Experimental Study on Hydration Heat Control of Mass Concrete by Vertical Pipe Cooling Method

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Abstract
Thermal cracking of slender mass concrete in attached walls, retaining walls and bridge towers, is controlled by mainly using low heat cement and the control joint. However, it is impossible to control thermal cracks perfectly because the external restraint is largely in these mass concrete members. In this study, to control the thermal cracking of slender massive concrete structures, a new pipe cooling method, which is the vertical pipe cooling method, was developed and a mock-up of a wall-type mass concrete specimen was tested to investigate the validity of this method. Each pipe is connected to the header pipe, and a drainage control cap is installed at the upper end of each pipe. As a result, the hydration heat of the pipe cooling specimen was about 8–14°C lower than that of the non-pipe cooling specimen and the tensile stress generated was smaller in the pipe cooling specimen than in the non-pipe cooling specimen. In the specimen without pipe cooling, a penetrating crack with a maximum width of 0.40 mm and length of 1250 mm occurred in the middle of the specimen.

Keywords: pipe cooling method; mass concrete; header pipe; drainage control cap

1. Introduction
Thermal cracking, which is caused by temperature changes due to the heat of hydration of the binder, occurs frequently in mass concrete structures. The combination of expansion and shrinkage due to thermal change and restraint causes the development of tensile stress within the concrete, and when the tensile stress is greater than the tensile strength of concrete, cracking will occur (ACI 224R-01, 2001). Building large structures such as long-span bridges, high-rise buildings, large power plants, and offshore structures is becoming more common, and thermal cracking in mass concrete is becoming a serious problem. Control of thermal cracking is very important because cracking has a deleterious effect on the quality and durability of concrete (Shang & Yi, 2013; Zhang et al., 2010).

To prevent thermal cracking of mass concrete, the hydration heat of concrete can be controlled by using a low-heat concrete mixture, the pre-cooling method, the pipe cooling method, etc. (KCI, 2009). The pipe cooling method can reduce the hydration heat of concrete by running cooling water through pipes installed horizontally in the concrete. The structures that typically use this method are gravity dams and massive foundations. The typical pipe cooling method is suitable for horizontally long and wide concrete structures, but is not appropriate for slender structures such as massive walls and piers.

To control the thermal cracking of slender, massive concrete structures, a new pipe cooling method, the vertical pipe cooling method, was developed. The applicability of this method was previously investigated by analytical studies (Lim et al., 2013; Seo et al., 2014). In the current study, a mock-up of a wall-type mass concrete specimen was tested to investigate the validity of this method. The hydration heat and stress behaviors of the concrete were monitored during the test, and cracking was observed.

2. Vertical Pipe Cooling Method
As shown in Fig.1., pipes are installed vertically to create a more effective pipe cooling method for slender and massive concrete structures. Each pipe is connected to the header pipe, and a drainage control cap is installed at the upper end of each pipe. The rate of flow of cooling water can be controlled by adjusting the levels of these caps (see Fig.1.). The cooling water pumped through the concrete reduces the hydration heat of the concrete, and the water that overflows can be reused for wet curing to improve the quality of the concrete (see Fig.1.).
3. Experimental Program
3.1 Test Specimens and Method
Table 1 shows a summary of the specimens tested in this study. The plain mass concrete wall specimens (the pipe cooling specimen and non-pipe cooling specimen) were fabricated to investigate the validity of the vertical pipe cooling method, and the details of these specimens are shown in Fig.2. Steel pipes, each with a diameter of 50 mm, were installed in the concrete wall at intervals of 1000 mm. The concrete for constructing the wall was poured a month after pouring the concrete for constructing the base. The location and installation of sensors are also shown in Fig.2. The temperature histories were measured by a thermocouple (capable of measuring a temperature range of -60–200°C), and total strain was measured by KM100B (±5000 × 10^-6 strain). A non-stress gauge, consisting of KM100B and a non-stress cylinder, was used to measure the strain under stress-free conditions from external restraints. Because this strain is not related to stress, it is called the stress-independent strain. The stress at the center of the concrete wall was measured by a stress sensor (GK-10N-505), which has a rated capacity of 30 MPa.

3.2 Mix Proportions and Materials
The mix proportions are shown in Table 2. The concrete for this study was made of ordinary Portland cement (specific surface area: 3300 cm²/g, specific gravity: 2.30) with a water/cement ratio of 0.48. Sand (specific gravity: 2.58, rate of absorption: 1.49%) and crushed stone (specific gravity: 2.70, rate of absorption: 0.57%) were used as the fine and coarse aggregates, respectively.

4. Results and Analysis
4.1 Concrete Properties
Cylinders 100 mm in diameter and 200 mm in height were cast to measure the concrete's mechanical properties. All specimens were demolded after 1 day and then stored in water at 20 ±2°C for 28 days. The compressive strength test, splitting tensile strength test, and Young's modulus test were carried out according to ASTM C 39 (ASTM, 2006), ASTM C 496 (ASTM, 2006), and ASTM C 469 (ASTM, 2010), respectively. The test results are shown in Fig.3. Using the equations below, the predicted values of compressive strength (eq. (1)) (AIJ, 2006; CEB-FIP, 1990), splitting tensile strength (eq. (2)) (AIJ, 2006), and Young's modulus (eq. (3)) (AIJ, 2006) are also shown in Fig.3. These equations are based on the experimental values obtained under the standard curing condition (20 ±2°C water curing); in general, there was good agreement between the calculated and experimental values. The equivalent age theory (eq. (4)) (Rastrup, 1954; Saul, 1951; Lachemi et al., 2007) was used to investigate the concrete's mechanical properties due to hydration heat of the mass concrete specimen. The concrete temperature measured at the center of the concrete wall was used in eq. (4). The results are shown in Fig.3. The predicted values of mechanical properties as a function of the equivalent age were around 10–15% higher than those under the standard curing condition.
where,

$t$: Age of concrete
$f_{28}$: Compressive strength at 28 days
$T$: Temperature of concrete ($^\circ$C)
$T_0$: Datum temperature (-10°C)
$\Delta t$: Duration of curing period at temperature $T$
$T_r$: Standard curing temperature (20°C)

4.2 Hydration Heat History

Water at 22°C was injected into the bottom pipe through a rubber hose at the rate of 3 L/min, and the smooth flow of cooling water could be controlled by adjusting the level of the caps at the ends of the pipes. Because a rapid decrease in temperature can cause an increase in tensile stress, the supply of cooling water was discontinued when the temperature of concrete started falling. Hydration heat histories of the mass concrete specimens are shown in Fig.4. The temperature of the concrete was 28°C when placed, and reached the maximum temperature about a day later. After reaching the maximum temperature, the concrete temperature decreased slowly, and reached the ambient temperature after about 8 days. The temperature of the concrete was the highest in the middle, and the temperatures at the top and the bottom behaved similarly. The maximum temperature differences between the pipe cooling specimen and the non-pipe cooling specimen are shown in Fig.5. The hydration heat of the pipe cooling specimen was about 8–14°C smaller than that of the non-
pipe cooling specimen. This experiment confirms that hydration heat can be effectively controlled using the vertical pipe cooling method.

4.3 Effective Young's Modulus

The Japan Society of Civil Engineers proposed a method to calculate the thermal stress of mass concrete using the effective tensile Young's modulus (JSCE, 1996). Where, the effective tensile Young's modulus means the Young's modulus considering stiffness reduction due to creep. The experimental values of the effective Young's modulus that considers creep effects can be obtained from the relationship between stress-dependent strain and the stress developed in concrete. The stress-dependent strain, which contributes to stress developments in concrete, can be obtained by subtracting the stress-independent strain from the total strain (eq. (5)) (Bazant, 1988; Yeon et al., 2013; Chu et al., 2013), and the stress-independent strain can be obtained using the non-stress gauge (KM100B + non-stress cylinder).

Figs. 6 and 7 show the strain and stress histories at the center of the pipe cooling and non-pipe cooling specimens, and the effective Young's modulus obtained...
from the relationship between stress-dependent strain and the stress developed in concrete are shown in Fig.8. The effective Young's modulus was approximately 50–60% (average value: 55%) of the value of Young's modulus predicted by eq. (3), which corresponds to results from previous studies (Aokage et al., 1986; Iki & Oguri, 1998).

\[ \varepsilon_c(t) = \varepsilon_e(t) - \varepsilon_f(t) \quad (5) \]

where,\n\[ \varepsilon_c(t): \text{Stress-dependent strain} \]
\[ \varepsilon_e(t): \text{Total strain} \]
\[ \varepsilon_f(t): \text{Stress-independent strain} \]

4.4 Stress Histories

Fig.9 shows the stress histories at three locations (top, center, and bottom) on the specimen. These stress histories were calculated using eq. (6) and the experimental values, where the effective Young's modulus was obtained by multiplying eq. (3) by a reduction factor (see Fig.8.). The splitting tensile strength as a function of the equivalent age is also shown in this figure. In the case of the pipe cooling specimen, it was impossible to calculate the stress histories at the bottom of the specimen owing to a fault in the strain gauge installed in the bottom of the specimen. Generally, the generated tensile stresses were smaller in the pipe cooling specimen than in the non-pipe cooling specimen. In the specimen without pipe cooling, a crack developed in the middle that penetrated the full thickness of the specimen and had a maximum crack width of 0.40 mm. This crack occurred at the bottom of the specimen after 4 days and then progressed to the top of the specimen. In the pipe cooling specimen, a crack occurred only at the bottom, and the maximum crack width was about 0.15 mm. Table 3 provides a summary of the cracking pattern.

\[ \sigma_e = \sum_{t=1}^{t} [E_e(t) \times (\varepsilon_e(t) - \varepsilon_e(t-1))] \quad (6) \]

where
\[ E_e(t): \text{Effective Young's modulus at age of } t \text{ days} \]
\[ \varepsilon_e(t): \text{Stress-dependent strain at age of } t \text{ days} \]

5. Conclusions

In this study, the vertical pipe cooling method, which is suitable for slender mass concrete structures, was developed and a mock-up was tested to investigate the method's validity. The results are as follows.

1) The pipes were installed vertically, and each pipe was connected by header pipes. The cooling water was injected into the concrete using rubber hose, and the smooth flow of cooling water was controlled by adjusting the level of a cap.

2) The hydration heat caused the structure to reach maximum temperature about a day later. After reaching the maximum temperature, the concrete temperature decreased slowly, and reached the ambient temperature about 8 days later. It was possible to reduce the hydration heat between 8 and 14°C by applying the vertical pipe cooling method.

3) The effective tensile Young's modulus, considering stiffness reduction due to creep, was obtained to calculate the thermal stress of mass concrete. The effective Young's modulus was around 50–60% (average value of 55%) of the predicted static Young's modulus. In general, the tensile stress generated was smaller in the pipe cooling specimen than in the non-pipe cooling specimen.

4) In the non-pipe cooling specimen, a penetrating crack with a maximum width of 0.40 mm and length of 1250 mm occurred in the middle of the specimen. In the case of the pipe cooling specimen, the crack occurred only at the bottom, and had a maximum width of 0.15 mm and length of 220 mm.

Table 3. Summary of Cracks Observed in the Tested Specimens

| Items                  | Pipe cooling specimen | Non-pipe cooling specimen |
|------------------------|-----------------------|---------------------------|
| Cracking age (day)     | -                     | 4–5                       |
| Crack length (mm)      | 320                   | 1250                      |
| Maximum crack width (mm)| 0.15                 | 0.40                      |
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