Experimental Research on the Hydration Heat Temperature Field of Hollow Concrete Piers

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Abstract: Measuring points were observed continuously to reveal the hydration heat temperature distribution of hollow concrete bridge pier. The results showed that as the thickness of the pier increased, the central temperature of the pier increased significantly due to hydration and the heat was difficult to be dissipated. The hydration temperature accounted for up to 70% of the maximum temperature rise during 20 h and reached the maximum temperature at 24 h after pouring the concrete. There was a jump value between the central temperature and surface temperature in a short period after removing the framework. The jumping was the most dangerous moment for the cracking of pier surfaces. Therefore, the formwork removal time has to be determined prudently and corresponding measures have to be conducted to reduce the possibility of pier surface cracking.

Keywords: Hollow concrete pier, hydration, temperature field, experiment.

1. INTRODUCTION

At present, with the increase of bridge spam, the height and thickness of bridge pier increase as well. The hydration temperature of high, thick and hollow concrete pier is seldom studied in China and abroad. During the hardening of the pier after pouring, the chemical reaction between cement and water produces hydration heat, which accumulates and leads to the increase of temperature. The internal temperature of the concrete can reaches more than 70°C [1-3]. As concrete members of ordinary size present favorable heat dissipation condition, there is slight internal and external temperature difference of the concrete, which generally doesn't cause serious hydration cracking. But large concrete shows distinct hydration. The external heat reduces quickly, so does the temperature; while the heat accumulated in the concrete cannot be dissipated in time. Therefore, a temperature gradient with low surface temperature and high internal temperature was generated and causes non-uniform temperature deformation, which generates large temperature stress with the structural and external constraints. The larger the concrete volume, the more difficult the accumulated heat to be dissipated, the larger the temperature difference, and the higher the temperature stress generated [4-6]. In many situations, owing to the improper treatment or control, the stress exceeds the tensile strength of concrete, thus causing cracking of concrete surface and potential risk of the structure in usage. Practice and theoretical research indicates that the hydration induced temperature stress is one of the major reasons of the cracking of large concrete [7, 8].

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By measuring the temperature of a hollow engineering concrete pier, its internal temperature field distribution was investigated and the influences of pier thickness on hydration temperature were analyzed. The research provided experimental data for controlling temperature cracks and computing temperature stress.

2. MATERIALS AND METHODOLOGY

2.1. Experimental Materials

P·O42.5R cement with a specific surface area of 3,800 cm^2/g and a loss on ignition of 1.4% and tap water were used. The designed strength grade of the concrete is C40 and each cube of concrete was made from materials such as 372 kg of cement, 718 kg of sand, 1,075 kg of stone, 65 kg of fly ash, 3.5 kg of water reducing agent and 160 kg of water. The concrete was poured in two times for 6 hours in total at ambient atmosphere temperature of $12\,^0C$. Besides, wood formwork was used.

2.2. Experimental Method

Hydration temperature was measured every 5 min for 130 h since the concrete was poured, and more than 1,600 groups of experimental data were obtained. The arrangement for measuring points of hydration temperature is displayed in Fig. (**1**). The points were numbered as 1, 2, 3, 4, 5, and 6 from outside to inside.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1. Temperature Variation Curve of Points on the Surface

The surface temperature here refers to the hydration temperature of 1# measuring point within 2 cm to the concrete

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surface. Fig. (**2**) shows the temperature variation curve based on the data measured in the experiments.

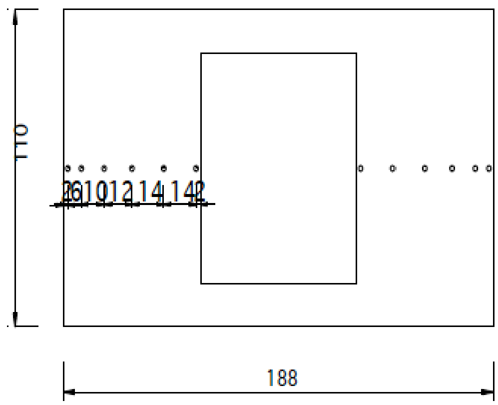


Fig. (1). Arrangement of measuring points (unit: cm).

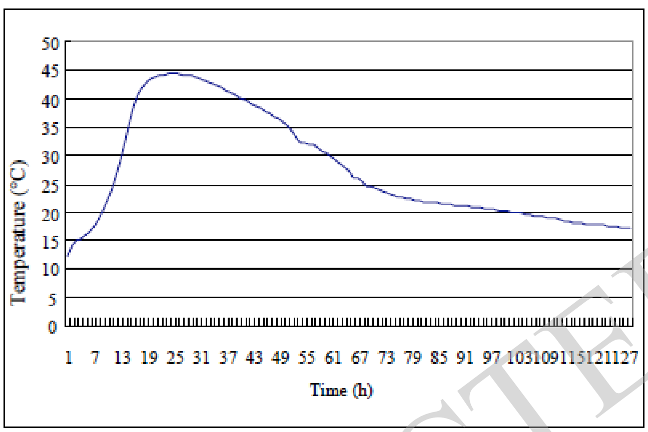


Fig. (2). Variation curve of surface hydration temperature.

Fig. (**2**) demonstrates that the hydration temperature increases rapidly within 18 h after pouring and reaches 72% of the maximum temperature rise. The maximum temperature reaches 44.4°C at 24 h after pouring. Then the temperature reduces slowly and a leap is observed in the curve at 52 h after pouring when the formwork is removed. Afterword, the temperature reduces rapidly. This is because the environmental temperature is low and the large temperature difference causes rapid dissipation of heat [9].

3.2. Hydration Temperature Variation Curve of Central Point

The hydration temperature variation curve of central point of the hollow concrete pier is displayed in Fig. (**3**). It demonstrates that the hydration temperature increases sharply during 20 h after pouring and accounts for 70% of the maximum temperature rise. It reaches maximum temperature (53.2°C) at 24 h after pouring. It indicates that the surface and center reaches their maximum temperatures simultaneously. But because of the low thermal conductivity of concrete, the farther the heat is away from the pier surface, the more difficult it dissipates. Therefore, the heat accumulates in the center of the pier for a long time and the center maintains a high temperature.

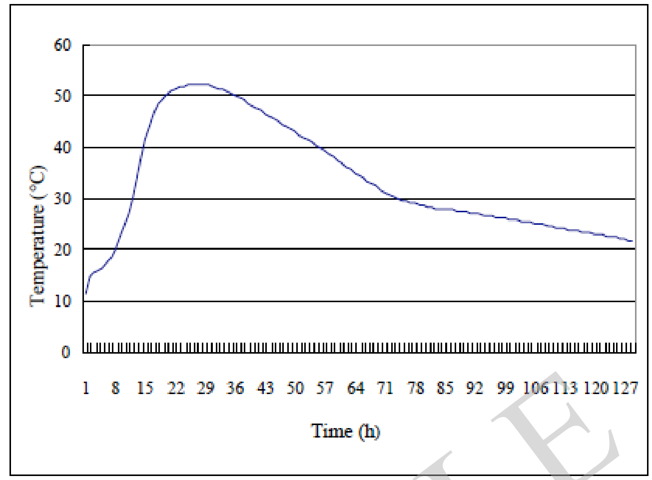


Fig. (3). Variation curve of hydration temperature of central point.

3.3. Hydration Temperature Difference between Surface and Central Points

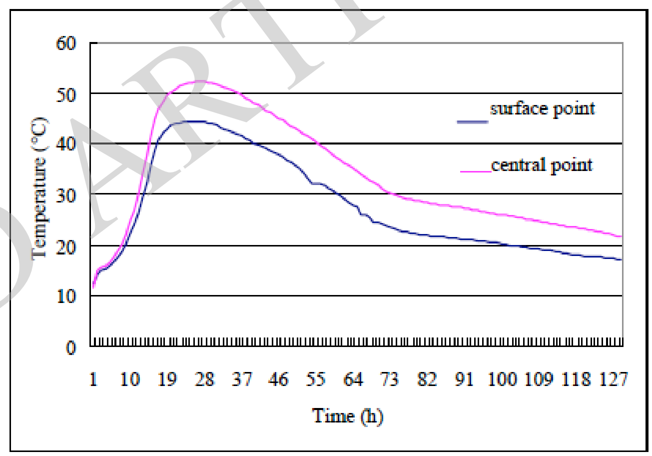


Fig. (4). Comparison of hydration temperature variations of surface point and central point.

The temperature monitoring data illustrate that the hydration temperature variations of surface and central points are basically simultaneously. They reach their maximum temperatures at 24 h after pouring, and the temperatures reduce smoothly with similar reduction curve. Figs. (**4**) and (**5**) show the comparison of hydration temperature variations of surface point and central point and the temperature difference curve of the both points. As the temperature variation of central point and surface point are not always simultaneous, their maximum temperature difference is not simply the difference between their maximum temperatures [10], but the asynchrony between the variations has to be considered.

Fig. (**5**) demonstrates that the maximum temperature difference of surface and central points is not the difference of their maximum temperatures, but the temperature difference increases with time. This is mainly because of the low thermal conductivity of concrete, which causes slow internal heat dissipation. As the pier center is far from the surface and most of the heat accumulates inside and is hard to be dissipated, the temperature reduces slowly and smoothly.

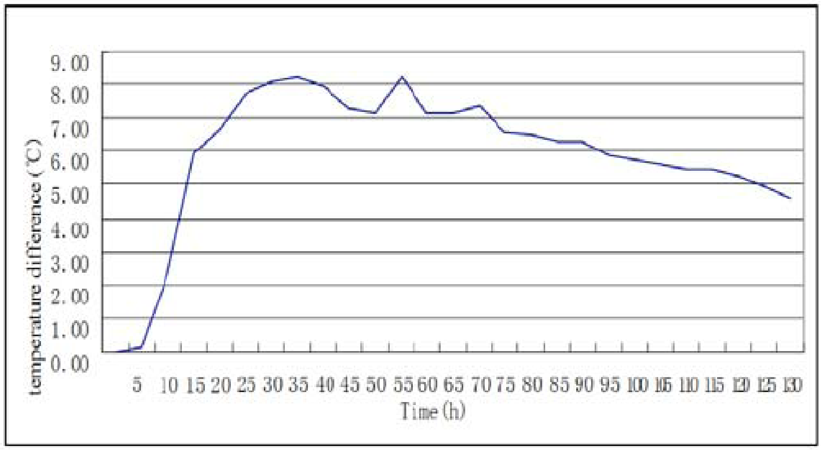


Fig. (5). Curve of hydration temperature difference between surface point and central point.

While, as influenced greatly by the outside temperature, the surface loses heat rapidly. As a result, the internal and external temperature difference increases with time. Even before the removal of formwork, there is large temperature difference between the central point and surface point at 120 h after pouring. When the formwork is removed, the surface temperature reduces sharply due to the low environmental temperature; while the central temperature shows slight variation owing to the thick wall and poor thermal conductivity of concrete. Therefore, the internal and external temperature difference increases further and jumps.

4. FINITE ELEMENT ANALYSIS

4.1. ANSYS Finite Element Modeling

Hydration heat, as an important factor that influences the temperature stress of concrete, is significantly associated with time. In the research, it is represented by the following composite exponential expression [11]:

$$Q(\tau) = Q_0\left(1-\exp(-a\tau^b)\right) \tag{1}$$

Where $Q(\tau)$ is the hydration heat accumulated at time τ; Q_0 is the total amount of hydration heat of cement (kJ/kg), coefficients a and b are constants; and τ is time.

$$\theta(\tau) = Q(\tau)(W+kF)/cp \tag{2}$$

The adiabatic temperature rise of concrete can be inferred using the expression of hydration heat of cement and represented as

Where W is the amount of cement used, c is the specific heat of concrete, ρ is the density of concrete, F is the amount of admixture used, k is reduction factor and k=0.25 for fly ash.

According to construction procedure, a poured block is considered as a part, and the poured element is processed using technology of birth and death of element [12]. SOLID70 heat element is applied. It is a conductive hexahedral 3-D element with 8 nodes, and adopts temperature as degree of freedom. There is merely a degree of temperature freedom for each node. The element is used for transient thermal analysis. Based on actual experimental model and parametric modeling using APDL, spatial finite element model is constructed for computation and analysis. The total node number and element umber are 39,640 and 35,876, respectively. ANSYS finite element model is illustrated in Fig. (**6**).

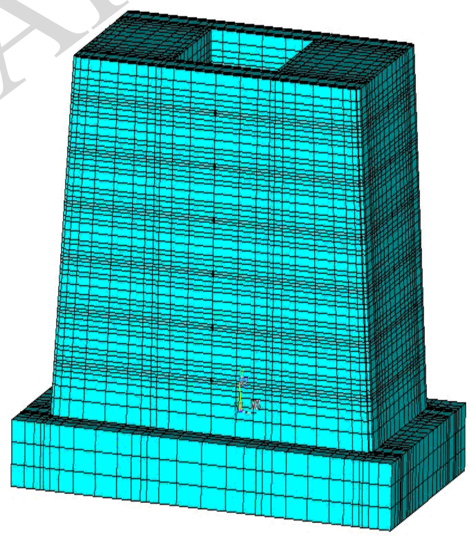
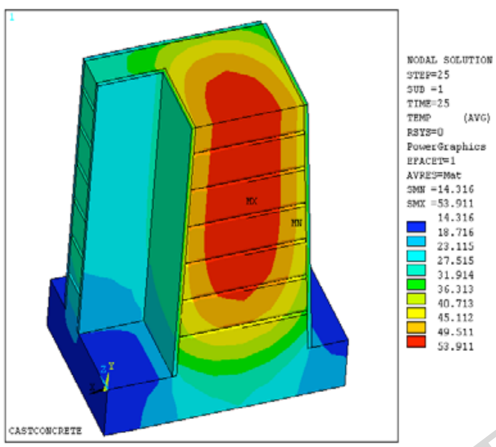


Fig. (6). Finite element model for the hollow concrete pier.

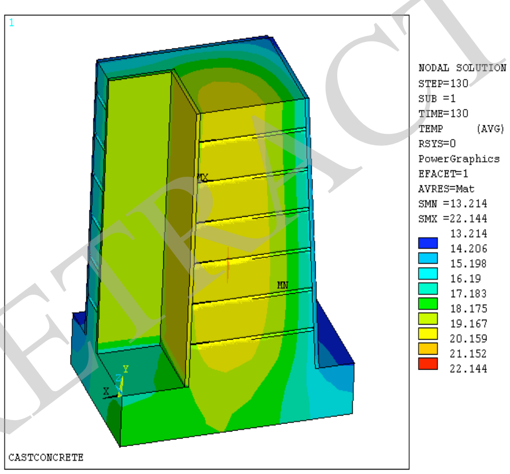
4.2. Computation and Analysis of Hydration Heat Temperature Field of the Concrete Pier

ANSYS finite element analysis is performed based on actual construction. In the computation, laminated pouring of concrete, layer thickness, hydration induced temperature rise and change, concrete creep, different material zones, pouring temperature, convection boundary condition, construction interval, *etc.* are considered to select proper load step based on actual experimental procedure. The measured daily average temperature is used. Fig. (**7**) displays calculated cloud picture of temperature at typical moments.

Fig. (**7**) shows that the temperature along cross section varies basically same at different times. As time passes, due to heat released by cement hydration, temperature of all the internal and external measuring points rises. According to measured data, a maximum internal temperature is generally measured at 30 h after pouring. Fig. (**4**) illustrates that at about 25 h after pouring, internal temperature reaches the maximum value, about 53.91°C, and the maximum temperature of surface point is also measured at about 25 h, but it reduces sharply at about 52 h. This is because the framework is removed at about that moment, when the outside temperature is far lower than the surface temperature. In the situation, the surface releases heat to outside environment and therefore reduces its temperature significantly. The temperature curves of central point and surface point vary basically same, but the maximum temperature of concrete surface is apparently lower than the internal one.



(a) 25h



(b) 130h

Fig (7). Temperature variation cloud picture of hollow concrete pier.

5. COMPARISON OF CALCULATED RESULTS AND MEASURED DATA OF HYDRATION HEAT TEMPERATURE FIELD

The finite element based calculation results of hydration heat temperature field of the concrete pier is compared with the measured data, as demonstrated in Figs. (**8**), (**9**), and (**10**).

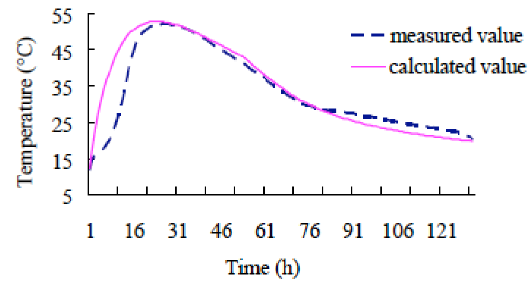


Fig. (8). Variation curves of measured temperature and computed temperature of surface point.

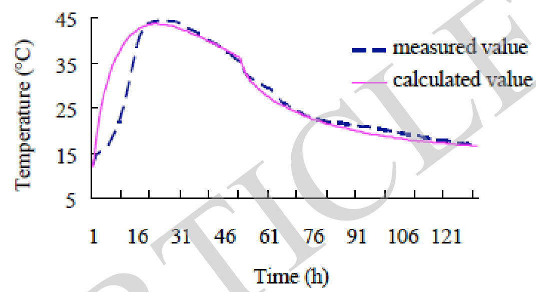


Fig. (9). Variation curves of measured temperature and calculated temperature of central point.

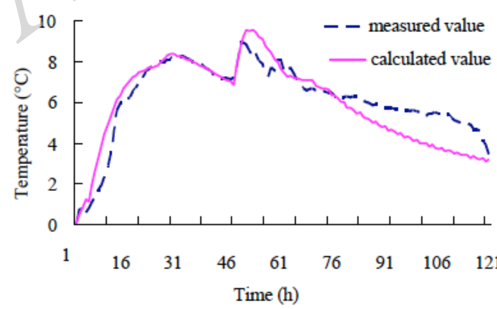
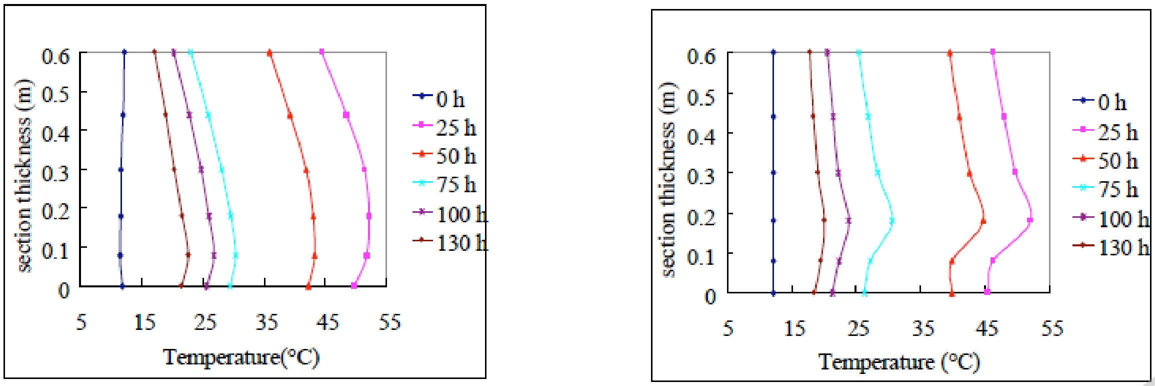


Fig. (10). Temperature difference curves between measured and calculated temperatures of internal and surface points that vary with time.

To conveniently compare temperature difference between surface point and central point of the concrete, variation curve of hydration heat temperature along cross section direction is drawn, as illustrated in Fig. (**11**).

The calculated and measured temperature curves state that their variations are consistent and they reach maximum temperatures almost at same time. But at initial stage, there is large error between the calculated temperature rising curve and the experimental measured one. This is caused by lots uncertain factors and the non-uniformity of pouring at initial stage, when the details and construction parameters cannot be accurately described using finite element computation. The construction parameters include the geometric structure model, natural conditions, and design variables in construction. Among which, the description of geometric model totally depends on construction progress and method. The external environment variations in construction include common parameters such as current air temperature, water



(a) ANSYS based theoretical computation results (b) Measured data

Fig. (11). Temperature distribution along cross section direction at different times.

temperature, ground temperature, sunshine, wind speed, etc., which are difficult to be measured. All these cause large error of the calculated results at initial stage.

The calculated temperature curve is smoother than the measured one, and there is large difference between the calculated and measured temperatures of internal and external points. This is because, after the formwork is removed, the surface is exposed in the air and directly influenced by outside conditions, which are simulated and described using fitted curve of outside air temperature. Moreover, the calculated and measured temperatures show consistent variation along cross section direction at same time with slight difference. The surface and central points of the concrete show maximum temperature difference (9.95°C) at 52 h after pouring first layer concrete, when the local environmental temperature is about 12°C. When the temperature of surface point reduces, that of the central point reduces slower, which increases the temperature difference between central point and surface point further. As a result, a larger temperature stress is contributed, thus increasing the possibility of surface cracking.

CONCLUSION

Reliable experimental data were obtained by carrying out continuous observation of hydration temperature field of the hollow concrete pier. The variation law of temperature with time obtained provided references for the construction of similar projects. The following conclusions were drawn in the research.

Engineers have to pay lots attention on the hydration heat harm for thick concrete bridge pier. The measured results can be used as reference data prior to the pouring of the concrete, to provide reference for the strength and position of measures for controlling temperature.

After the pier concrete pouring is accomplished, the internal and external temperature difference shows a jump value in a short period after the removal of the formwork. The jumping is just the most dangerous moment of surface cracking of bridge pier. Therefore, the removal time of the formwork has to be determined prudently and corresponding measures have to be taken to reduce the jumping, therefore reducing the possibility of surface cracking of the pier.

With the increase of the thickness of the bridge pier, the central temperature increases significantly due to hydration and the heat is difficult to be dissipated. In the situation, the method of keeping the formwork for longer time exhibits limited effect in reducing the internal and external temperature difference. Certain amount of cooling pipes have to be set inside the pier to effectively decrease the temperature difference by means of circulation cooling, thus preventing the occurrence of early cracks. The measurement of internal temperature field of concrete, and the master for the variation trend of the internal temperature at any time are significant for the early mechanical property of concrete and the control of temperature stress and temperature cracks.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

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