Construction and Building Materials 45 (2013) 192–198

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Application of a thermal stress device for the prediction of stresses due to hydration heat in mass concrete structure

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HIGHLIGHTS

- We described actual restraint and temperature conditions via stress device in mass concrete.
- We obtained consistent results in construction site and indoor stress device.
- We could reasonably predict the internal stress due to hydration heat in mass concrete.
- Stress device could facilitate the prediction of hydration-induced stress in mass concrete.

ARTICLE INFO

Article history:
Received 27 September 2012
Received in revised form 17 March 2013
Accepted 18 March 2013
Available online 4 May 2013

Keywords:
Mass concrete
Thermal stress device
Thermal stress

ABSTRACT

To predict thermal stress independent of uncertain material properties of early age concrete, a new thermal stress device was developed by Kim et al. in [1]. Several experiments and numerical analyses were performed to verify its validity. However, the application of the device in a real structure has yet to be attempted. Thus in this paper, the application of a stress device for predicting hydration-induced thermal stress in an actual structure is investigated. For this purpose, a series of experiments were performed by varying the amount of restraint in the thermal stress device. The reasonably good agreement between the restraint strains from the site and the stress device indicates that variation of the thermal stress at any position in concrete structures can be measured during the design stage even when the properties of the concrete are uncertain. The application of various degrees of constraint at a site can be achieved by the thermal stress device by varying the thermal expansion coefficient and the cross sectional area of the restraining frame.

1. Introduction

The heat of hydration became a major issue after the 1930s when the large dams which had been constructed were damaged by thermal cracking [2,3]. In mass concrete structures such as gravity dams and reactor containment buildings at nuclear power plants, a steep thermal gradient within the concrete could arise due to the hydration heat of cement and due to heat transfer, thus causing the concrete structures to be exposed to the possibility of thermal cracking when subjected to external or internal restraints. In general, thermal cracks occur when the thermal stresses exceed the tensile strength of the concrete.

When constructing mass concrete structures using high-strength concrete made with relatively high amounts of binder, the thermal stress developed in a structure due to the hydration heat of the cement presents a serious problem as regards the integrity of the structures. More precisely, specific thermal stress damages the structure and degrades its structural serviceability as well as its water tightness and durability. Therefore, estimating the existing thermal stresses and the thermal cracks in concrete structures is vital. The thermal stresses are calculated by the finite element method (FEM), which is the most commonly used numerical method, and they are measured by experimental methods using special equipment or gauges in actual and simulated structures or by thermal stress measurement devices with equipment in a controlled laboratory setting. When using numerical methods, a fundamental limitation stems from the difficulty associated with predicting the properties of concrete such as the modulus of elasticity, the coefficient of thermal expansion and the effect of creep. The problems with experimentally obtained results are their economic inefficiency and uncertainty related to the field condition.

For an accurate prediction of the thermal stress at the design stage (i.e., before the actual construction begins), it is necessary

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http://dx.doi.org/10.1016/j.conbuildmat.2013.03.056

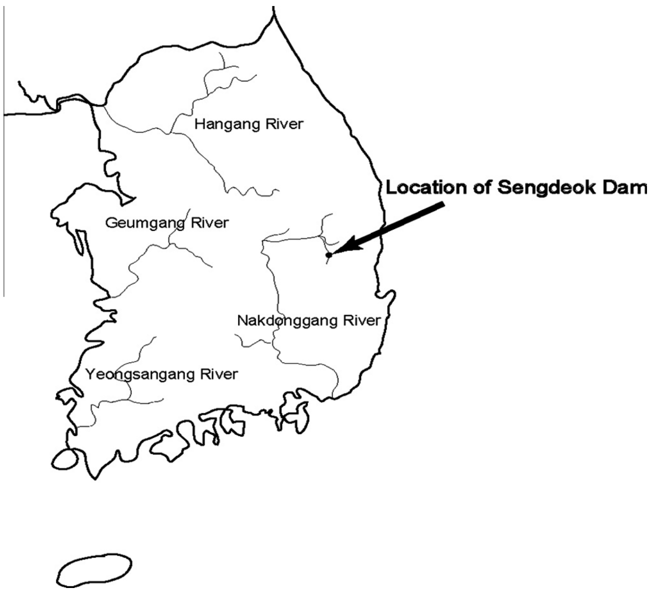

Fig. 1. Location of Seongdeok dam site in Republic of Korea.

to develop a suitable experimental method that can simultaneously incorporate the effects of the actual restraint conditions, the temperature history, and the material properties over time, especially the elastic modulus of concrete. To predict the thermal stress independent of uncertain material properties in early-age concrete, a new thermal stress device (TSD) was developed by Kim et al. [1]. Several experiments and numerical analyses were performed to verify its validity [1,4]. However, an application of the device to a real structure has yet to be investigated.

2. Review of laboratory methods used for the measurement of thermal stress

Various types of laboratory equipment have been invented in Japan [5,6] and Europe [7–10] since the early 1980s in an effort to reproduce the thermal stress in simulated structures so as to validate the results reported in numerical and experimental techniques. Tazawa and Iida [5] investigated hydration heat-induced thermal stresses in concrete and their mechanism using thermal crack experimental apparatus. Experimental measurements of the effective modulus of elasticity of mass concrete have been made with a similar apparatus by Aokage et al. [6]. The cracking frame developed in Germany at the Technical University of Munich estimates thermal stresses and cracking patterns in early-age concrete [7,8]. A temperature stress testing machine (TSTM), a modified version of the cracking frame was developed [9,10] based on a cracking frame that can measure restraint forces directly with the help of a built-in load cell and step motors that control the deformation of concrete specimens to a minimum value of 0.001 mm. Variable restraint conditions from 0% to 100% in accordance with an experimental objective can be achieved using the TSTM. Another variable restraint testing machine (VRTM) was built by modifying the TSTM for use under simulated completely-restrained condition [11].

A thermal stress device (TSD) was developed specifically for laboratory uses by Kim et al. [1]. The TSD 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. Fig. 2 shows the basic concept of the TSD. 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 exposed to the same temperature history (Fig. 2a), the variation of resultant stresses, which is occurred because of the differences of the thermal expansion coefficient between the frame material and concrete, 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. 2b). 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. 2c). Fig. 3 shows the shape and dimensions of the device. The coefficient of the thermal expansion of concrete and other cement-based materials is easily controlled using the TSD. Quantitative measurements of thermal stress changes using the TSD under various environmental and restraint conditions can be done even when the properties of the concrete are not measured separately. The detailed information pertaining to the device can be found in the literature [1,4].

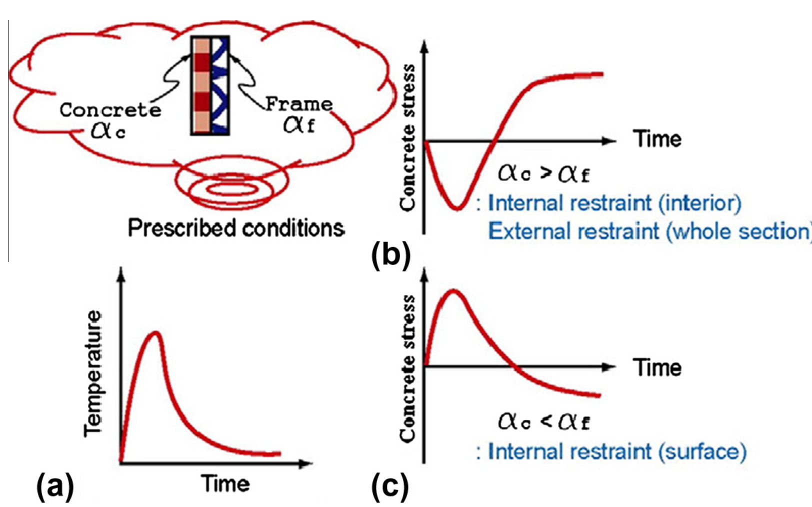

Fig. 2. Concept of the thermal stress device: (a) prescribed temperature history, (b) frame material with a thermal expansion coefficient lower than that of concrete, and (c) frame material with a thermal expansion coefficient higher than that of concrete [1].

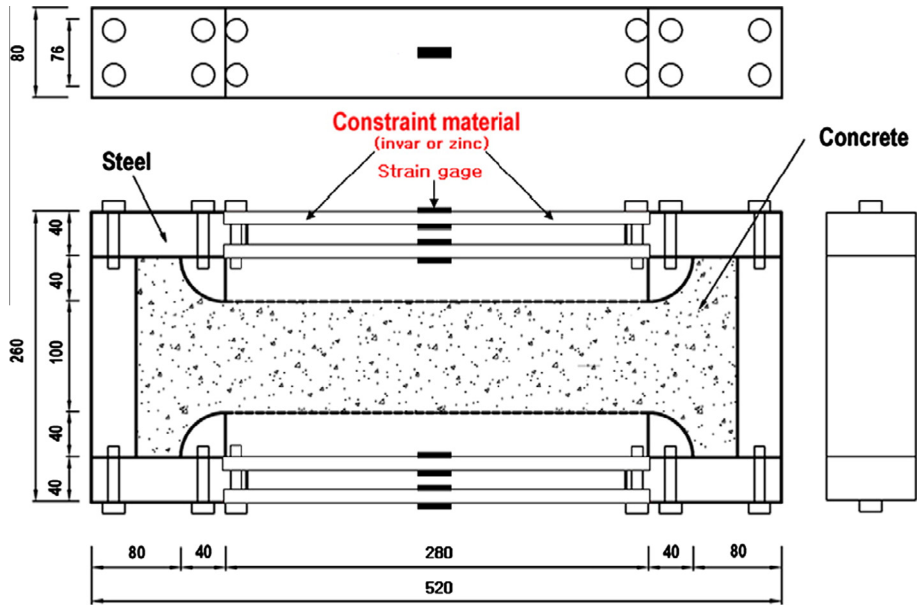

Fig. 3. Shape and dimensions of the thermal stress device [1].

3. Research significant and definitions

3.1. Research significant

As mentioned previous, several experiments and numerical analyses were performed to verify the validity of the TSD [1,4]. However, an application of the TSD to a real structure has yet to be investigated.

Thus, in this study, the application of the TSD to predict the stress due to hydration heat in real structures is investigated. A series of TSD tests are performed in a laboratory to predict the thermal stress of an actual dam structure when subjected to various restraint conditions. The experimental results of the free and restraint strain are compared with the results obtained directly from the cofferdam of the Seongdeok dam site (Fig. 1). From this, a stress–restraint strain relationship is developed based on the experimental results of the stress device, which enables the prediction of the thermal stress that developed under the same conditions at the site.

3.2. Definitions and terminologies

The total strain of concrete is consists of the stress-independent component and the stress-dependent component. A stress-independent strain includes both the thermal strain and the shrinkage strain. When a stress-independent strain is restrained, a stress will be developed and corresponding stress-dependent strain will occur. A stress-dependent strain includes both the elastic strain and the creep strain.

4. Measurement of the temperature history and the thermal strain in the field

The field results of the temperature history and corresponding strain at the center of Lift-6 of Block-4 (BL4) in Fig. 4 were directly obtained from the cofferdam of the Seongdeok dam site in Korea (Fig. 1). In the field, the temperature history and strain were monitored using a thermo-couple (TC) and embedment strain gauges. Two types of embedment strain gauge were installed. The one (KM-100B and EGP) is to measure total strain which includes both the stress-independent strain and the stress-dependent strain. The other (NSG (non-stress gauge)) is to measure stress-independent strain which is related with the temperature variation and shrinkage. The NSG is consists of an embedment strain gauge (KM-100B) and a meshed steel tube. An embedment strain gauge inside the meshed steel tube, which prevents the restraint load to transfer inside, measures the stress-independent strain. Fig. 4 represents the location and installation of the measuring instruments at the actual dam site. The purpose of obtaining the temperature history from the site is to use this temperature history to simulate the temperature of the center of Lift-6 of BL4 for the measurement of the corresponding restraint strain and thermal stress by the stress device, as explained in Section 5.2.

5. Laboratory experiments for measuring the stress by the TSD

5.1. Mixture proportion of the concrete and the experimental variables

Table 1 shows the mixture proportion of the concrete used in the laboratory and Lift-6 of BL4 in Fig. 4 at the actual dam site. All the materials, i.e., the cement, the coarse and fine aggregate, and the admixture used in the laboratory were imported directly from the dam site. After mixing the concrete, gravel of a size larger than 25 mm was removed from the mixed concrete by wet sieving. As the cross-sectional dimensions of concrete specimen is 80 mm × 100 mm so according to standard practice largest size of aggregate must be smaller than one third of least dimension of the mold.

Table 2 represents the experimental variables adopted in this study. The variable degree of external restraint that can occur in a realistic structure was achieved by varying the thickness of the restraining bar of the stress device (Fig. 3). An additional test was also performed under a restraint-free condition to obtain the stress-independent component of the strain i.e., the sum of the temperature and the shrinkage strain.

5.2. Experimental procedure

Before pouring the concrete, stress devices (with restraining bar thicknesses of 10 mm, 20 mm and 40 mm) were placed in an

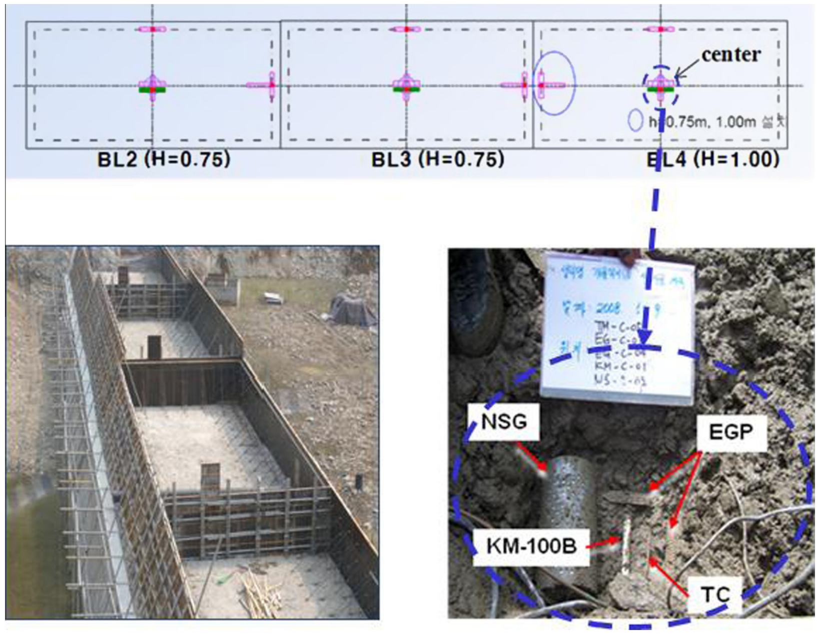

Fig. 4. Construction site showing blocks and lifts just before pouring of concrete (below left), and position (above), along with installing of measuring instruments (below right) of temperature history (TC), stress-independent strain (NSG), and total strain (KM-100B and EGP).

Table 1
Mixture proportion of the concrete.

W/B	S/a (%)	Unit content (kg/m^3)					
		W	*C*[c]	*S*	*G1*[a]	*G2*[b]	AD[d]
0.55	29.8	100	182	614	611	843	1.82

[a] *G1* (150–40 mm).
[b] *G2* (40–5 mm).
[c] Type IV cement.
[d] 1% of cement.

Table 2
Experimental variables.

Material of restraining bar	Thicknesses of plates of restraining frame (mm)	Thermal expansion coefficient ($\times 10^{-6}$/°C)	Elastic modulus (MPa $\times$ 10^3)	Remarks
Invar	10 20 40	1.5	28.3	Variable external restraint
Without restraining bar	–	–	–	Restraint free

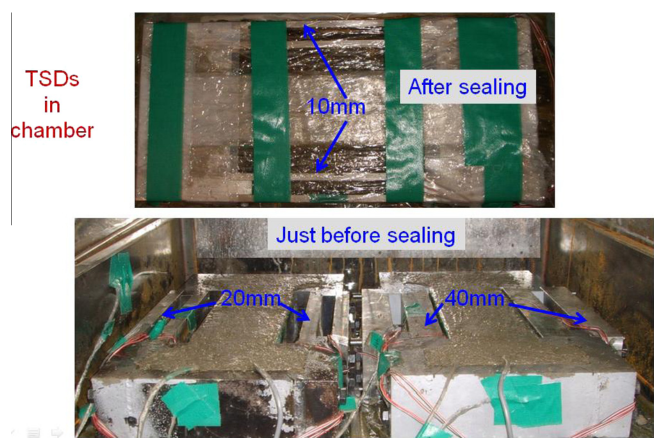

Fig. 5. Thermal stress devices (TSDs) after concrete pouring, where, device with thickness of restraining bar 10 mm is sealed, while other devices with thickness of restraining bar 20 mm and 40 mm are shown just before sealing.

environmental chamber at a controlled initial temperature (22 °C) and humidity (90%). This was done to minimize the influence of external factors. Prior to the mixing of the concrete, the temperature history obtained from site for center of Lift-6 of BL4 was programmed in the environmental chamber. At the design stage with an absence of the temperature history obtained from site, analysis results of temperature history by FEM method could be used because the thermal analysis is quite reliable than the stress analysis despite of the uncertain early-age properties of concrete (i.e., the elastic modulus, coefficient of thermal expansion, and creep) [12,13].

In each stress device, a thermo-couple and an embedment strain gauge (EGP-5-120) were embedded in the center of the concrete. A thermo-couple was embedded to verify that the resulting temperature of the concrete and the programmed temperature were identical. Embedment strain gauges were used to measure the total strain of the concrete, which includes both the stress-dependent strains and the stress-independent components. An additional experiment was performed under a restraint-free condition (Table 2) to obtain the stress-independent strain. The stress-dependent strain can be obtained by subtracting the stress-independent strain from the total strain. The left and right surfaces of the specimen were covered with thin acrylic plates before the placing of the concrete. These plates were removed 6 h after the pouring of the concrete, when measureable or effective deformations takes place. The humidity inside the environmental chamber was maintained in excess of 85% to reduce the drying shrinkage throughout the experiment. After removing the acrylic plates, all exposed surfaces of the specimen were wrapped with heat-resistant sealing film to prevent moisture evaporation. This helped to minimize the plastic and drying shrinkage which otherwise would occur. Measurements were automatically logged by a

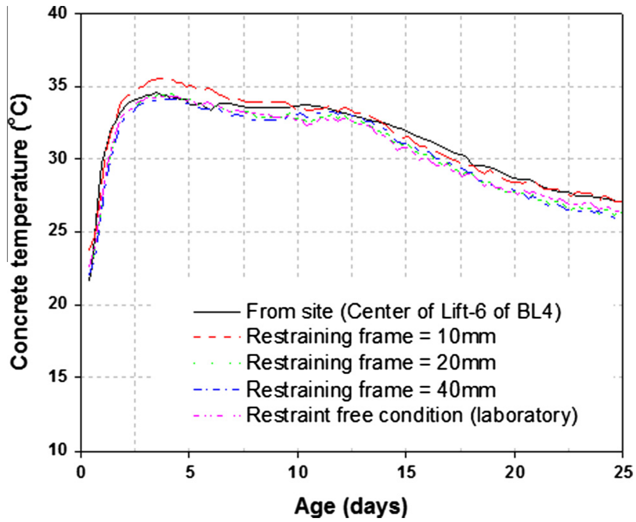

Fig. 6. Comparison of temperature history for center of Lift-6 of BL4 obtained from site and measured in laboratory.

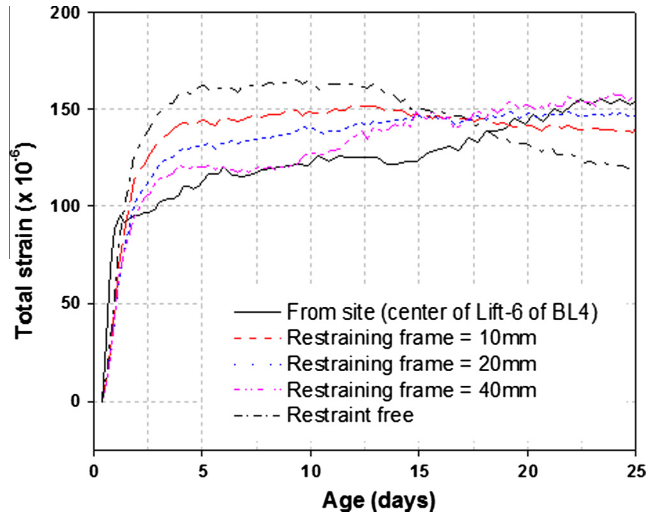

Fig. 8. Comparison of total strain (includes stress-independent and stress-dependent strain) for center of Lift-6 of BL4 obtained from site and measured in laboratory under various restraint conditions.

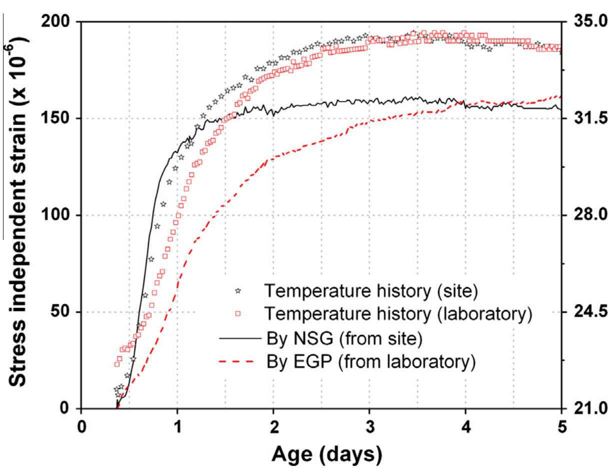

Fig. 7. Comparison of temperature history and stress-independent strain for center of Lift-6 of BL4 obtained from site and measured in laboratory.

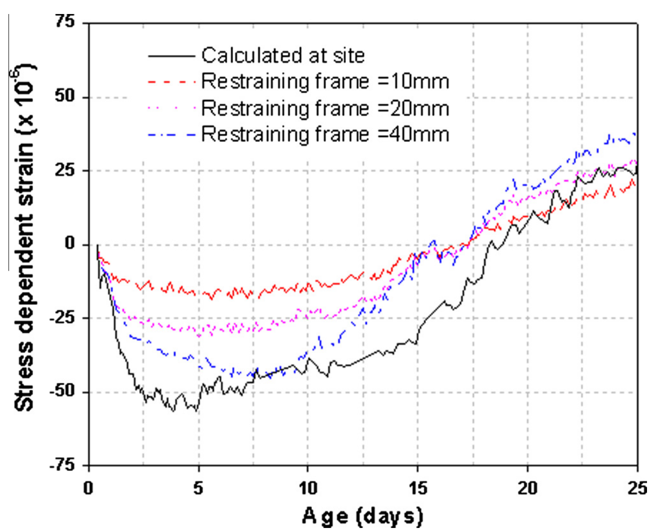

Fig. 9. Comparison of restraint strain (stress-dependent strain) for center of Lift-6 of BL4 obtained from site and measured in laboratory.

data logger at regular intervals. Fig. 5 shows the experimental set-up of the stress devices after the pouring of the concrete.

6. Estimation of the stresses and related discussion

Figs. 6–8 present a comparison of the temperature history, the stress-independent components of the total strain under the restraint-free condition, and the total strain under various degrees of restraint and in the restraint-free condition, respectively. Good agreement is observed for the temperature history obtained from the site and in the laboratory experiments on the stress device, as shown in Fig. 6. However, in Fig. 6, it was noted that the stress-independent strain obtained by the non-stress gauge (NSG) at the site contains some error. This can be clearly identified by noting the difference between the trends of the temperature curve and the stress-independent strain recorded at the site. Finally, a comparison of the restraint strain obtained from the site and the stress device was made, as shown in Fig. 9. The restraint strains shown in Fig. 9 were calculated by subtracting the stress-independent strain shown in Fig. 7, as measured in the laboratory and not at the site, from the respective total strain shown in Fig. 8. The restraint strain at the site is depicted in Fig. 9 after compensating for the difference in the temperature between the site and the laboratory (Fig. 6). This figure shows that reasonably good agreement exists between the experimental results and the data obtained from the site. The trend in the restraint strain is similar to the results for the mass concrete subjected to an external restraint.

Based on the current restraint strain results, the thermal stress in an actual concrete structure can be obtained by an analysis if the elastic modulus of the concrete and the visco-elastic properties are known. However, it is very difficult to evaluate the creep of concrete at very early ages. The stress measured from the device shown in Fig. 3, where the frame bars act as the restraining material simultaneously from the very beginning of the process, considers the variation of the elastic modulus and creep effect. Therefore, the stress device was used to measure the thermal stress of concrete directly by means of a load cell or via electric strain gauges mounted on the surface of the restraining bars shown in Fig. 3. Fig. 10 shows the development of the thermal stress when the

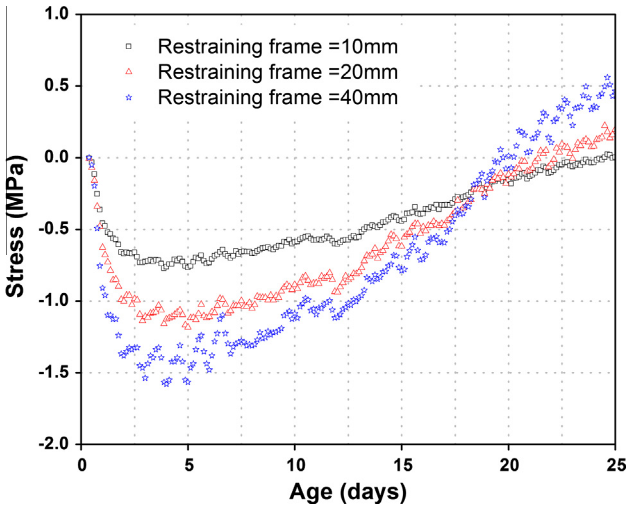

Fig. 10. Development of restraint stress of concrete subjected to various degrees of restraint in stress device.

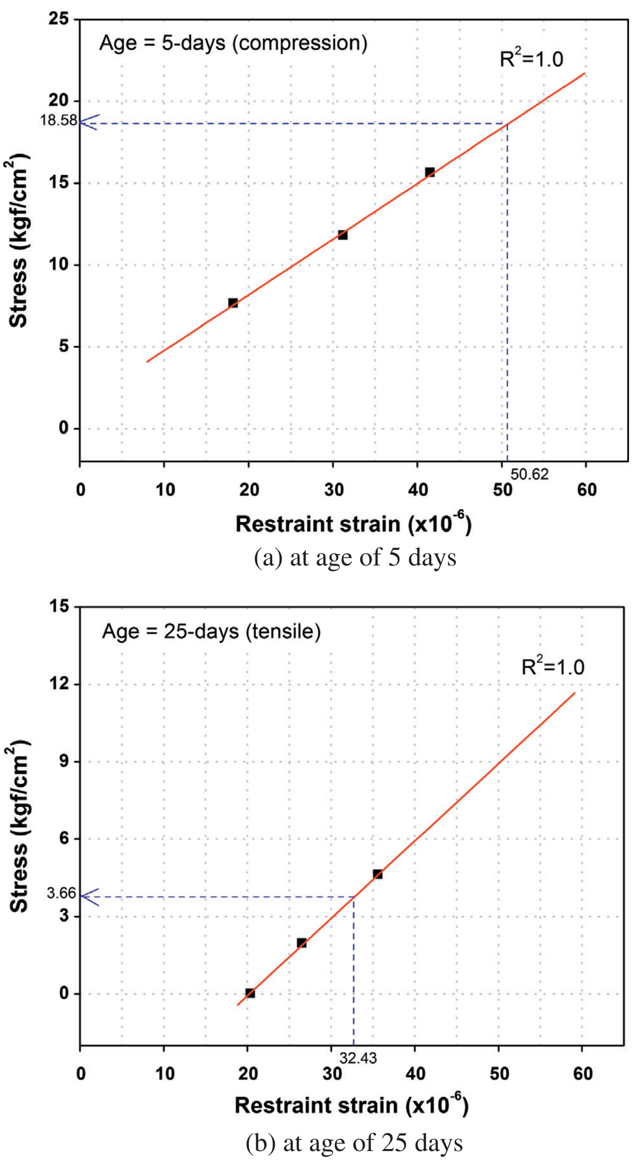

Fig. 11. Development of restraint stress–strain relation using stress measuring device.

sample is subjected to various degrees of restraint by the stress device. A detailed procedure to calculate the stress from the measured force of the load cell or from the measured strain of the electric strain gauge can be found in the literature [1,4].

Once the restraint strain and the stress are measured by the stress device, the relationship between the restraint strain and the stress at a certain age can be determined with respect to the degree of restraint. Consequently, this can help to predict the stress corresponding to the measured or calculated restraint strain. Fig. 11 shows the stress-restraint strain relationship with respect to the degree of restraint for certain ages of 5 days and 25 days. For example, the stress at the site at the ages of 5 days and 25 days can be predicted using the proposed relationship. At the ages of 5 days and 25 days, the restraint strains at the site are 50.62 $\mu\varepsilon$ in compression and 32.43 $\mu\varepsilon$ in tension (Fig. 9). The corresponding are 1.858 (compressive) and 0.366 MPa (tensile). Hence, it can be concluded that the stress device can successfully predict thermal stresses in the design stage of concrete structures. The effect of aging and the amount of restraint as they pertain to the development of the stress that can occur in realistic structures can be incorporated. Also, the influence of the uncertain early-age properties of concrete (i.e., the elastic modulus, coefficient of thermal expansion, and creep) that affect the generation of thermal stress and the resultant thermal cracking was well incorporated as the temperature and degree of stress development in restrained members can be determined simultaneously in the laboratory from the very beginning of the process.

Nevertheless the reasonably good agreement is observed between the experimental results of the strain and the strain obtained from the site, some errors was also observed. This might be because the dam structure is the internal restraint structure, where the restraint ratio varies as the surrounding concrete hardens. The restraining bar of the device cannot be replaced during the experimental process. Therefore, the device has shortcomings to perfectly simulate the real structure, where the restraint ratio varies.

7. Conclusions

In this paper, the application of a thermal stress device (TSD) to predict the stress caused by hydration heat was investigated. The results of the temperature history and the restraint strain were obtained from a site corresponding to pre-defined locations in a dam structure. The relationship between the stress and the restraint strain was determined to predict the thermal stress at the design stage. From the results obtained in this study, the following conclusions were drawn:

– A comparison of the test results and the site results as regards the restraint strain confirms the accuracy and thus the applicability of the stress device to predict the stress at the design stage of concrete structures.
– The possibility of testing for variable degrees of restraint by the stress device allows the determination of the required degree of restraint for any specified location in a real structure.

Acknowledgements

This work (20101620100140, 20111520100090) was supported by the Nuclear Research & Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy. The authors wish to express their gratitude for the financial support that has made this study possible.

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