Factors and Simulation of Temperature Field of the Green Cake during the Setting Process of the Autoclaved Aerated Concrete

Yufeng Su1,2*, Haifeng Li1 and Shiying Liang1
1 School of Materials Science and Engineering, Tongji University, Shanghai, 201804, China
2 Key Laboratory of Advanced Civil Engineering Materials of Ministry of Education, Tongji University, Shanghai, 201804, China
Email: tjcl.syf@tongji.edu.cn

Abstract. The effects of initial temperature and water to material ratio on hydration heat of Autoclaved Aerated Concrete (AAC) slurry were studied. The effects of curing temperature and mold conditions on the temperature field of the green cake during the setting process were analyzed. The temperature distribution green cake was tested and simulated by finite element software. The results show that the higher the initial temperature, the higher the rate of hydration heat, but does not affect the total hydration heat of slurry. When the water to material ratio increases, the maximum temperature rise of slurry decreases. When the curing temperature of the green cake increases, the temperature field remains unchanged, the maximum temperature rise increases, and the temperature difference in the same dimension decreases. The size and distribution of the temperature in the height direction is affected by the mold conditions on the upper surface of the green cake, while the temperature in the radius direction is affected by the mold conditions on the side of the green cake, but the distribution law remains unchanged. The finite element model of temperature field of green cake in the setting process of AAC is established and has good accuracy with the test values.

Keywords. Autoclaved aerated concrete, hydration heat release, temperature field, finite element simulation.

1. Introduction
Autoclaved aerated concrete products, as a new self-insulating wall material can significantly improve the thermal insulation performance of the building envelope. At present, there are many studies on the pouring stability, gas generation and thickening, bubble and pore structure, and production technology of Autoclaved Aerated Concrete (AAC) slurry. Xu Qing [1] studied the influence of the aluminium powder content, the ratio of dissolved ore, and the alkali composition the retarder content, and the slurry pouring temperature on the pouring stability of the alkali slag aerated concrete slurry. Wang Jie [2] studied the effect of the fineness of fly ash and quicklime on the influence of the initial expansion of the slurry and the gasing process of AAC. Su Yufeng [3] studied the influence of the mass fraction of NaOH solution and the viscosity of the cellulose ether solution on the stability of the bubbles in the green cake, and the mechanism of foam stabilizer.

ABAQUS finite element software is often used to the research the temperature field in the mass concrete. Piyius Raj Singh [4] used ABAQUS software to simulate the temperature field of mass concrete with pipeline cooling system and accurately verified the measured temperature data.
Kodur [5] simulated the temperature field in the hydration of ultra-high performance concrete and studied the effect of the mix ratio, block size, reinforcement mesh and insulation layer on the temperature rise. Few studies have researched the temperature field of the green cake during the setting process of AAC.

To improve the uneven setting degree of the green cake, it is necessary to study and analyze the temperature field of the cake. This paper tests and simulates the temperature field in the setting process of the green cake, studies the influence like initial temperature, water-material ratio, curing temperature and mold conditions on the temperature field, and establishes a finite element model of the temperature field.

2. Experiment

2.1. Materials
Cement P·I 52.5 is produced by Wuhan Weishen Technology Development Co., Ltd. Quartz sand was purchased from Gongyi Hengxin Filter Material Factory. Lime, gypsum, and aluminium powder paste are all provided by Shantou Bo Environmental Materials Co., Ltd.

2.2. Testing Equipment
Electric heating constant temperature blast drying box, hydration temperature test device [6, 7] (figure 1), thermocouple temperature measurement line, temperature recorder, constant temperature and humidity test box.

![Figure 1. Hydration temperature test device.](image)

1. Stirrer; 2. Temperature recorder; 3. Foam insulation barrel; 4. 1000 mL beaker; 5. Insulation lid.

2.3. Methods of Testing

2.3.1. Slurry Preparation Method. When preparing the autoclaved aerated concrete slurry, first mix the quartz sand and gypsum and pour it into the water, stir for 60 seconds and then add cement, then stir for 60 seconds, add lime, and continue stirring for 90 seconds before pouring. The total amount of lime and cement in the dry material is 30%, the lime-cement ratio is 1:1, quartz sand is 65%, and 5% gypsum is added as the conditioning material.

2.3.2. Performance Test Methods. The hydration temperature test device was used to test the hydration exothermic temperature rise curve of slurry, and the stirring rate was 400±5 r/min. A thermocouple temperature measuring line, a temperature recorder and a constant temperature test box are used to record the temperature field in the cake during the setting process.

2.4. Finite Element Simulation of Temperature Field
The temperature field of AAC cake is a transient temperature field with an internal heat source and the heat release rate of the internal heat changes with time. The third boundary condition is defined on the
surface boundary of the cake and the mold in contact with air.

2.4.1. Basic Assumption. 1) It is assumed that the cake is an isotropic homogeneous material, and the main thermophysical parameters do not change with temperature and time; 2) It is assumed that there is only heat convection on the contact surface between the cake and air and between the mold and air; 3) It is assumed that the contact condition between the cake and the inner surface of the mold is ideal, and the contact thermal resistance is ignored.

2.4.2. Simulation Steps. 1) Establish the geometric model: establish the model according to the geometric size of the mold; 2) Definition of material properties: the material parameters used in this analysis are shown in table 1.

| Materials | Density (kg/m³) | Thermal Conductivity (W/(m·K)) | Specific heat capacity (J/(kg·K)) |
|-----------|----------------|-------------------------------|----------------------------------|
| Cake      | 1700           | 0.310                         | 1980                             |
| EPS       | 30             | 0.042                         | 1380                             |
| Iron      | 7250           | 49.900                        | 480                              |

- Dividing finite element mesh: hexahedral dc3d8 eight-node linear heat transfer element is selected.
- Set transient heat transfer analysis step: according to the requirements of the green cake setting process time, the time is 200 min, which is divided into 50-time steps.
- Applied load: the heat release inside the green cake is realized by defining the cake heat flux, and the temperature rise curve of slurry hydration measured in the previous test is applied by the method of amplitude curve.
- Boundary conditions: the convective heat transfer boundary conditions of the air contact surface are defined by the curing temperature and heat transfer coefficient.

3. Results and Discussion

3.1. Influencing Factors on the Heat Release of the Slurry

3.1.1. Influence of Initial Temperature on Heat Release of the Slurry. Water materials ratio (w/m) of slurry is 0.55. According to the actual production, the initial temperatures are 40 °C, 45 °C, 50 °C, 55 °C. The test results are shown in figure 2 and figure 3.

![Figure 2](image1.png)  
**Figure 2.** Influence of initial temperature on the temperature rise of slurry.

![Figure 3](image2.png)  
**Figure 3.** Influence of initial temperature on the rate of temperature rise of slurry.

Figure 2 shows when the initial temperature is increased from 40 °C to 55 °C, the maximum temperature rise of the slurry is the same, all are about 27 °C, but the time to reach the maximum
temperature rise is shortened from 180 min to 55 min. Figure 3 shows when the initial temperature increases from 40 °C to 55 °C, the height of the second exothermic peak of the hydration gradually increases and moves forward. This is because the amount of raw materials in the slurry is the same, and the hydration heat during hydration process is the same. The increase of the initial temperature accelerates the hydration reaction of the slurry and shortens the hydration time.

It can be seen that the initial temperature does not affect the hydration heat release of the slurry, but affects its hydration heat release rate. The higher the initial temperature, the faster is the heat release rate.

3.1.2. Influence of w/m on the Hydration Heat. The initial temperature of the slurry in this section is 40 °C, and w/m is 0.50, 0.55, 0.60, 0.65, 0.70 (the total mass of solid raw materials remains unchanged). The test results are shown in figure 4 and figure 5.

Figure 4. The influence of w/m on hydration temperature rise of slurry.

Figure 5. The effect of w/m on the rate of temperature rise of slurry.

Figure 4 shows when w/m rises from 0.50 to 0.70, the maximum rising temperature drops from 33 °C to 20 °C. Figure 5 presents, as w/m increases from 0.50 to 0.70, the second exothermic peak gradually decreases. This is because when w/m is relatively large, there is relatively less cementitious material in the slurry and water is relatively more.

It can be seen that as w/m increases, the heat release of the slurry per unit mass of cementitious material gradually decreases, and the rate of hydration heat decreases also.

3.2. Influence Factors on the Temperature Field of the Cake during the Setting Process

3.2.1. Influence of the Curing Temperature on the Temperature Field of the Cake. The initial temperature of the slurry is 40°C, and w/m is 0.55. In this experiment, a self-made mold with a lid is used for the insulation barrel. The size of the mold and the arrangement of temperature measurement points(1, 2, 3...13) are shown in figure 6. According to the actual production, the curing temperature is set as 0 ℃, 20 ℃, 40 ℃, 60 ℃. The results are shown in figures 7 - 9.

Figure 6. Insulated mold with lid (mm).
**Figure 7.** Influence of curing temperature on the temperature on the central axis of the cake.

**Figure 8.** Influence of the curing temperature on the temperature in the height direction of the side of the cake.
Figure 9. Influence of the curing temperature on the temperature in the radial direction of the bottom of the cake.

Figure 7 presents, the temperature field of each point on the central axis of the cake at different curing temperatures is: point 4>point 5>point 3>point 2>point 1. It is because there is a gap between the lid of the test mold and the barrel, and part of the hydration heat is lost to the air, while the temperature at the measuring point 4 was the highest, which was below the central position. Figure 7 shows also, that as the curing temperature rises from 0°C to 60°C, the maximum temperature rise at each point on the central axis gradually rises from 35°C to 47°C, and the difference between the maximum temperature rise and the minimum temperature rise 7°C gradually decreased to 4°C. It is because when the curing temperature increases, the hydration heat of the slurry is less dissipated to the air, the temperature in the cake rises, and the difference in the hydration process at each point decreases.

Figure 8 presents the temperature field of each point in the height direction of the cake under different curing temperatures is: point 9≈point 10>point 11>point 12>point 13. When the curing temperature rises from 0°C to 60°C, the maximum temperature rise at the temperature measurement point in the height direction increases from 33°C to 44°C, and the temperature rise difference decreases from 13°C to 4°C. It is because the lower the curing temperature, the more the cake loses heat, which in turn delays the hydration process.

Figure 9 presents the temperature rise curves of each point in the radius of the bottom of the cake under different curing temperatures are not much different. From the enlarged figure, the temperature field law is: point 5>point 6>point 7>point 8. Point 9, that is, the highest temperature at the central axis of the cake, the farther away from the central axis, the lower the temperature. It is because the hydration heat is lost to the environment through the mold, and the closer the mold is, the more heat is lost. As shown in figure 9, when the curing temperature rises from 0°C to 60°C, the maximum temperature rise at each point in the radius of the bottom of the cake increases from 34°C to 45°C, and the temperature difference gradually decreases from 1°C to 0.4°C.

In summary, the curing temperature does not affect the temperature field distribution in the cake.
but affects the temperature value. As the curing temperature increases, the maximum temperature rise of each point in the cake gradually increases, and the difference between the maximum temperature rise and the minimum temperature rise in the same dimension gradually decreases.

3.2.2. Influence of Mold Conditions on the Temperature Field of the Cake. The initial temperature of the slurry is 40°C, and w/m is 0.55. Take the curing temperature of 60°C as an example, add two molds of an uncovered insulated barrel (figure 10) (points 1, 2, 3…13) and an iron cube (figure 10) (points 1, 2, 3…13), and compare with the temperature field of the cake in the above-mentioned insulated barrel mold. As shown in figure 11 to figure 13.

![Figure 10. Insulated mold without lid (mm) and iron cube mold.](image)

![Figure 11. The influence of mold conditions on the temperature on the central axis of the cake. (T=60°C).](image)
Figure 12. The influence of mold conditions on the temperature in the height direction of the side of the cake. (T=60℃).

Figure 13. The influence of mold conditions on the temperature in the radial direction of the bottom of the cake. (T=60℃).
As shown in figure 11 and figure 12, in the insulated mold without a lid, the temperature on the central axis of the cake is point 5 > point 4 > point 3 > point 2 > point 1. The temperature field of temperature measurement points along the side height direction is point 9 > point 10 > point 11 > point 12 > point 13, which is the same as the temperature field on the central axis, that is, the bottom surface temperature is the highest along the height direction of the cake, and the closer it is to the upper surface, the lower the temperature is. The temperature of point 1 and point 13 near the upper surface of the green cake gradually approaches the curing temperature from the initial temperature. This is due to the convection heat loss between the upper surface of the green cake and the air in the insulated barrel without cover, and the closer to the bottom of the mold, the less the heat loss.

As shown in figure 11 and figure 12, in the iron cube mold, the temperature field state of the temperature measuring points on the central axis of the cake is point 3 > point 2 > point 1. The temperature field law of the temperature measuring points in the side height direction is point 5 > point 6 > point 7, point 9 > point 10 > point 11. That is to say, the bottom temperature is the highest in the height direction of the green cake, and the closer it is to the upper surface, the lower the temperature is. It is due to the convection between the cake and the mold and the air.

It can be seen from figure 13 that the temperature difference of the temperature measurement points on the bottom radius of the cake is not obvious. It can be seen from the enlarged view that the temperature field of each point on the bottom radius of the insulated mold is: point 5> Point 6>Point 7>Point 8>Point 9. The temperature field results of the temperature measurement points in the radius direction of the cake in the iron cube mold are point 3>point 4>point 5 and point 3>point 8>point 9. That is, the temperature at the centre axis of the cake is the highest, and the farther from the centre axis the lower the temperature. It is because heat is lost to the air through the mold, and the closer to the centre axis, the less heat is lost.

It can be seen from figure 11 to figure 13 that the temperature of the cake in the mold of the insulated barrel with lid is higher than that in the mold of the insulated barrel without a lid. It is because, in the mold of the uncovered insulated barrel, heat is lost through the connection between the upper surface of the cake and the air. When the cover is added, the contact between air and the cake is blocked, and the heat lost in the cake is greatly reduced. Therefore, the mold conditions on the upper surface of the cake have a greater influence on the temperature field in the cake. In actual production, the method of covering the mold with thermal insulation materials such as polystyrene plastic board and rock wool board can be adopted to reduce the heat loss in the cake and reduce the temperature field gap in the cake.

It can also be seen from figure 11 to figure 13 that the temperature of the cake in the mold without lid is higher than that in the iron cube mold. This is because the thermal conductivity of the iron mold is larger than that of the insulated barrel, and a large amount of heat in the cake is lost to the environment. Therefore, the mold conditions on the side of the cake have a greater influence on the temperature field in the cake. In the production process, a mold with better insulating performance can be used to pour the slurry to reduce the heat loss to the environment and improve the uniformity of the temperature field in the cake.

To sum up, the mold conditions have a greater impact on the temperature field of the cake during static placing. The size and distribution of the temperature in the height direction of the cake are affected by the mold conditions on the upper surface of the cake, and the temperature in the radius direction is affected by the temperature field of the cake. The mold conditions on the side of the cake are affected, but the distribution law is not affected. In actual production, the heat loss in the cake can be reduced by covering the mold with thermal insulation material and the mold with better thermal insulation performance, and the uniformity of the temperature field in the cake can be improved.

3.3. Simulation of the Temperature Field of the Cake in Static Placing
According to the basic assumptions and analysis steps, the temperature field of the cake during the setting process is simulated when the initial temperature is 40 °C and the curing temperature is 60 °C.
3.3.1. Simulation of the Temperature Field of the Cake in the Insulated Mold with Lid. The convective heat transfer coefficient $h_1$ of the contact surface between the mold and the air of the insulating barrel is 90 W/(m$^2$·K) by comparing the simulation results of the temperature measurement points 13 and 14 with the measured data. The simulation result of the temperature field of the cake in the mold with a lid during the setting process is shown in figure 14. For the convenience of the display, the temperature field cloud diagram of the half cake is selected. The comparison result of the simulation result and the measured data is shown in figure 15.

The convective heat transfer coefficient $h_1$ of the contact surface between the mold and the air of the insulated bucket is 90 W/(m$^2$·K) by comparing the simulation results of the temperature measurement points 13 and 14 with the measured data. The simulation result of the temperature field of the cake in the mold with a lid during the setting process is shown in figure 14. For the convenience of the display, the temperature field cloud diagram of the half cake is selected. The comparison result of the simulation result and the measured data is shown in figure 15.

**Figure 14.** The temperature field cloud diagram of the cake in the mold of the insulated bucket with lid.

**Figure 15.** Comparison of simulation and actual measurement of the temperature field of the cake in the mold of the insulated bucket with lid.
Figure 14 presents the temperature of the cake in the mold of the insulated bucket with lid gradually increases with the time. The temperature at the bottom of the cake is the highest, and the closer to the upper surface, the lower the temperature. That is, the simulated temperature field law in the cake is the same as the actual measurement result.

Figure 15 shows the maximum difference between the simulation result of the temperature rise of the cake in the mold of the insulated bucket with lid and the measured temperature rise is 0.81°C, indicating that the simulation result can be in good agreement with the measured temperature rise data. Therefore, the finite element model of the temperature field in the process of static placing of the cake in the mold with lid established in this section has high accuracy.

3.3.2. Simulation of the Temperature Field of the Cake in the Insulated Mold without Lid. The convective heat transfer coefficient $h_2$ of the contact surface between the cake and the air can be obtained by comparing the simulation results of temperature measurement points 1, 13 with the measured data as 60W/(m²·K).

Figure 16 shows the simulation result of the temperature field of the cake in the mold of the uncovered insulated bucket during the setting process, and the comparison result between the simulation result and the measured data is shown in figure 17.

![Figure 16. The temperature field cloud diagram of the cake in the mold of the insulated bucket without a lid.](image1)

![Figure 17. Comparison of simulation and actual measurement of the temperature field of the cake in the insulated mold without a lid.](image2)

Figure 16 shows in the first 40 minutes of the setting process, the temperature of the upper surface of the cake is the highest, and it gradually rises from the initial temperature to the curing temperature. This is because the slurry in the cake just started to hydrate in the early stage of the static placing, and the temperature of the cake is lower than the curing temperature. At this time, the air transfers heat to
the cake by convection with the upper surface of the cake, causing its temperature to rise until it is the curing temperature is the same. After 40 minutes, the temperature in the green cake gradually increased, and the temperature in the bottom area was the highest, and the closer to the upper surface, the lower the temperature. This is because, with the setting time, the binding material (lime and cement) gradually hydrates and releases more heat, and part of the heat is lost to the environment through the upper surface convection.

Figure 17 shows, the simulation result of point 1 is far from the actual measured value. This is because, there are more thermocouple wires at point 1, and more heat is dissipated into the environment through the wires, resulting in a lower temperature rise than the simulated value. The maximum difference between the simulation results and the measured temperature rise of other temperature measurement points is 0.99℃, which indicates that the finite element simulation results can be consistent with the measured data. Therefore, the finite element model of the temperature field established in this section in the process of the cake in the uncovered insulated mold is gaseous and static placing with good accuracy.

3.3.3. Simulation of the Temperature Field of the Cake in the Iron Cube Mold. The convective heat transfer coefficient \( h_3 \) of the contact surface between the iron mold and the air is 4000 W/(m\(^2\)·K) by comparing the measured data at the temperature measuring points 12 and 13 with the simulation results. The simulation result of the temperature field of the cake in the iron cube mold is shown in figure 18, and the comparison result between the simulation result and the measured data is shown in figure 19.

![Figure 18. The temperature field cloud diagram of the cake in the iron cube mold at setting process.](image-url)
Figure 18 presents in the first 80 minutes of the setting process, the temperature at the corners of the upper surface of the cake are the highest, which gradually increases from the initial temperature to the curing temperature. After 80 minutes, the temperature in the cake gradually increases, and the temperature in the lower area was the highest. The closer to the upper surface, the lower the temperature. This is because the temperature in the cake is lower than the curing temperature in the early stage of setting process, and the heat in the air is transferred to the cake until the temperature is the same as the curing temperature. As the binding material gradually hydrates and releases more heat, the temperature in the cake gradually rises, and part of the heat is lost to the environment.

Figure 19 presents, the measured results of points 7 and 11 in the cake in the iron cube mold within 80 minutes before the static placing are far from the simulated temperature rise. This is because the points 7 and 11 are arranged in the mold, the cake and the air. The place where the participants meet is greatly affected by the environment. The maximum difference between the simulation results and the measured values of the other points is 1.85°C, indicating that the simulation results are consistent with the measured temperature. The finite element model of the temperature field of the cake in the iron cube mold established in this section is accurate.
4. Conclusions
1) The initial temperature of raw materials does not affect the hydration heat of autoclaved aerated concrete slurry but affects its hydration heat release rate. The higher the initial temperature, the faster the heat release rate. The water to material ratio has a great influence on the hydration heat of the slurry, which is mainly reflected in the increase of the corresponding mixing water volume of the unit binding material (lime and cement), resulting in the decrease of the maximum temperature rise of the slurry.

2) The air temperature around the green cake (curing temperature) does not affect the temperature field distribution law in the cake but affects the absolute value of the internal temperature. With the increase of curing temperature, the maximum temperature rise of green cake gradually increases, and the difference between the maximum temperature rise and the minimum temperature rise on the same dimension gradually decreases.

3) The mold condition has a great influence on the temperature field of the green cake. The size and distribution of the temperature along the height direction are affected by the mold conditions on the upper surface of the green cake, and the temperature in the radial direction is affected by the mold conditions on the side of the green cake, but the distribution law is not affected.

4) Under the premise of the basic assumptions in this paper, the finite element software is used to simulate the temperature field in the cake of the insulated mold with lid, the insulated mold without lid and the iron cube mold respectively, which has a good correlation with the measured value.

Acknowledgements
The financial support from National Key Research and Development Projects of China (No. 2016YFC0700802).

References
[1] Xu Q 1998 Experimental study on pouring stability of alkali slag aerated concrete slurry Development Guide to Building Materials 20 38-45 (in Chinese).
[2] Wang J, Wu CY 2015 Influence of the fineness of fly ash and lime on the performance of lightweight autoclaved aerated concrete Brick-Tile 04 8-11 (in Chinese).
[3] Su Y F, Zhang H, and Zhang H 2017 Effect of viscosity of slurry on stability of aluminum powder bubble Journal of Building Materials 20 506-510 (in Chinese).
[4] Piyius R S, Durgesh C R 2018 Effect of piped water cooling on thermal stress in mass concrete at early ages J. Eng. Mech 144(3).
[5] Kodur V K R, Bhatt P P, Soroushian P and Arablouei A 2016 Temperature and stress development in ultra-high performance concrete during curing Constr. Build. Mater 122 63-71.
[6] Zhang H, Su Y F and Yang Z H 2018 Early hydration process of the cement-lime system ce/papers 2 125-129.
[7] Zhang H Yang Z and Su Y F 2019 Early hydration and setting process of cement-hydrated lime system at different curing temperatures IOP Conf. Ser.: Mater. Sci. Eng. 592 124-129.