determination of the TDC involves an uncertainty; a sudden temperature change imposed on a specimen results in a slower deformation response. This time-dependent deformation is in addition to the “background” AD; and of course means that the calculated TDC-value depends on what part of the deformation is considered to be caused by the sudden temperature change. This “delayed temperature response” differs between heating and cooling steps, and its magnitude varies with degree of hydration and moisture content. We believe the effect to be strongly related to moisture redistribution, which is an effect also discussed in the literature. More work is needed to understand the effect, which is fundamental to separate the two types of deformation TD and AD.

Fig. 1 Development of the thermal dilation coefficient (TDC) vs. time for different temperature regimes. Concrete with w/b-ratio of 0.40, 5% silica fume and 28 vol% binder. /1/
Fig. 2  Effect of the degree of capillary saturation (DCS) on the thermal dilation coefficient (TDC) of a w/b = 0.40 concrete. /1/

3. Autogenous Deformation

The easiest approach to modeling AD would be if it could be considered a simple thermally activated quantity and applying the maturity concept to construct the AD for any given temperature development based on one isothermal measurement. This approach has been documented not to work /1, 3, 4/. Fig. 3 shows isothermal AD curves (positive value is shrinkage) at 4 temperatures, and Fig. 4 the corresponding stress development curves under 100% restraint for parallel tests in a TSTM-rig. All curves are zeroed at $t_0$, the time at which the concrete is sufficiently stiff for AD to generate significant stresses /2/. Fig. 3 shows clearly that a simple maturity transformation of the time scale cannot make the curves coincide; the rate of AD development is not simply related to temperature, and the amount of AD is strongly temperature dependent in a non-systematic manner.
Fig. 3 Autogenous deformation after $t_0$ during isothermal tests at different temperatures. a) shows the first week and b) shows all results (1 month). W/b = 0.40 concrete. /1/

Fig. 4 Restraint stresses during isothermal tests at different temperatures. a) shows the first week and b) shows all results (1 month). W/b = 0.40 concrete. /1/

In /1/ new strategies were tried out to investigate the topic further. Fig. 5 shows examples of temperature histories that formed the “experimental strategy” during the work. The different temperature histories are briefly described below:

- During isothermal tests the “pure” effect of AD is measured.
- In “poly-isothermal” tests the concrete was cast with a fixed starting temperature from mixing (20 °C in Fig. 5) until 8 hours were the temperature was increased in steps of 7-10 °C until the desired isothermal temperature were reached. This “final” isothermal level (45 °C in Fig. 5) was then maintained until the end of the test. At each temperature step the thermal dilation coefficient (TDC) can be calculated.
Different temperature histories imposed to concrete specimens in order to separate thermal dilation (TD) and autogenous deformation (AD). /1/

- During “smooth” realistic temperature histories, of course, TD and AD occur simultaneously and the individual behavior of the two cannot be observed directly.
- In “saw-toothed” tests the principle is to superimpose temperature steps of 2 - 10 °C for some hours duration on either isothermal or realistic temperature developments. This scheme allows the calculation of TDC at each step, and then to calculate AD by removing the TD-contribution from the total measured movement.

Fig. 6 shows the results of “poly-isothermal” experiments where the temperature was imposed in a more realistic manner than in “pure” isothermal tests by steps to 35 °C from two initial temperatures; 13 °C and 20 °C (denoted “poly-isothermal”, see Fig. 5). The right side of Fig. 6 shows the resulting AD after the thermal contribution has been removed by curve fitting. Again there is an influence of temperature that precludes the application of a simple maturity transformation of the time scale.
For the realistic case when the concrete heats up and then cools down the situation is even more complicated. Fig. 7 shows an example where the concrete has been heated to 60 °C (hence the notation “saw 60 A” etc.) using different temperature step configurations to allow calculation of TDC development also. The total deformation was measured in each case, and the TDC-values plotted were determined from the sudden deformation at each temperature step. The AD plots are the result of subtracting the TD from the measured total deformations. Fig. 7 shows a new type of behavior; during the cooling phase (after about 24 hours) there is first a positive AD, followed by a negative (expansion!) phase /1/, /3/. This phase continuous for a while after isothermal conditions are reached, demonstrating that the phenomenon is real and not a product of the calculation procedure. Over longer times the AD again becomes a gradual contraction /1/.

This type of behavior has been found also for other concrete mixes /4/, and we believe it demonstrates clearly that the AD is a very complicated function of the entire temperature history of a given concrete. It also demonstrates that modelling of AD for stress and cracking risk calculations requires extensive testing before we can construct models with general validity. We believe the experimental approach outlined above is a good starting point in this process.
Fig. 7  Saw-toothed realistic tests with 60 °C maximum: Calculated thermal dilation coefficient (TDC) in a), and remaining autogenous deformation in b) (zeroed at $t_0$). TDCs from "poly-isothermal" test are included in a).
4. Conclusions

- The AD (autogenous deformation) of concrete is a very complicated function of the entire temperature history of the concrete which cannot be characterized by one or a series of isothermal tests at different temperatures.

- Our recommended approach is to superimpose temperature steps periodically on a realistic temperature curve. The deformation steps are then used to calculate the TDC (thermal dilation coefficient), which allows the calculation of the TD (thermal dilation) for the given temperature history. Subtracting the TD from the total measured deformation yield the AD.

- Systematic application of this approach to a variety of different concrete mixes in different laboratories should be the basis for constructing mathematical models for AD for use in calculations of stress development and crack risk.

5. References


/2/ Bjøntegaard Ø., Kanstad T., Sellevold E.J. and Hammer T.A. (1999), ‘Stressinducing Deformations and Mechanical Properties of High Performance Concrete at Very Early Ages’, In the 5th International Symposium on Utilization of High Strength/High Performance Concrete, Sandefjord, Norway
