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Test method for determining coefficient of thermal expansion of high-performance concrete at early age

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Abstract: This paper presents a new experimental approach to determine the coefficient of thermal expansion of concrete at early age, in which sealed concrete prisms (75x75x295mm) are subjected to temperature cycles from 25 to 30°C in an environmental chamber from the time of setting to seven days. The entire test apparatus, including moulds and sensors, was carefully temperature-calibrated to obtain highly accurate measurements. A new calculation method is proposed to eliminate autogenous shrinkage from the measurements before the coefficient of thermal expansion is determined from the thermal deformation obtained as a function of time. For the high-performance concretes tested in this study (with and without internal curing), it was found that the coefficient of thermal expansion decreased towards a minimum value of 8 x 10^{-6}/°C one day after the setting of concrete, and increased gradually up to a value of 10.5 x 10^{-6}/°C at 7 days. The increased concrete moisture due to internal curing did not appear to affect the coefficient of thermal expansion.

1. Introduction

Thermal stresses have been a major cause of early-age cracking in concrete structures. The wider use of high-performance concrete (HPC) with high cement content may aggravate this problem if the rise of concrete temperature due the exothermic hydration reaction is not controlled during construction. With the rapid changes in the microstructure of the concrete during cement hydration, thermal expansion of concrete is not proportional to temperature changes at early age. This makes it difficult to accurately predict the thermal deformation of concrete at early age – a time at which the risk of cracking is high.

It is well known that the coefficient of thermal expansion (CTE) of mature concrete is mainly influenced by the type of aggregate [1]; however, very limited data can be found on the time-evolution of the CTE in young hardening concrete. The general agreement is that the initial value of CTE is relatively high in fresh concrete (above 20×10^{-6}/°C), and reduces rapidly to approximately 10×10^{-6}/°C during the hardening process [1]. High values of CTE in fresh concrete are attributed to the predominance of unbound water in the liquid phase, which has a CTE about seven times that of mature concrete. Later, when the microstructure of concrete has started to form, a solid material behaviour takes place, resulting in a lower and more stable coefficient of thermal expansion.

At very early-age, however, no general agreement exists in the literature on the time-evolution of the concrete CTE. Some researchers found that its value is independent of age [2], while others reported that it slightly increases over time [3], or slightly decreases over time [4]. Recent work [5] reported that the value of CTE decreases for the first 10-12 hours after casting, and increases over time until a constant value is reached a few days later. The amount of work reported in the literature on the CTE of young concrete is rather limited. It is therefore difficult to establish typical values of CTE for young concrete because the solid nature of the material is in transition and the early non-thermal effects of hydration are superimposed on the thermal effects [6].

Measuring thermal expansion of concrete is not straightforward, as it is a heterogeneous, porous and aging material. Two main approaches for measuring the thermal deformation at early age have been used in the literature: (i) elimination of autogenous shrinkage from the total deformation measured by subjecting two identical concrete samples to two different temperature histories; and (ii) subjecting one concrete sample to repeated temperature cycles. Both approaches are described as follows:

In the first approach, used by Laplante [7], two samples were made from the same concrete and placed in flexible plastic moulds. One of the two samples was thermally insulated, and both were instrumented with embedded strain gauges and thermocouples. Under constant ambient temperature, the two concrete samples were monitored for strain and temperature due to shrinkage and heat produced by cement hydration. The data analysis consisted of: (i) calculating the maturity of the samples by the equivalent time method; (ii) plotting the strain differences between the two samples as a function of their temperature differences; and (iii) determining the CTE from the slope of the curve at given maturities. It is possible, however, that the accuracy of the obtained CTE may decrease after several days when the temperature difference between the two concrete samples becomes small.

In the second approach, used by Bjontegaard [8], a concrete sample was subjected to a realistic temperature history, which was superimposed by small temperature cycles. The amplitude of these cycles was kept small enough to assume a constant CTE during the cycle, but high enough to obtain acceptable measurement accuracy. The period of these cycles was short enough to reduce autogenous shrinkage effects, but long enough to avoid thermal gradients in the concrete sample. In this case, the use of the maturity concept is not required.

Although these approaches seem appropriate for determining the CTE of concrete at early age, no general agreement exists in the literature on the test method to adopt. A clear consensus is needed in order to reliably predict the behaviour of concrete structures at early-age.

This paper presents a new experimental approach for the determination of the coefficient of thermal expansion of concrete at early age under stress-free conditions, with the assumption that thermal and autogenous deformations are not coupled [7]. Test results for two slightly different formulations of high-performance concrete are also presented to confirm the validity of the approach. The test apparatus and calibration procedure presented in this paper had been initially developed for an NRC study on autogenous shrinkage of high-performance concrete structures [9], in which it is important to account for the thermal effects at early age.

2. Proposed test apparatus and calibration method

In the proposed test, a group of 3 sealed concrete prisms are monitored simultaneously in an environmental chamber from the time of setting to at least 7 days of age with temperature cycles varying from 25 to 30°C at the rate of 3 full temperature cycles per day (i.e. 4 hours between the minimum and maximum temperatures).

Figure 1 presents a diagram of the apparatus used for the test. Each mould, made of 9.5-mm thick cold rolled steel plates, had inside dimensions of 75x75x295 mm, which are similar to those of standard moulds for free shrinkage testing according to ASTM C157. Each mould was placed on the web of a structural steel section, to which the displacement transducers (LVDTs) were also attached. Short vertical spacers between the steel mould and the structural steel section ensured that all sides of the mould were exposed to the same ambient temperature. A foam rubber pad, placed between the floor of the environmental chamber and the test apparatus, minimized the ambient vibration (in the environmental chamber). Inside the steel mould, the walls were coated with a layer of petroleum gel and a thin plastic film to reduce friction between the steel walls and the concrete. The end plates (75x75x9.5 mm) of the mould were lined with 1.5-mm thick closed-cell foam rubber sheets to allow free movement of the concrete sample in the longitudinal direction, especially during the thermal expansion periods.

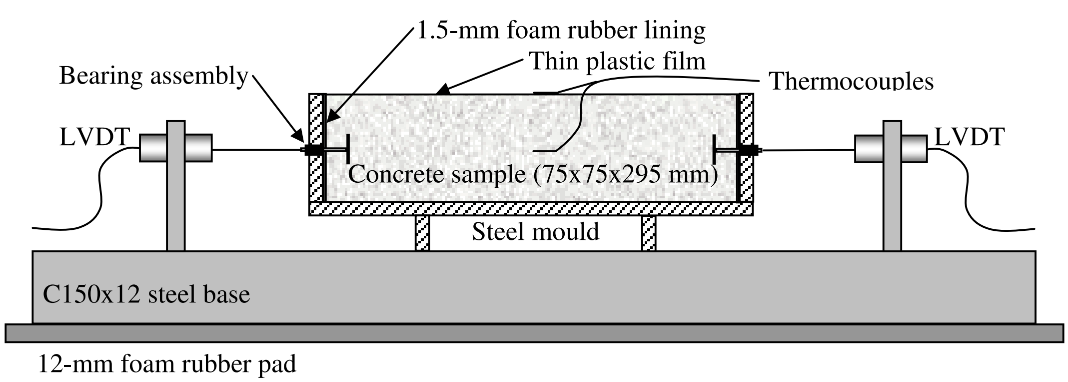

Figure 1: Diagram of test apparatus (showing 1 of the 3 identical setups)

The longitudinal deformation of each concrete prism was measured using a displacement transducer at each end of the mould. These sensors, fixed to the structural steel base of the test apparatus, were connected to 20-mm diameter metal discs by stainless steel extension shafts. The discs were embedded in the ends of the prism during concrete placement. The extension shafts were guided by oil-impregnated bronze bearings mounted in small openings in the mould end plates in order to eliminate transverse displacement of the discs during concrete placement and before the setting of concrete. The concrete temperature was measured by thermocouples embedded in the centre and at the surface of each concrete prism. The ambient temperature in the environmental chamber was monitored with a resistance temperature detector (RTD).

The above measures, taken in the assembly of the test apparatus, were deemed necessary to maximise the accuracy of the readings in order to reduce the error in the determination of the CTE, especially at very early age when its value changes rapidly. It is therefore important to ensure that: (i) concrete deformation is free; (ii) external drying is prevented; and (iii) temperature is uniform in the concrete sample [10].

In this type of experiment, the temperature effects, other than thermal expansion of concrete, must be reduced in order to ensure an accurate determination of the concrete CTE. Both the instrumentation and the test apparatus can be significantly affected by changes in temperature. These temperature effects can be estimated, in theory, using the temperature calibration curves provided by the manufacturer of the sensors, the theoretical CTE of steel and the geometry of the test apparatus. However, it is highly recommended to determine the calibration curve for a given test apparatus by experimental testing in a controlled environment, since theoretical calculations may be based on some uncertain assumptions, thus reducing the accuracy of the measurements.

Three identical test apparatus were built for this experiment and calibrated in an environmental chamber. Their calibration procedure consisted of testing each of the three test apparatus alternatively with three different metal blocks of experimentally predetermined coefficients of thermal expansion. The metals selected were as follows: (i) Kovar, with a measured CTE of 7.2 $x10^{-6}$/°C; (ii) stainless steel 17-4PH, with a measured CTE of 10.7 $x10^{-6}$/°C; and (iii) stainless steel 316, with a measured CTE of 16.4 $x10^{-6}$/°C. This combination of metals was selected for its relatively wide range of CTE in order to cover the range normally expected for concrete made with different types of aggregate. The size of the metal blocks (275 mm long, 75 mm high and 25 thick) was similar to the size selected for the concrete samples except for their thickness since they were machined from 25-mm thick plates. The three test apparatus with the metal blocks were subjected to temperature cycles varying from 20 to 30°C with an intermediate step at 25°C. The amplitude of these temperature cycles was selected to be slightly larger than the amplitudes planned for the tests on the concrete samples. The thermal deformation of each metal block was measured by two LVDTs with their shafts threaded into the metal block. Friction was minimised by applying a thin plastic film and petroleum gel under the metal blocks.

Figure 2 shows the average strains and temperature measured during the calibration of the test apparatus using the three metal blocks (only two full temperature cycles are shown for clarity). Each of these strain curves represents an average of three individual experiments, where each metal block was tested in each of the three apparatus. It is shown that the Kovar block provided the most significant response to the temperature changes while the stainless steel 316 gave the least significant response, due to their different coefficients of thermal expansion. These strain and temperature calibration data were then used to determine the average CTE measured for each metal block on the three test apparatus.

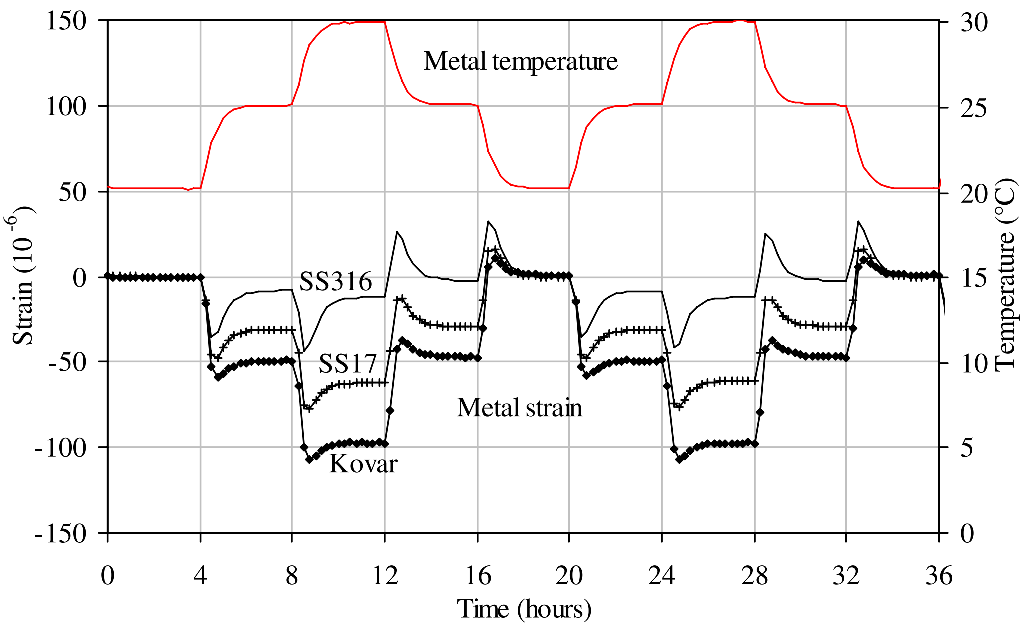

Figure 2: Strain and temperature measured during calibration of apparatus

Figure 3 shows the average calibration curve for the three test apparatus obtained by plotting the known CTE of the metal blocks against their measured CTE in the test apparatus. Each data point is an average of three tests conducted in a different apparatus. The ordinate of the linear regression line in Figure 3 provides the average CTE of the test apparatus, which is 17.1×10^{-6}/°C. It can also be observed that all measured values of CTE are negative, because the CTE of the test apparatus is higher than the CTE of the metal blocks, as expected.

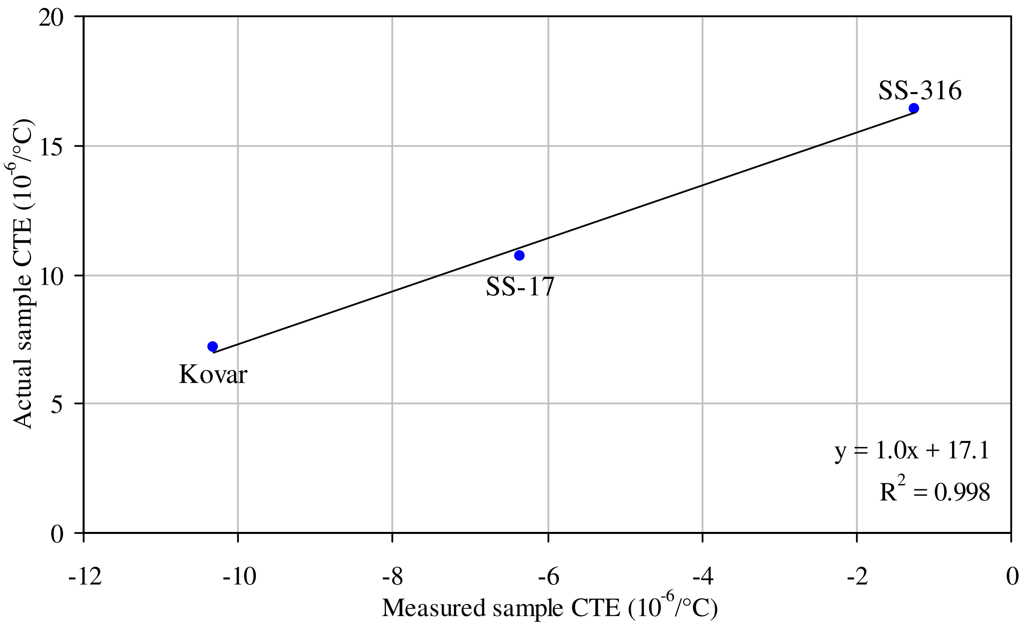

Figure 3: Average calibration curve obtained for test apparatus

3. Thermal expansion of high-performance concrete

Two HPC mix designs, with a water to cementitious materials ratio (w/cm) of 0.35, were used in this study: (i) a typical HPC under sealed curing conditions, and (ii) a low-shrinkage HPC under sealed and internal curing conditions. The internal curing technique consisted of providing internal curing water to cement for improved hydration and reduced internal drying by replacing a volume fraction of the normal-weight (NW) sand by pre-soaked porous lightweight (LW) sand. This LW sand had a moisture content close to 22% by mass. Table 1 presents the two concrete mix designs. Table 2 provides the measured concrete properties, where it can be seen that both concretes reached similar 7-day compressive strengths (50 MPa), however with slightly different air contents. More information on internal curing and its benefits can be found elsewhere [9,11].

Table 1 – Concrete mix designs (for 1 m^3)

Constituent	Reference HPC	Internally-cured HPC
w/cm	0.35	0.35
Water, kg/m^3	150	155
Silica Fume Cement, kg/m^3	429	442
NW sand (max. 5 mm), kg/m^3	870	522
LW sand (max. 5 mm), kg/m^3	–	250
Stone (max. 10 mm), kg/m^3	863	888
Superplasticizer, L/m^3	4.02	2.24
Water reducer, L/m^3	0.87	0.90
Air entrainer, L/m^3	0.01	0.03

Table 2 – Measured concrete properties

Property	Reference HPC	Internally-cured HPC
Slump, mm	150	65
Air content, %	6.5	5.5
Volumetric mass, kg/m^3	2318	2260
Time of setting, hour	6	5
7-day compr. strength, MPa	50	52

The thermal expansion test conducted on the reference HPC will be presented first. Concrete was placed in the three steel moulds and the top surfaces were sealed with plastic sheet to prevent drying shrinkage. The moulds were then placed in the environmental chamber at an initial ambient temperature of 25°C. Two hours after concrete placement, temperature cycles from 25 to 30°C were initiated using a regular saw-tooth pattern. Each target temperature was maintained constant for 3 hours and 45 minutes, with a 15-minute ramp between each temperature step, resulting in three full cycles (or six steps) per day. This 3h45min duration was long enough to reach a stable and uniform temperature in the concrete samples at the end of each step. The amplitude of the temperature cycle (5°C) was selected small enough to obtain frequent values of CTE at early age, as thermal equilibrium is reached more rapidly in the samples. With such small temperature variations, the temperature effect on the development rate of CTE over time can be considered small.

Figure 4 presents the ambient temperature in the environmental chamber, the average concrete temperature and the average concrete strain measured over time (only 3 cycles are shown for clarity).

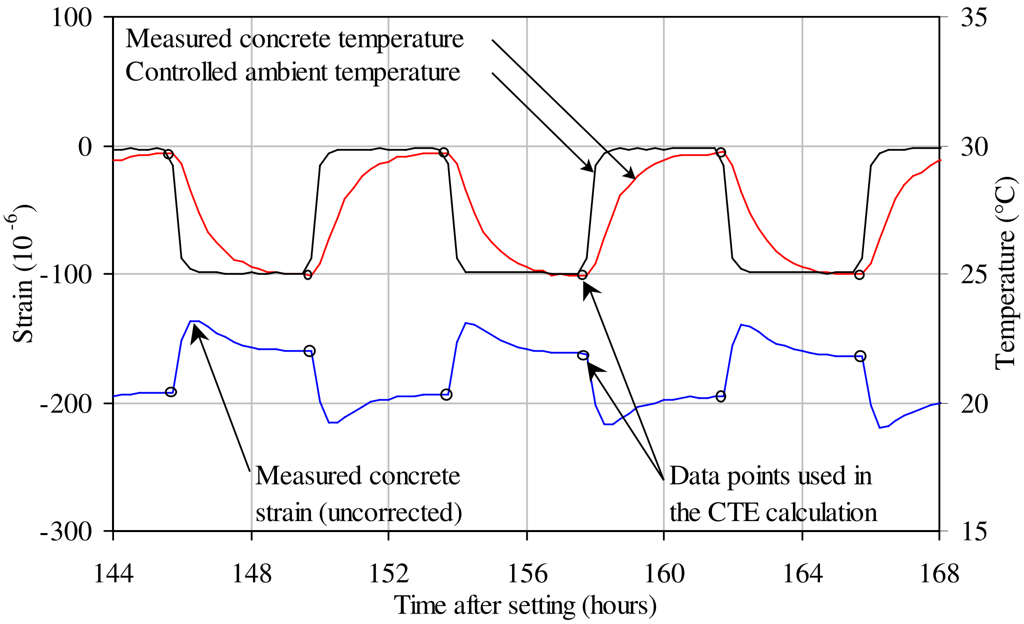

Figure 4: Temperature and strain measured in reference HPC

The total concrete strain was calculated from the measured concrete displacement, and then corrected for temperature effects as follows:

$$\varepsilon_{tot} = \varepsilon_{test} + \alpha_a (T_c - T_{ci}) \tag{1}$$

where ε_{tot} is the temperature-corrected total strain after the setting of concrete, ε_{test} is the uncorrected strain measured in concrete after setting, α_a is the coefficient of thermal expansion of the apparatus (17.1x10^{-6}/°C, from Fig. 3), T_c is the actual concrete temperature, and T_{ci} is the initial concrete temperature at the time of setting.

Figure 5 shows the selected data representing the total strain (average of 3 tests), shrinkage strain and thermal strain obtained in concrete at the end of each temperature step. The concrete shrinkage strain curve (i.e. the non-thermal strain component) was determined by fitting a moving average curve to the total strain curve. The thermal strain was then calculated by subtracting the shrinkage strain from the total strain at any given time, as follows:

$$\varepsilon_{th} = \varepsilon_{tot} - \varepsilon_{sh} \tag{2}$$

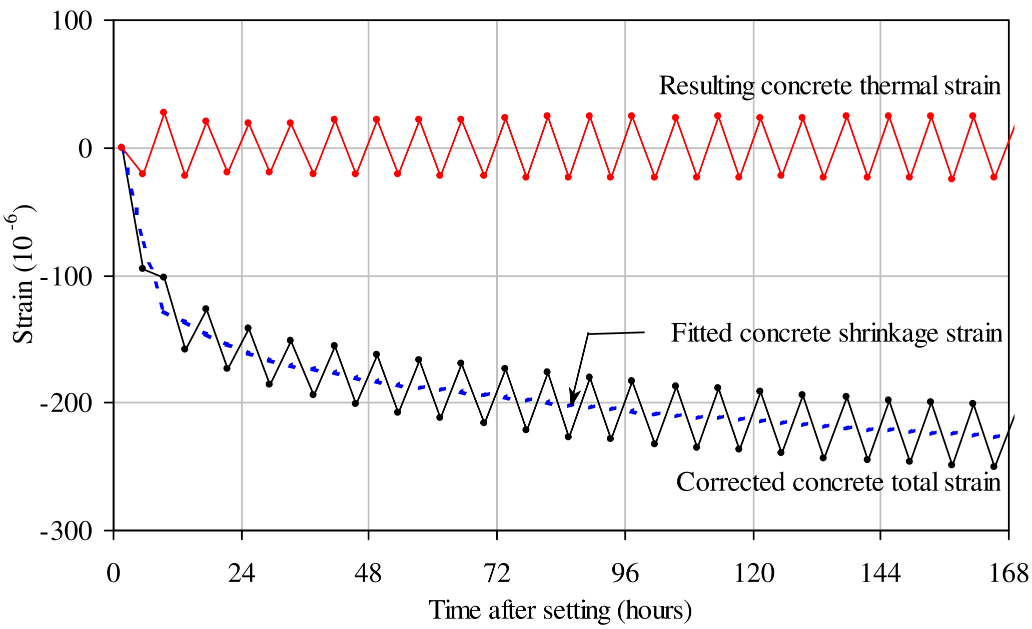

Figure 5: Selected total, shrinkage and thermal strains in reference HPC

4. Thermal expansion of internally-cured high-performance concrete

The reasons for testing an internally-cured HPC were: (i) to verify the effect of increased moisture content in concrete on the coefficient of thermal expansion, and (ii) to verify the validity of the proposed method on a low-shrinkage concrete. Since the determination of the thermal strain depends on the difference between the shrinkage and total strains, it was deemed necessary to verify if the use of a low-shrinkage concrete could improve the accuracy of the tested thermal expansion coefficient.

For the internally-cured concrete, Figure 6 presents the ambient temperature, the average concrete temperatures and the average concrete strain measured as a function of time (only 3 cycles are shown for clarity). The concrete temperature was measured at the centre (solid line) and the surface (dash line) of the concrete sample. These two curves show excellent temperature uniformity within the concrete sample, which never exceeded a difference of 0.4°C at the end of any given cycle.

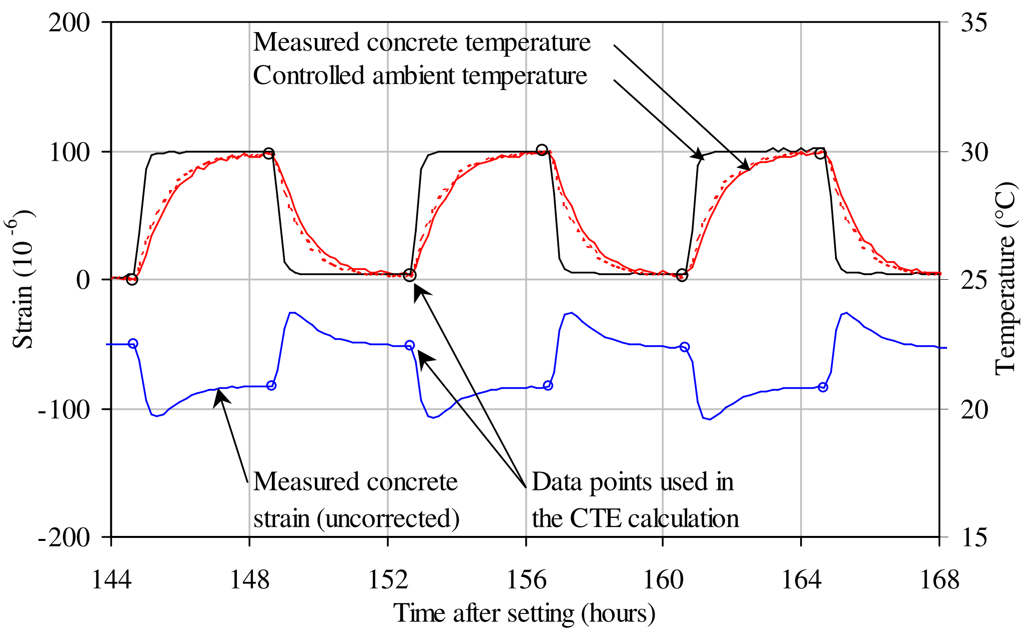

Figure 6: Temperature and strain measured in internally-cured HPC

Figure 7 presents the selected data representing the total strain (average of 3 tests), shrinkage strain and thermal strain obtained in concrete at the end of each temperature step. A first observation is that internal curing, which provided nearly 55 kg/m^3 of internal curing water to the concrete, reduced autogenous shrinkage considerably from -225 to -30 $\mu\varepsilon$ at 7 days (external drying prevented in both cases). The benefits and effectiveness of internal curing in preventing shrinkage and associated tensile stresses in HPC have been clearly demonstrated in previous studies [9,11].

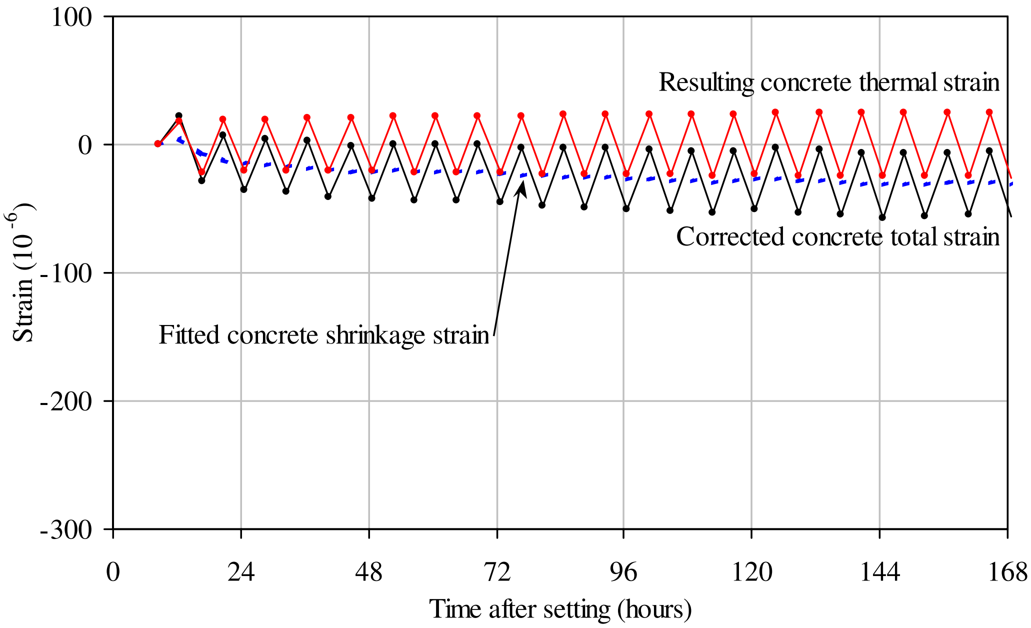

Figure 7: Selected total, shrinkage and thermal strains in internally-cured HPC

5. Resulting coefficients of thermal expansion

The concrete CTE at any given time was calculated with the following equation:

$$\alpha_c = \frac{\Delta\varepsilon_{th}}{\Delta T_c} = \frac{(\Delta\varepsilon_{tot} - \Delta\varepsilon_{sh})}{\Delta T_c} \quad (3)$$

where α_c is the CTE of concrete at a given time, $\Delta\varepsilon_{th}$ is the incremental change in thermal strain between two temperature steps, $\Delta\varepsilon_{tot}$ and $\Delta\varepsilon_{sh}$ are the incremental changes in total and shrinkage strains, respectively, and ΔT_c is the incremental change in temperature between two steps.

Figure 8 shows the values of CTE obtained for the two HPC tested in this study, where each curve is an average of three tests. It appears that the increased concrete moisture content provided by internal curing did not affect the time-evolution of CTE. In general, the CTE of either HPC reached a minimum value of $8\text{x}10^{-6}$/°C one day after setting, and gradually increased up to a value near $10.5\text{x}10^{-6}$/°C at the age of 7 days, with a slightly faster increase during the first 3 days. This initial increase in the apparent CTE at early age may be due to the combined effects of several competing factors, including cement hydration and self-desiccation [6]. The time-evolution of the CTE shown in Figure 8 is also in good agreement with the test results obtained by Bjontegaard and Sellevold [5].

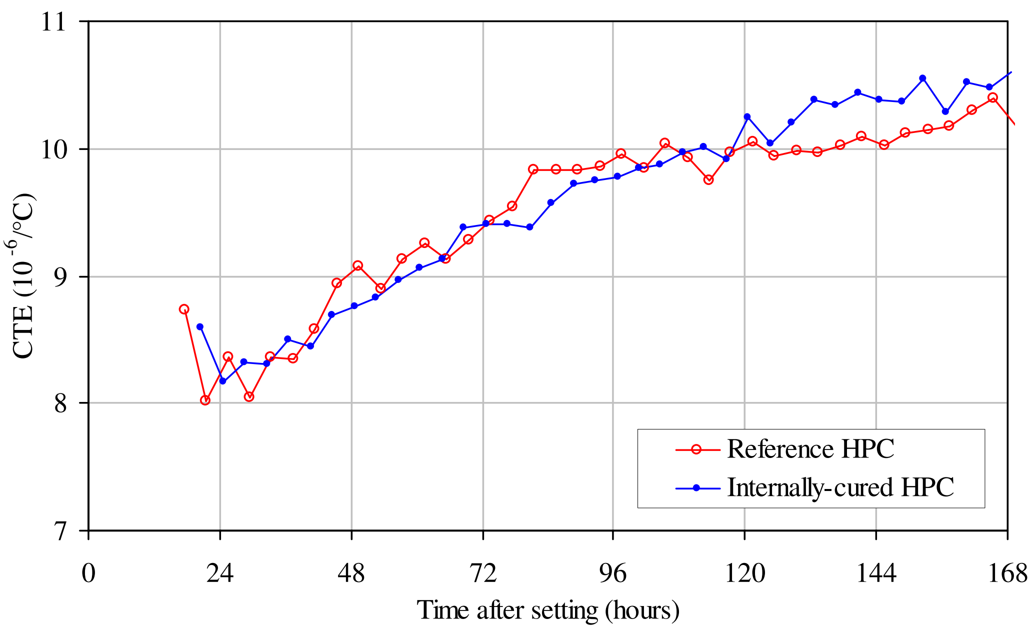

Figure 8: Time-evolution of thermal expansion coefficient of concrete

The average curves in Figure 8 show that the accuracy of the proposed method was not affected by the amount of shrinkage developing in concrete. For each concrete type, a standard deviation of 0.5×10^{-6}/°C and a coefficient of variation of 5% were found between the three individual prisms over a 7-day period.

6. Summary and conclusions

A new experimental approach was developed to determine the coefficient of thermal expansion (CTE) of concrete at early age. Two high-performance concretes (HPC) were tested with and without internal curing, which can reduce shrinkage. The following conclusions are drawn:

- The proposed test and analysis method allows an accurate determination of CTE from only 12 hours after setting of concrete, with an average coefficient of variation of 5% between the test samples;
- The CTE of HPC was observed to reach a low value of 8×10^{-6}/°C only 24 hours after setting and increased gradually up to 10.5×10^{-6}/°C at the age of 7 days, with a slightly faster increase in the first 3 days;
- The higher concrete moisture content provided by internal curing resulted in a considerable decrease in autogenous shrinkage without affecting the CTE of concrete;
- The different amounts of shrinkage observed during testing did not affect the accuracy of the proposed CTE calculation method.

7. Acknowlegements

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8. References

[1] RILEM (1998): “Prevention of thermal cracking in concrete at early ages”, *State-of-the-Art Report Number 15*, prepared by Rilem Technical Committee 119, Editor R. Springenschmid, E & FN Spon, London, England, 348 p.

[2] Mitchell, D. Khan, A.A., Cook, W.D. (1998): “Early age properties for thermal and stress analyses during hydration”, in *Material Science of Concrete V*, Editors J. Skalny and S. Mindess, The American Ceramic Society, 265-305.

[3] Wittmann, F., Lukas, J. (1974): “Experimental study of thermal expansion of hardened cement paste”, *Materials and Structures*, No. 40, 247-252.

[4] Emborg, M. (1989): “Thermal stresses in concrete structures at early ages”, *Doctoral Thesis*, Lulea University of Technology, Division of Structural Engineering, Sweden, 280 p.

[5] Bjontegaard, O., Sellevold, E.J. (2001): “Thermal dilation and autogenous deformation”, in *RILEM International Conference on Early Age Cracking in Cementitious Systems*, Editors K. Kovler and A. Bentur, Haifa, RILEM, 63-70.

[6] Lange, D.A., Altoubat, S.A. (2003): “Early thermal changes”, in *Early age cracking in cementitious systems*, *State-of-the-Art Report No. 25*, prepared by Rilem Technical Committee 181, Editor A. Bentur, RILEM, 37-38.

[7] Laplante, P., Boulay, C. (1994) : “Évolution du coefficient de dilatation thermique du béton en fonction de sa maturité aux tout premiers âges”, Materials and Structures, Vol. 27, No. 10, 596-605.

[8] Bjontegaard, O. (1999): “Thermal dilation and autogenous deformation as driving forces to self-induced stresses in high-performance concrete”, *Doctoral Thesis*, The Norwegian University of Science and Technology, Division of Structural Engineering, Trondheim, Norway, 256 p.

[9] Cusson, D., Hoogeveen, T. (2006): "Preventing Autogenous Shrinkage of High-Performance Concrete Structures by Internal Curing", *S.P. Shah Symposium on Measuring, Monitoring and Modeling Concrete Properties*, July, Alexandroupolis, Greece, 8 p.

[10] Boulay, C. (2003): “Determination of coefficient of thermal expansion”, in *Early age cracking in cementitious systems*, *State-of-the-Art Report Number 25*, prepared by Rilem Technical Committee 181, Editor A. Bentur, RILEM, 217-224.

[11] Bentur, A., Igarishi, S., and Kovler, K. (2001): "Prevention of Autogenous Shrinkage in High Strength Concrete by Internal Curing Using Wet Lightweight Aggregates", Cement and Concrete Research, 31 (11) 1587-1591.