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Development of new device for measuring thermal stresses

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Abstract

In recent years, numerous analytical and experimental researches have been performed on the prediction of thermal stresses in mass concrete structures. However, due to the difficulty of the problem, limitations still exist for both analytical and experimental methods of measuring thermal stresses in mass concrete. In this research, a new experimental device measuring thermal stresses directly in a laboratory setting is developed. The equipment is located in a temperature chamber that follows the temperature history, which has been previously obtained from temperature distribution analyses. Thermal forces are measured continuously by two load cells in the device. The results show that the thermal stresses estimated by the newly developed device agree well with general stress variations in actual structures.

Keywords: Thermal stress; Modulus of elasticity; Coefficient of thermal expansion; Developed device; Degree of constraint

1. Introduction

When constructing structures using mass concrete or high-strength concrete, specific thermal stress produced in a structure due to the hydration heat of cement could pose a serious problem to the integrity of structures. Specific thermal stress damages a structure and degrades the structural serviceability, water tightness, and durability. Therefore, estimating the existing thermal stresses and the thermal cracks in concrete structures becomes vital. Specific thermal stresses are calculated by finite element method (FEM), which is the most commonly used analytical method, and are measured by experimental methods using a special equipment or gauge in actual and simulated structures or a thermal stress measuring device in controlled laboratory setting equipment. With respect to the analytical methods, a fundamental limitation is derived from the difficulty of predicting concrete properties, such as modulus of elasticity, coefficient of thermal expansion, and others. The problems with experimentally obtained results are their economic inefficiency and uncertainty related to field conditions. Therefore, developing a laboratory or controlled experimental device that can accurately measure thermal stresses of concrete with various mixing proportion and multiple loading conditions is urgently needed.

In Japan and Europe, experimental laboratory equipment were invented and researches have been actively pursued since early 1980s. Tazawa and Iida [1] investigated hydration heat-induced thermal stresses in concrete and their mechanism using thermal crack experimental apparatus. Aokage et al. [2] also experimentally measured effective modulus of elasticity of mass concrete with a similar apparatus. In Germany, the Technical University of Munich (TUM) developed an experimental tool called “cracking frame” and estimated thermal stresses and cracking pattern of early age concrete [3–5]. TUM also invented the Temperature Stress Testing Machine (TSTM), a modified version of the cracking frame [6,7].

In this study, a laboratory test device measuring thermal stress was developed. The developed device can easily control the experimental variables, such as coefficient of thermal expansion of concrete and other cement-based materials. It is also designed to quantitatively measure the change of thermal stresses in various environmental conditions using a temperature and humidity chamber.

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2. Development of thermal stress measuring device

2.1. Background

Fig. 1 shows the basic concepts in developing a thermal stress measuring device. It is important to note that the thermal expansion coefficient of the frame material is different from that of concrete. When concrete and frame material are applied with same strains under the prescribed temperature history (Fig. 1(a)), the variation of resultant stresses is dependent on thermal expansion coefficient of the frame material. More specifically, when a frame material with lower thermal expansion coefficient than that of concrete is used, this setup produces thermal stresses at interior of structures subjected to internal restraint or whole section of structures subjected to external restraint in actual structures (Fig. 1(b)). However, if a frame material with higher thermal expansion is used, this setup produces thermal stresses at the surface of structures subjected to internal restraint in actual structures (Fig. 1(c)).

Based on the above concept and ‘‘cracking frame’’ design, the thermal stress measuring device is developed. This system can effectively measure thermal stresses within concrete specimens in a laboratory, offsetting uncertain properties of concrete. Fig. 2 shows the overall design of the system and the detailed descriptions of the device.

The shape and dimensions of the device is similar to that of the ‘‘cracking frame’’ invented in Germany. The experimental procedures follow the procedures used for the thermal crack apparatus developed in Japan. However, the developed device is less expensive to manufacture and enhances the weaknesses that existed in the previously developed apparatuses. Temperature control of ‘‘cracking frame’’ was based on a semiadiabatic condition using wood and polystyrene, and thermal crack apparatus used thin copper or polyethylene plate to prevent drying shrinkage. However, the developed device is tested in a temperature and humidity chamber where the applied temperature is defined by a user and the humidity of over 85% is maintained to minimize drying.

2.2. Experimental method

Two load cells are used for measuring restrained forces in a frame. Thermocouples or temperature gauge are set at a chamber, frame, and concrete specimens to ascertain the applied temperature. To reduce plastic and drying shrinkages from occurring in concrete specimens at early ages, humidity is kept at over 85%. Effect of hydration heat on the applied temperature is ignored since the depth of specimens is no more than 80 mm (Fig. 2) and thermal transfer is active at open surfaces of a concrete specimen. The left and right side surfaces of the specimen indicated as a dotted line in Fig. 2 is covered with thin steel plates before placing concrete. The plates are removed 6 h later. Also, friction between specimen and thin bottom plate supporting a frame is minimized by painting grease and oil on the thin steel plate. The application of lubrication during the test is controlled based on preliminary examinations.

To predict thermal stresses in structures using the developed device, a temperature analysis is first performed, followed by experiments at a temperature and humidity chamber preprogrammed based on analysis results.

To eliminate the unknown and external factors of experiments, the developed frame and specimen materials such as aggregates and water are kept at a constant temperature by storing them in the same temperature and humidity chamber before casting of specimens. Even though painstaking effort has been undertaken to control the temperature of the specimens and the frame, temper-

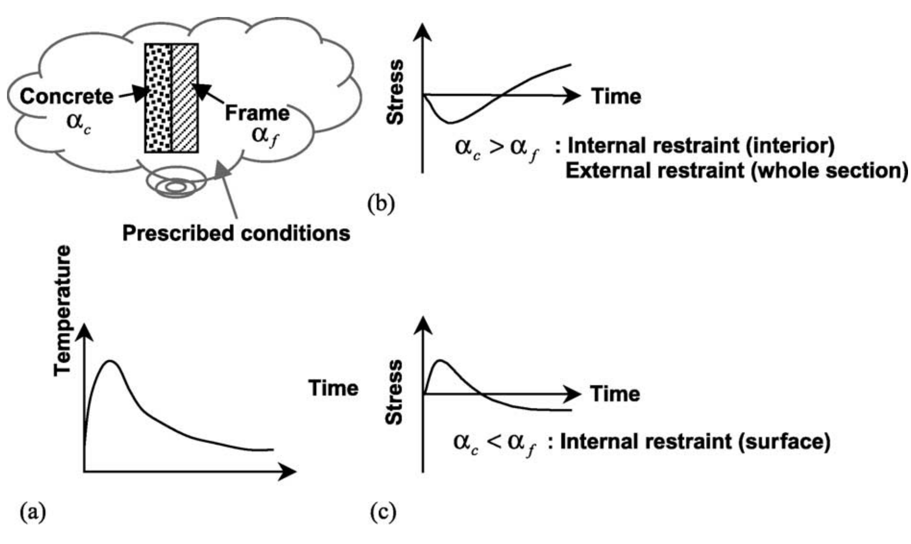

Fig. 1. Concepts of the development of thermal stress measuring device. (a) Prescribed temperature history. (b) Frame material with lower thermal expansion coefficient than that of concrete. (c) Frame material with higher thermal expansion than that of concrete.

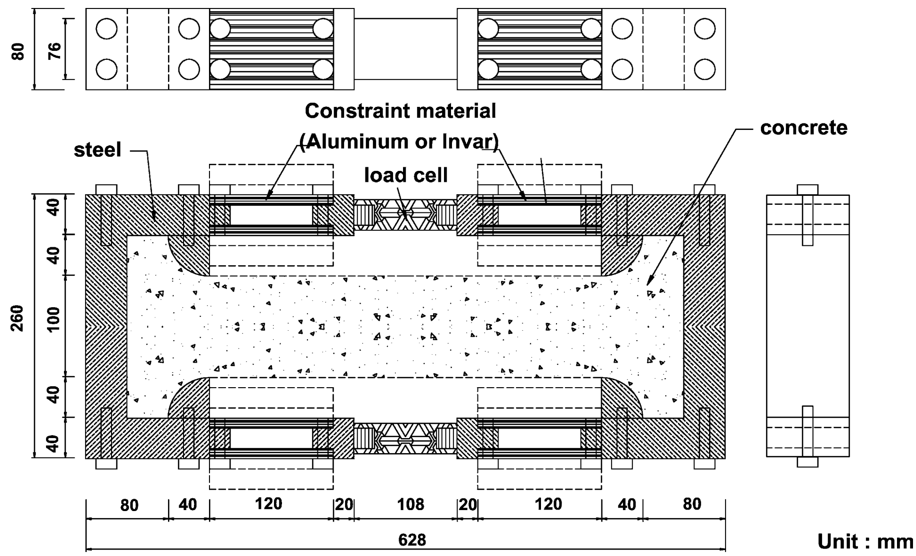

Fig. 2. Shape and dimensions of the developed device.

ature changes can occur due to the transportation and other procedures before and during the experiment. Therefore, the chamber is fixed at a required initial temperature for 6 h after placing the frame and concrete specimen before the test. Then, the chamber is programmed to follow the required temperature history.

2.3. Measurement of thermal stresses

For the prediction of thermal stresses, uncertainties in material properties of early age concrete such as elastic modulus and coefficient of thermal expansion can be ignored using the developed device. More specifically, concrete specimens are placed in a frame attached with various metal plates of different thermal expansion coefficient. This frame setup under a known temperature history allows prediction of thermal stresses in concrete structures with a fully restrained condition.

Under a fully restrained condition, thermal stress of concrete is expressed as (Eq. (1))

$$f_{c,res} = \frac{F_{c,res}}{A_c} \tag{1}$$

where, $f_{c,res}$ and $F_{c,res}$ are thermal stress and force of concrete at fully restrained condition, respectively; and A_c is the cross-sectional area of the concrete specimen in the frame.

However, an application of the fully restrained condition is not feasible in this device. Therefore, the evaluated stress is modified and expressed as (Eq. (2))

$$f_c = \frac{F_c}{A_c} \tag{2}$$

where f_c and F_c are the evaluated stress and force from a concrete specimen, respectively.

In the same manner, the evaluated stress of the frame is expressed as

$$f_s = \frac{F_s}{A_s} \tag{3}$$

where f_s and F_s are the evaluated stress and force of the frame, respectively, and A_s is the cross-sectional area of the frame.

A force equilibrium condition of the frame and the concrete specimen can be expressed as

$$f_s A_s = A_c f_c. \tag{4}$$

Inserting Eq. (3) into Eq. (4) and solving for f_c, the thermal stress of concrete is expressed as

$$f_c = \frac{F_s}{A_c} = \frac{F_s' - F_{comp}}{A_c} \tag{5}$$

where F_s' is the measured force from load cells and F_{comp} refers to the compensation forces of load cells. Compensation force is induced by temperature compensation of load cells, which can be obtained from preliminary tests. Under the same temperature and humidity conditions to that of the main test, the preliminary tests were performed prior to casting concrete to estimate the temperature compensation force of the developed system with load cells.

Once the values for F_s and A_c at a specific time are experimentally obtained, thermal stress of an early age concrete can be calculated using Eq. (5). It is important to note that the thermal stress of early age concrete can be calculated even though its elastic modulus and thermal expansion coefficient are uncertain.

Table 1
Materials used in the experiments and their properties

Material	Thermal expansion coefficient ($\times 10^{-6}$/°C)	Modulus of elasticity ($\times 10^4$ MPa)
Concrete	10	2.94
Steel	11	20.6
Aluminum	24	7.18
Invar	4.5	2.83

2.4. Degree of constraint in the device

To reproduce variable restrained conditions like that of the TSTM, metal plates with a different coefficient of thermal expansion from that of concrete are set between two crossheads of the device. Fig. 2 shows the core of the developed device with metal plates between two crossheads. Theoretically, if the coefficient of thermal expansion or conductivity of the metal plates is zero, then fully or 100% restrained condition can be reproduced. However, a material with zero coefficient of thermal expansion does not exist. Therefore, materials with various coefficients of thermal expansion are used to effectively reproduce internal and external restrained conditions as described previously.

Metal plates with various cross-sectional areas as well as coefficient of thermal expansions can vary the degree of constraint. This variation of the degree of constraint can be obtained from the following mathematical procedures.

In this developed device, the constraint force of concrete specimen is actually obtained from constraint metals and load cells. From the same axial displacement condition ($\delta_l + \delta_m = \delta_c$), the following equation is obtained.

$$l_l\left(\alpha_l \Delta T + \frac{F_s}{E_l A_l}\right) + l_m\left(\alpha_m \Delta T + \frac{F_s}{E_m A_m}\right) = l_c\left(\alpha_c \Delta T - \frac{F_s}{E_c A_c}\right) \tag{6}$$

where, l, α, and E are length, coefficient of thermal expansion, and elastic modulus, correspondingly. Subscripts l, m, and c represent load cell, constraint metal, and concrete, correspondingly.

From Eq. (6), the constraint force F_s is expressed as

$$F_s = \frac{l_c\alpha_c - l_l\alpha_l - l_m\alpha_m}{l_l/(E_l A_l) + l_m/(E_m A_m) + l_c/(E_c A_c)} \Delta T. \tag{7}$$

Since $l_c = l_m + l_l$, Eq. (7) can be modified as

$$F_s = \frac{(\alpha_c - \alpha_l)l_l + (\alpha_c - \alpha_m)l_m}{\left(\frac{1}{E_l A_l} + \frac{1}{E_c A_c}\right)l_l + \left(\frac{1}{E_m A_m} + \frac{1}{E_c A_c}\right)l_m} \Delta T. \tag{8}$$

If E_c and A_c are constants in Eq. (8), the constraint force increases with the difference of coefficient of thermal expansion between concrete and frame materials (i.e., load cells and constraint metals) denoted as $(\alpha_c - \alpha_l)$ or $(\alpha_c - \alpha_m)$, and axial stiffness of frame denoted as $(E_l A_l)/l_l$ or $(E_m A_m)/l_m$. Therefore, the degree of constraint in the developed device can be varied by using frames with various coefficients of thermal expansion and cross-sectional areas.

Additionally, by directly measuring the displacement of a concrete specimen in the developed device, δ_c, with linear displacement transducers, uncertain material properties of early age concrete such as modulus of elasticity and coefficient of thermal expansion can be evaluated from Eq. (6).

Table 1 tabulates various materials used for a verification of the developed device and their thermal expansion coefficients and elastic moduli.

3. Experimental results

3.1. Concrete test results

3.1.1. Mix proportion

The detailed mix proportion of concrete is shown in Table 2.

3.1.2. Mechanical characteristic of concrete

In this study, experiments for two representative cases are performed. One is the interior of concrete structures subjected to internal restraint or the whole section subjected to external restraints. The other is the surface of concrete structures subject to internal restraint. For these cases, concrete cylinder specimens with ϕ 100 × 200 mm are cured at different temperature histories shown in Fig. 3(a) and Fig. 4(a). Table 3 shows test results for compressive and tensile strengths and elastic moduli of concrete. The experiment is performed for 4 days in a temperature and humidity chamber. Cylinder specimens are cured under the same temperature and humidity conditions as those from the experiments with the developed device. As shown in Table 3, the concrete compressive and tensile strengths and elastic moduli for interior location are relatively higher than those located at the surface. This is due to the difference in the concrete maturity even when the specimen is cast from the same batch.

3.2. Test results in the developed system

3.2.1. Plate material (aluminum) with higher thermal expansion coefficient than concrete

To verify the validity of the developed device, tests using aluminum plate, which has a higher coefficient of

Table 2
Mix proportion of concrete

W/C	S/A	Unit content (kg/m^3)				
		Water	Cement	Fine aggregate	Coarse aggregate	Admixture
0.5	0.42	181	360	707	989	1.81

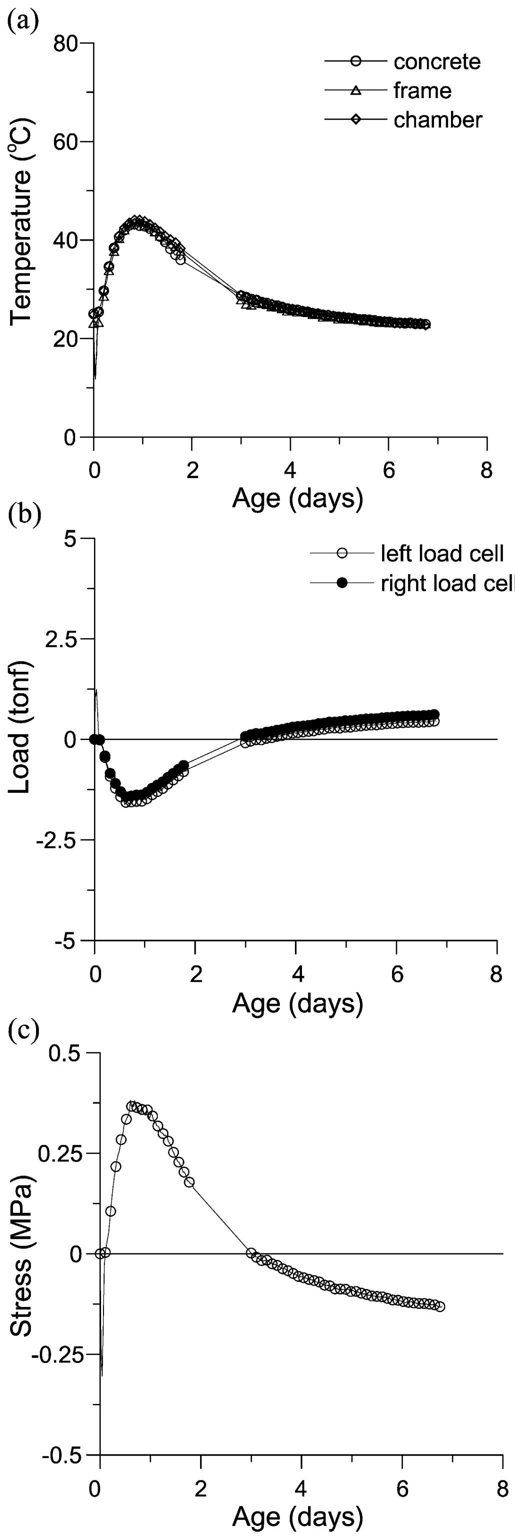

Fig. 3. Test results in aluminum frame (W/C = 0.5, tension is positive). (a) Temperature history. (b) Restrained load of frame. (c) Stress of concrete.

thermal expansion than that of concrete, is performed. Fig. 3(a) shows the measured temperatures of the concrete, aluminum plate, and chamber. In Fig. 3(a), it is important to note that the measured temperatures of the concrete specimen, the frame, and the temperature chamber are similar to the temperatures calculated from the analysis

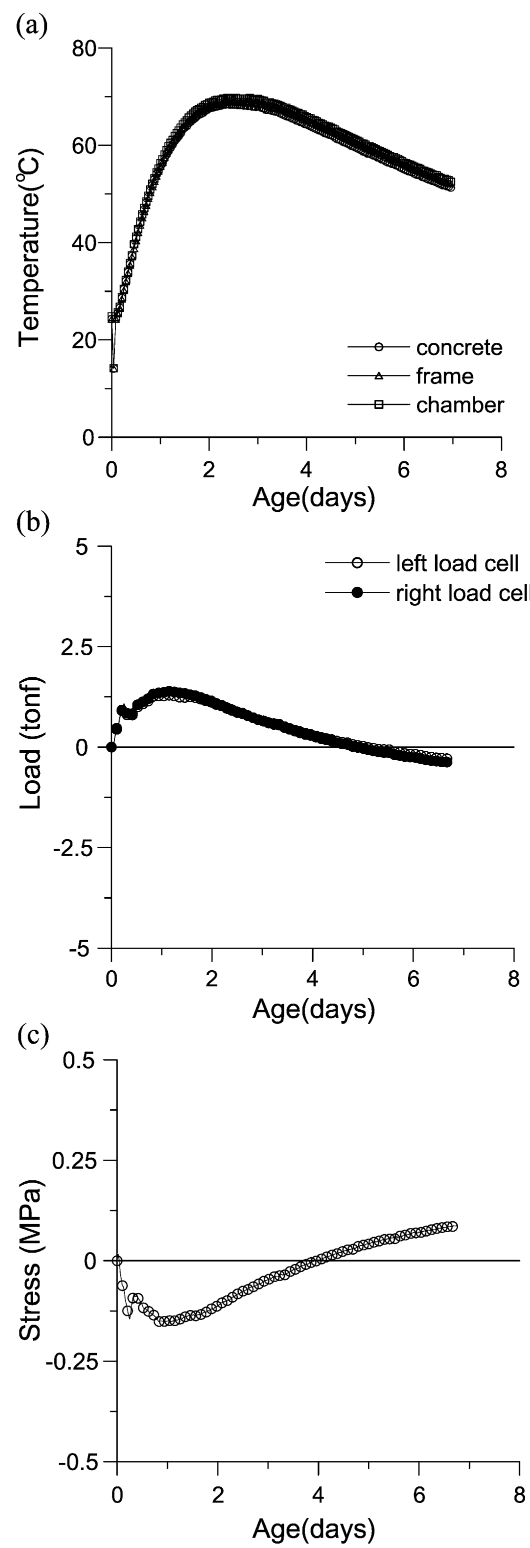

Fig. 4. Test results in invar frame (W/C = 0.5, tension is positive). (a) Temperature history. (b) Restrained load of frame. (c) Stress of concrete.

(within 1% of error). Therefore, the assumption of ignoring hydration heat of cement in concrete specimen is validated.

Fig. 3(b) shows the variation of restrained load of the frame with time. In Fig. 3(b), it is important to note that the compressive loads are measured in the initial stage followed by the measurement of tensile loads during the descending part of the temperature curve.

Using the restrained loads in Fig. 3(b), restrained thermal stresses acting on the concrete specimen are computed by Eq. (4) as shown in Fig. 3(c). Fig. 3(c) is similar to the variation of thermal stresses appearing in the surface of mass concrete structures [8]. Generally, thermal stresses initially are tensile and decrease gradually after the peak values at surfaces of structures. This is due to the fact that differential volume change based on temperature distribution is restrained by continuity of cross-section, which is called "internal restraint." Therefore, it is safe to assume that the developed system can reproduce thermal stresses at surfaces of a structure subjected to internal restrained condition.

3.2.2. Plate material (invar) with lower thermal expansion coefficient than concrete

Fig. 4 shows the results from the experiment using invar plates. Fig. 4(a) shows a similar tendency as the test results obtained using aluminum plate. Fig. 4(c), however, indicates that the developed device can reproduce thermal stresses at the interior of structures subjected to internal restraint or the whole section of structures subjected to external restraint.

To verify Eq. (8), an equation representing numerical constraint forces, the computed stresses using Eq. (8) are compared to the experimentally obtained stresses of concrete using aluminum plates (Fig. 5). In this calculation, temperature history in Fig. 3(a) and measured elastic modulus of concrete in Section 3.1.2 were used. Furthermore, the following data are used in the calculation: coefficient of thermal expansion of 12.0×10^{-6}/°C for concrete and load cell and 24.0×10^{-6}/°C for aluminum plates, length of 9.6 and 24.0 cm for load cell and aluminum plates, respectively, and elastic moduli of 20.6 and 7.18 MPa for load cell and aluminum plates, respectively. In Fig. 5, the difference between calculated and experimental results is due to the inaccurate input data, such as properties of load cell and concrete as well as inelastic deformation due to creep of concrete.

Table 3
Mechanical properties of concrete

Age (days)	Compressive strength (MPa)		Splitting tensile strength (MPa)		Modulus of elasticity ($\times 10^4$ MPa)	
	Surface	Interior	Surface	Interior	Surface	Interior
1	18.4	25.4	2.59	3.04	1.96	2.65
2	23.4	33.9	2.95	3.60	2.25	2.74
3	26.0	34.3	3.25	3.69	2.55	2.94

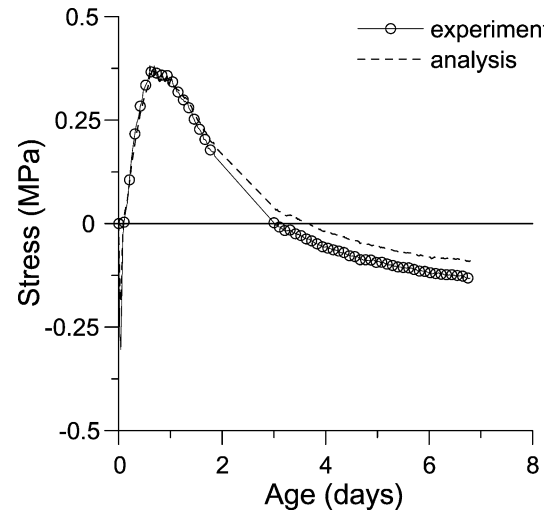

Fig. 5. Comparison between experimental and calculated results.

4. Conclusions

From the results obtained using the developed thermal stress measuring device, the following conclusions can be drawn.

1. This device shows the possibility of measuring thermal stress variations of any position in concrete structures using different thermal expansion coefficient plates even though properties of concrete are uncertain.
2. The application of various degrees of constraint can be achieved by using constraint frame material with different thermal expansion coefficient and cross-sectional area than those of concrete.
3. A commercialized chamber, which is able to control temperature and humidity, can be used with this developed device.

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