NRC Publications Archive Archives des publications du CNRC

Measuring early-age coefficient of thermal expansion in high-performance concrete

Cusson, D.; Hoogeveen, T. J.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

Publisher's version / Version de l'éditeur:

International RILEM Conference on Volume Changes of Hardening Concrete [Proceedings], pp. 1-10, 2006-08-20

NRC Publications Archive Record / Notice des Archives des publications du CNRC :
<https://nrc-publications.canada.ca/eng/view/object/?id=526a1044-7058-4a1b-9f29-aad032508a6b>
<https://publications-cnrc.canada.ca/fra/voir/objet/?id=526a1044-7058-4a1b-9f29-aad032508a6b>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site
<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at
PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

<http://irc.nrc-cnrc.gc.ca>

Measuring early-age coefficient of thermal expansion in high-performance concrete

NRCC-45428

Cusson, D.; Hoogeveen, T.J.

A version of this document is published in / Une version de ce document se trouve dans:
International RILEM Conference on Volume Changes of Hardening Concrete: Testing and Mitigation (Lyngby, Denmark, August 20, 2006)

National Research
Council Canada

Conseil national
de recherches Canada

Canada

MEASURING EARLY-AGE COEFFICIENT OF THERMAL EXPANSION IN HIGH-PERFORMANCE CONCRETE

Daniel Cusson and Ted Hoogeveen

National Research Council Canada, Ottawa, Canada

Abstract

This paper presents an experimental approach to determine the coefficient of thermal expansion of concrete at early age, in which a group of three sealed concrete prisms ($75 \times 75 \times 295 \text{ mm}^3$) are subjected to $25\text{--}30^\circ\text{C}$ temperature cycles in an environmental chamber from set time to an age of at least seven days. The concrete deformation is measured with high-precision displacement sensors and the temperature is measured by thermocouples embedded in the concrete prisms. The coefficient of thermal expansion is determined as a function of time by direct calculation on the measured data.

For the high-performance concrete used in this study, it was found that the coefficient of thermal expansion decreased towards a minimum value of $6 \times 10^{-6}/^\circ\text{C}$ one day after the setting of concrete, and then increased linearly until a more stable value of $8 \times 10^{-6}/^\circ\text{C}$ was reached at the age of 4 days.

1. INTRODUCTION

1.1 Thermal behaviour of concrete at early age

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 directly 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 concrete 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 used in the mix [1]; however, very limited data can be found on the time-evolution of the CTE during the hardening process of concrete. The general agreement is that the initial value of the coefficient of thermal expansion is relatively high in fresh concrete (above $20 \times 10^{-6}/^\circ\text{C}$), and reduces rapidly to approximately $10 \times 10^{-6}/^\circ\text{C}$ during the setting 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 much lower and more stable coefficient of thermal expansion.

During the few days after set time, however, no general agreement exists in the literature on the time-evolution of the concrete CTE. Some researchers have found that its value is relatively independent of age [2], while others have reported that its value slightly increases with time [3], or slightly decreases with time [4]. Recent work [5] reported that the value of CTE decreases considerably 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 very 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].

1.2 Existing methods for testing thermal expansion of concrete at early age

For an inert homogenous solid under a stress-free condition, measuring the coefficient of thermal expansion is rather straightforward, as a temperature difference is imposed on a sample and the resulting deformation is measured. Concrete, however, is an heterogeneous, porous and aging material, which presents difficulties at both the testing and analysis stages. For example, measuring small displacements in fresh or hardening concrete is a challenge. Embedded strain gauges have been used [7], however, they should be of small size and low rigidity, as it is crucial not to restrain the movement of the concrete being tested. Linear variable displacement transducers (LVDT) are the most widely used type of sensors for this type of test, because they are accurate and reusable [8]. Two main methods for measuring the thermal deformation of concrete at early age have been used in the literature: (i) elimination of autogenous shrinkage by subjecting two concrete samples to two different temperature histories; and (ii) temperature variations imposed on the same concrete sample.

In the first method [7], it was proposed to use two concrete samples made from the same concrete batch and placed in flexible plastic moulds. One sample was thermally insulated and the other not, and were instrumented with embedded strain gauges and thermocouples. 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 against their temperature differences; and (iii) determining the CTE from the slope of the curve at given values of maturity. However, it was also reported that this method provided accurate measurements only when the rate of temperature change is sufficiently high, which therefore excludes the beginning of setting, the period of peak temperature and the end of cooling [7].

In the second method [9], one concrete sample is subjected to a realistic temperature history, which is superimposed by small temperature cycles. The amplitude of these cycles must be small enough to assume a constant CTE during the cycle, but high enough to obtain acceptable measurement accuracy. The period of these cycles must be short enough to eliminate autogenous shrinkage effects, but long enough to avoid thermal gradients in the concrete sample. In this case, the CTE of concrete can be determined at any given time, and the use of the maturity concept is not required. Although this method seems to be the most promising one for determining the CTE of concrete at early age, no general agreement exists in the literature on the test method to adopt.

1.3 Scope of study

This paper presents an experimental approach to determine the coefficient of thermal expansion of concrete at early age under stress-free and isothermal conditions, with the assumption that thermal deformation is reversible. The main objectives of the paper are: (i) to describe the experimental approach for determining the CTE in high-performance concrete, especially at early age; and (ii) to describe the thermal expansion behaviour of a typical HPC made of ASTM Type 1 cement and limestone coarse aggregate.

The test apparatus and calibration procedure presented in this paper had been initially developed for the study of autogenous shrinkage in high-performance concrete structures [10], in which it is necessary to account for the thermal effects at early age.

2. EXPERIMENTAL PROGRAM

2.1 Test apparatus

In this test, a group of 3 sealed concrete prisms are tested simultaneously in an environmental chamber from the fresh state to at least 7 days of age under isothermal conditions, with 25-30°C temperature cycles at the rate of 6 temperature steps per day.

Figure 1 presents a diagram and Figure 2 shows a photograph of the test apparatus used for the test. Each mould was made of cold rolled steel plates with inside dimensions of 75x75x295 mm³, which are close to those of standard moulds for free shrinkage testing, according to ASTM C157. Each mould was standing on the web of a structural steel section, on which the displacement transducers 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. Inside the steel mould, the walls were coated with a layer of Vaseline and a thin plastic film to reduce friction between the steel walls and the concrete. The end plates (75x75 mm²) were lined with 1.5-mm thick closed-cell foam rubber sheets to allow movement of the concrete sample in the longitudinal direction, especially during the thermal expansion periods.

Figure 1: Diagram of test apparatus

Figure 2: Photograph of three test apparatus

The longitudinal deformation of the concrete prism was measured using two LVDT located at the ends of the mould. These sensors, fixed to the C-channel 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 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 placement and before setting of concrete.

The concrete temperature was measured by a thermocouple embedded in the concrete at the centre of the prism. The ambient temperature in the environmental chamber was monitored with a second thermocouple.

The above measures, taken in the construction 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 coefficient of thermal expansion, especially at very early age when its value can change rapidly. In such a test, it is important to ensure that: (i) deformations are stress-free; (ii) external drying is prevented; and (iii) temperature is uniform in the sample [8].

2.2 Calibration of test apparatus

In this type of experiment, the temperature effects, other than thermal expansion of concrete, must be eliminated in order to ensure an accurate determination of the concrete CTE. Both the instrumentation and the test apparatus itself are significantly affected by changes in temperature. These undesirable temperature effects can be eliminated by calculation, in principle, from 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 the theoretical calculation may be based on some uncertain assumptions, thus reducing the accuracy of the measurements.

The three test apparatus built for this experiment were calibrated in an environmental chamber. The calibration procedure consisted of testing the three test apparatus with three metal blocks of known coefficients of thermal expansion. The metals selected were: (i) Kovar, with a CTE of $5.1 \times 10^{-6}/^{\circ}\text{C}$; (ii) stainless steel 17-4PH, with a CTE of $10.3 \times 10^{-6}/^{\circ}\text{C}$; and (iii) stainless steel 316, with a CTE of $16.0 \times 10^{-6}/^{\circ}\text{C}$. This combination of metals was selected for its relatively wide range of CTE values in order to cover the range of CTE values that are normally expected for concretes of all ages made with different types of aggregate. During calibration, the three apparatus with the metal blocks were subjected to regular 20-30°C temperature cycles with an intermediate step at 25°C. The amplitude of these temperature cycles used during the calibration of the test apparatus was selected to be slightly larger than that of the temperature cycles planned for testing the concrete CTE.

2.3 Testing of thermal expansion of high-performance concrete

The HPC used in this study was made of ASTM Type 1 cement including silica fume, had a cement-sand-stone mass ratio of 1:2:2, and a water-to-cement ratio of 0.35. The coarse aggregate was limestone with a max. size of 10 mm. The slump, air content, time of setting and 7-day compressive strength were 150 mm, 6.5%, 6 hours and 50 MPa, respectively.

Concrete was placed in three steel moulds and the top surface was 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, the isothermal condition was initiated by cycling the temperature in the chamber between 25°C and 30°C using a saw tooth pattern. Each end temperature was maintained constant for 4 hours, including a 15-minute ramp between each temperature step, resulting in three full cycles (or six steps) per day. The constant temperature period was long enough to ensure stable and uniformly distributed temperature in the concrete sample. The amplitude of the temperature cycle (5°C) was selected small enough to maximize the number of cycles per day and obtain more values of CTE at early age. With such small temperature changes, the temperature effect on the development rate of the CTE with time can be considered small. This effect can be easily accounted for by using the maturity method [11].

3. TEST RESULTS

3.1 Calibration results

Figure 3 shows the strains and the temperature measured during the calibration of the three test apparatus using the three metal blocks (only two full cycles are shown for clarity). It can be seen that the Kovar block provided the most significant response to the temperature changes while the stainless steel 316 (SS316) gave the least significant response. This is because the SS316 block and the test apparatus had somewhat similar values of CTE. The strain and temperature calibration data, as shown in Figure 3, were first used to determine the average CTE obtained for each metal block on the three test apparatus.

Figure 3: Strain and temperature measured during calibration of test apparatus

Figure 4: Average calibration curve obtained for test apparatus

As shown in Figure 4, the average calibration curve for the test apparatus was obtained by plotting the theoretical CTE of the metal samples against their measured CTE obtained in the three test apparatus. The ordinate of the linear regression line shown in Figure 4 provides the average CTE of the three test apparatus ($17.6 \times 10^{-6}/^{\circ}\text{C}$). It can be observed that all measured values of CTE are negative, because the CTE of the test apparatus was higher than the CTE of the metal blocks (i.e. the apparatus responded more rapidly than the metal blocks to a temperature change). With this method, using a test apparatus with a CTE higher than that of concrete is favourable, since a more significant response to small temperature changes will be measured on concrete samples, thus improving the accuracy of the measurements.

3.2 Thermal expansion test results

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

$$\varepsilon_{tot}^{corr} = k_a \varepsilon_{tot}^{meas} + \alpha_a (T_c - T_{cs}) \quad (1)$$

where ε_{tot}^{corr} is the temperature-corrected total strain after setting, ε_{tot}^{meas} is the total strain measured in concrete after setting, k_a is a calibration factor (1.20), α_a is the coefficient of thermal expansion of the calibrated test apparatus ($17.6 \times 10^{-6}/^{\circ}\text{C}$), T_c is the actual concrete temperature, and T_{cs} is the concrete temperature at set time. Figure 5 presents the imposed temperature history, the resulting concrete temperature and the corrected total strain (only 3 full cycles are shown for clarity). Note that the sharp strain peaks are only the results of temporary lack of thermal equilibrium between the apparatus and the concrete due to the rapid temperature changes between steps. They should be ignored in the analysis [9].

Figure 5: Detailed temperature and total strain measured in concrete samples

Figure 6: Selected total, shrinkage and thermal strains in concrete

The concrete temperature and the total concrete strain measured at the end of each constant-temperature period (identified by the circles in Figure 5) were used for the calculation of the thermal strain data. Figure 6 shows the selected data representing the total, shrinkage and thermal strains obtained at the end of each temperature step. The concrete shrinkage strain curve (i.e. the non-thermal component of strain) was determined by fitting a moving average curve to the values of total strain. The thermal strain was then calculated by subtracting the shrinkage strain from the total strain at any given time. Finally, the concrete CTE at any given time was calculated as follows:

$$\alpha_c = \frac{\Delta \varepsilon_{th}}{\Delta T_c} = \frac{(\Delta \varepsilon_{tot} - \Delta \varepsilon_{sh})}{\Delta T_c} \quad (2)$$

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. It is suggested to calculate the CTE starting with the 3rd value of thermal strain, since the first and second values may be too small to achieve an accurate calculation of the CTE. Figure 7 shows the resulting values of CTE obtained on three samples of high-performance concrete used in this study. As shown, the average CTE reached a minimum value of $6 \times 10^{-6}/^\circ\text{C}$ one day after setting, and increased almost linearly up to a value of $8 \times 10^{-6}/^\circ\text{C}$ at the age of four days, after which time the CTE value remained almost constant. This initial variation in the apparent coefficient of thermal expansion at early age may be due to the combined effects of several factors, including cement hydration and self-desiccation [6]. The time-evolution of the CTE shown in Figure 7 is in good agreement with the results obtained by Bjontegaard and Sellevold [5].

Figure 7: Time-evolution of coefficient of thermal expansion

It can also be observed from Figure 7 that the method provided precise results, as an average standard deviation of $0.3 \times 10^{-6}/^{\circ}\text{C}$ from the average was found, irrespective of time after the setting of concrete. Before the final set time, this experimental method cannot be applied. In most structural applications, however, in which the stresses are of major concern, the knowledge of the CTE of concrete before set time is not important.

4. SUMMARY AND CONCLUSIONS

An experimental approach was developed to determine the coefficient of thermal expansion (CTE) of concrete at early age. The size of the concrete samples was large enough to allow testing of concrete containing large aggregate. The test apparatus and the procedures used for calibration and testing were carefully designed in order to provide high-precision determination of CTE. For the high-performance concrete used in this study, the early-age CTE was found to reach a minimum value of $6 \times 10^{-6}/^{\circ}\text{C}$ one day after setting, followed by a linear increase until a more stable value of $8 \times 10^{-6}/^{\circ}\text{C}$ was reached at the age of four days. This change in the apparent coefficient of thermal expansion at early age may be due to the combined effects of several factors, including cement hydration and self-desiccation.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of Mr. G. Pye of NRC in assisting with the preparation of the high-performance concrete.

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 Number 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, 596-605.
- [8] 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.
- [9] 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.
- [10] 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.
- [11] Zhang, J.; Cusson, D.; Mitchell, L.D.; Hoogeveen, T.J.; Margeson, J.C. (2005): "The Maturity approach for predicting different properties of high-performance concrete", 7th International Symposium on Utilization of High-Strength/High-Performance Concrete, SP-228-11, Vol. 1, June, Washington, USA, 135-154.