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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.

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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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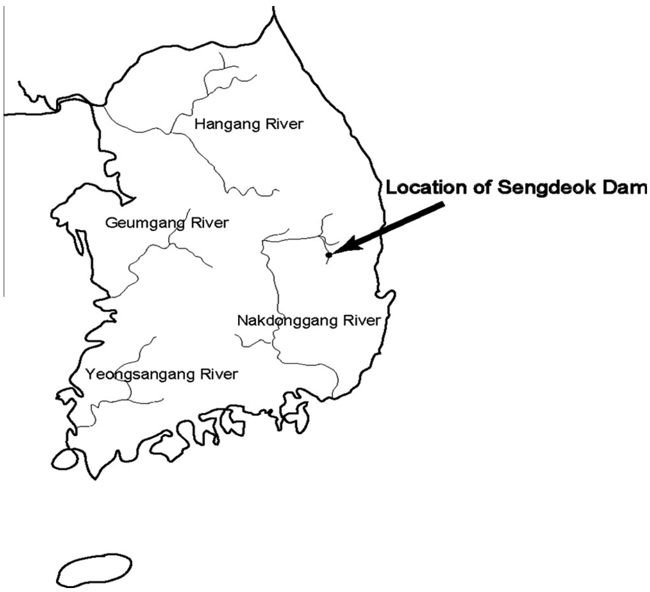

Fig. 1. Location of Seongdeok dam site in Republic of Korea.

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].

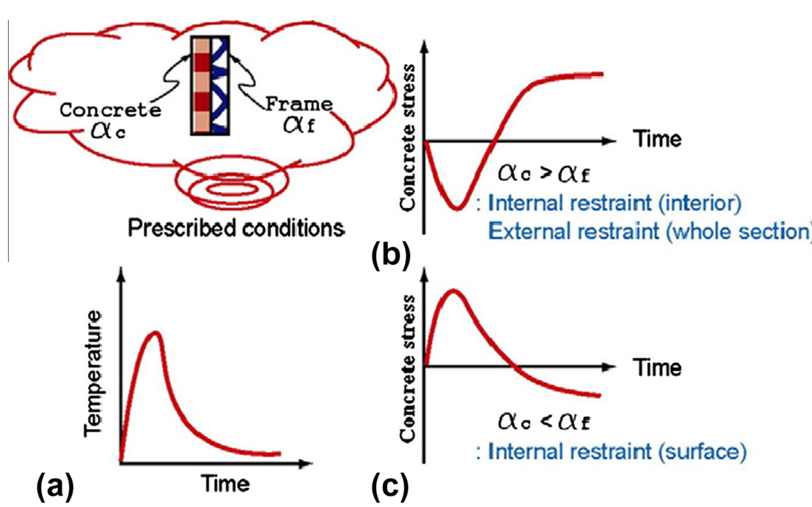

Fig. 2. Concept of the thermal stress device: (a) prescribed temperature history, (b) frame material with a thermal expansion coefficient lower than that of concrete, and (c) frame material with a thermal expansion coefficient higher than that of concrete [1].