Temperature Variation of the Early-age Massive Concrete in Freezing Vertical Shaft Wall

Zhijie Chen, Hongguang Ji

Abstract—**A large number of vertical shaft wall cracks have been found in recent years. This paper proposes that these cracks are caused by the release of huge hydration heat of the early-age massive concrete exerting great impact on the following working reliability despite the traditional thought that the damage should emerge during the working period. The temperature field monitoring method was applied to the auxiliary vertical shaft of Yingpanhao coal mine during the massive concrete construction of the inner shaft wall. The analysis of the monitored data of 0-28 days reveals that the temperature distribution and variation rule of inner and outer shaft wall, as well as the freezing wall are given. The results indicated that the concrete at the middle of inner shaft wall came to the peak temperature 75.65℃ in 20-24 hours, which was several days earlier than normal massive concrete. Due to minus-temperature of the freezing shaft wall, there was a maximum temperature gradient through the inner, outer and the freezing shaft wall, and the temperature differential between the outer side of inner wall and the outer wall was up to 42.49℃ at the 16th hour age. Moreover, the strongly continuous hydration heat would drastically change the original temperature field of the outer and freezing shaft walls, and the drastic changes in temperature and the extended solidification point would easily make the internal deformation and the accompanying cracks of concrete, which indicated that the shaft wall would work with injury since the early-age with the ever-increasing risk of cracking.**

Index Terms—**Vertical shaft wall, massive concrete, hydration heat, temperature variation, early-age cracking**

I. Introduction

A great number of engineering practices show that about 80% cracks in concrete structures did not resulted from their deficiency of bearing ability, but from the non-load stress of concrete materials under the influence of temperature and humidity of the environment[1]. Many studies on the internal stress of the early-age massive concrete have been conducted for a long time[2,3,4,5,6,7]: for instance, Bazant[8,9,10] proposed a model of crack band to calculate the temperature cracks of concrete. RILEM Technical Committee 119 called an international conference with the theme of "Avoidance of thermal cracking in concrete at early ages" which provided abundant information for early cracks of the concrete[11,12]. Wang[13,14] analyzed the development of early-age temperature stress concrete accompanied by the age and put forward the assessment method of concrete early cracks. And Zhang[15] researched can be omitted the influence of temperature on the hydration reaction rate and creep properties of early-age concrete.

There are also many studies on cracks of freezing shaft walls. Huang[16] applied field studies to the temperature variation of shaft walls during production period. Jing[17,18,19,20] studied the shaft wall temperature stress at the melting stage of freezing shaft walls and established a prediction theory on vertical shaft wall cracks. Liu[21,22] then demonstrated temperature stress resulting from the temperature difference between the inner and outer vertical shaft walls, and proposed to correct the code for design of coal mine shaft and chamber of China.

However, there is lack of researches associating the cracks of shaft walls with the early-age hydration heat of massive concrete during the construction of vertical shafts. The high-grade concrete largely used in vertical shaft walls boasts high-grade as well as significant hydration heat. The temperature variation of shaft walls are quite obvious with the influence of strong hydration heat, and the influence of temperature stress with a sharp change of temperature transitory on the concrete structure in strength growing period cannot be ignored.

The temperature environment of freezing shaft wall will be very complicated for the concrete of inner shaft wall are simultaneously informed by the cross-ventilation of inner surface of shaft wall, hydration heat during the massive concrete construction of the inner shaft wall and solidification point of freezing shaft wall. In this paper, it will discuss on the shaft wall temperature distribution and variation in the age of 0-28 days, based on the interaction of the cross-ventilation of inner surface of wellbore temperature, concrete hydration heat and freezing temperature.

II. The Engineering Situation and Monitoring System

A. *The Engineering Situation*

Yingpanhao coal mine is located in Bayan Qaidam mining area at the Wushenqi Autonomous Banner, southwest of Ordos City, China. The stone revealed by borehole drilling mainly includes medium-grained sandstone, fine-grained sandstone, coarse-grained sandstone, siltstone, as well as a little sandy mudstone, mudstone and coal seam. Shaft

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characteristic is shown in Table 1.

TABLE I
CHARACTERISTICS OF SHAFT WALL

Strata	Vertical depth / m	Wall-thickness / mm	Concrete strength grade
Quaternary System	0-100	Outer shaft wall 550	C50
		Inner shaft wall 900	C60
Cretaceous Zhidan Formation	100-185	Outer shaft wall 400	C50
		Inner shaft wall 900	C40
	185-280	Outer shaft wall 40	C50
		Inner shaft wall 900	C50
	280-360	Outer shaft wall 400	C50
		Inner shaft wall1150	C50
	360-430	Outer shaft wall 400	C50
		Inner shaft wall 1150	C60
Jurassic Anding Formation	430-500	Outer shaft wall 400	C50
		Inner shaft wall 1400	C60
	500-540	Outer shaft wall 400	C50
		Inner shaft wall 1400	C65
Jurassic Zhiluo Formation	540-561	Outer shaft wall 400	C50
		Inner shaft wall 1400	C70
	561-570	Shaft crib 1803	C70
	570-590	Outer shaft wall 400	C50
		Inner shaft wall 1403	C60
	590-635	Outer shaft wall 400	C50
		Inner shaft wall 1403	C65
	635-680	Outer shaft wall 400	C50
		Inner shaft wall 1403	C70
	680-698.5	Outer shaft wall 400	C50
		Inner shaft wall 1403	CF70
Jurassic Yanan Formation	698.5-711.5	Shaft crib 1803	CF70
	711.5-729.5	Outer shaft wall 400	C50
		Inner shaft wall 1550	CF70
	729.5-759.5	Shaft crib 1950	CF70
	759.5-789.5	Outer shaft wall 400	C50
		Inner shaft wall 1550	CF70

The auxiliary vertical shaft of Yingpanhao coal mine has a net diameter of 10m, and its designing vertical depth is 789.5m, using freezing method in the shaft sinking engineering.

B. *The Monitoring Horizon of Sensors*

Monitoring Horizon

According to the progress of the project and the actual strata conditions, monitoring horizon is set up at the section in vertical depth of 424m over the cross-section of shaft wall. The monitoring horizon is shown in Table 2 for reference.

TABLE II
MONITORED LAYERS OF SENSORS

Monitoring horizon	Strata	Vertical depth / m
Cross-section of shaft wall	Cretaceous Zhidan formation	424

Sensors Arrangement

In order to obtain the accurate temperature variation of inner, outer and freezing shaft walls, the detailed laying positions of sensors in the shaft wall sections are as below:

There were seven temperature measuring spots in total to monitor temperature changes from inner side to outer side of the inner shaft wall. 1# and 2# sensors were at inner side of the inner (I-I) shaft wall; 3# and 4# in the middle of the inner (M-I) shaft wall; and 5#, 6# and 7# at the outer side of inner (O-I) shaft wall, respectively. Furthermore, we planted sensors of 8#-outer (O) shaft wall and 9#-freezing (F) shaft wall to the outer wall 325mm far from the outer side of the inner shaft wall and freezing shaft wall 625mm far from the outer side of the inner shaft wall by punching. The specific setting position of sensors is shown in Figure 1.

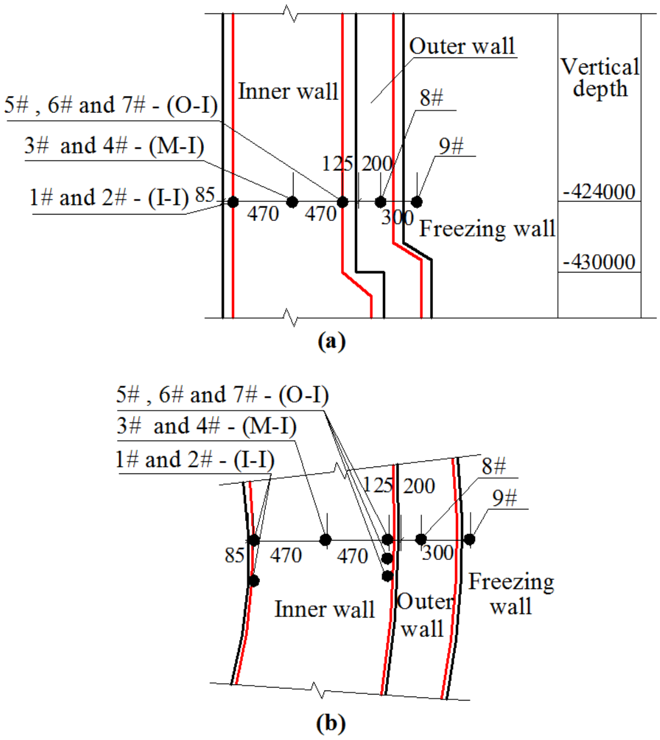

Fig. 1. Location of sensors (a-Vertical profile; b-Cross section).

Therefore, nine temperature measuring spots composed the system to obtain the temperature variation from the inner side of the inner (I-I) shaft wall, via the middle sides of the inner (M-I) shaft wall and the outer sides of the inner (O-I) shaft wall and the outer (O) shaft wall to the freezing (F) shaft wall.

C. *The Monitoring System*

The monitoring system mainly consists of four main components, including data terminal (computer), data acquisition unit, sensors and power. Schematic diagram of monitoring system is shown in Figure 2.

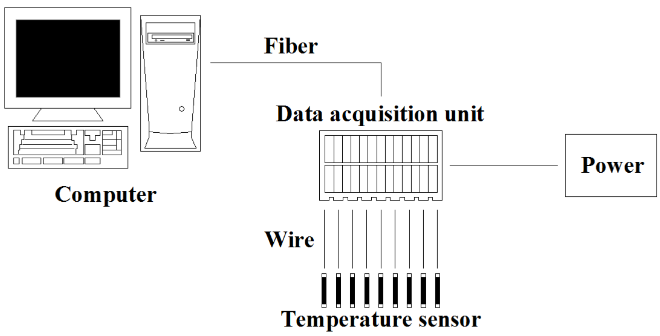

Fig. 2. The schematic diagram of the system

Fig. 3. Data acquisition unit waterproof sealing (a- Data acquisition unit; b- Interior waterproof; c- Exterior waterproof)

Sensors, data acquisition unit and power are installed and fixed at the measuring spots during the concrete pouring process of the inner wall. The sensors are linked to acquisition unit with wires, and the acquisition unit took timing temperature data acquisition and automatic storage according to the settings, before finally the monitoring data are transferred from acquisition unit to data terminal through the optical fiber as the real-time monitoring of the shaft wall temperature change was recorded.

The collection unit has inner and outer double waterproof, and the data acquisition unit waterproof sealing is shown in Figure 3.

III. Monitoring Results and Analysis of the Inner Shaft Wall

A. *Monitoring Results*

The initial temperature of 1# and 2# sensor was 18.35℃ and 18.64℃ respectively.

The temperature of the I-I shaft wall rose rapidly and arrived at peak value at the curing age of the 22th hour and 20th hour respectively, in the wake of which the temperature reduced quickly until the 3th day. 3-7 days later, the temperature dropping rate began to decrease. The temperature dropping rate became steady at the age of 7-14 days. At the age of 14-28 days, the temperature became stable. 1# and 2# sensors were 24.57℃ and 25.61℃ respectively at the age of the 14th day, and at the age of the 28th day the temperature were 17.43℃ and 16.47℃ respectively. The descending rate of the 1# and 2# sensors' temperature during 14-28 days was about 0.51℃/d and 0.65℃/d respectively, shown in Figure 4.

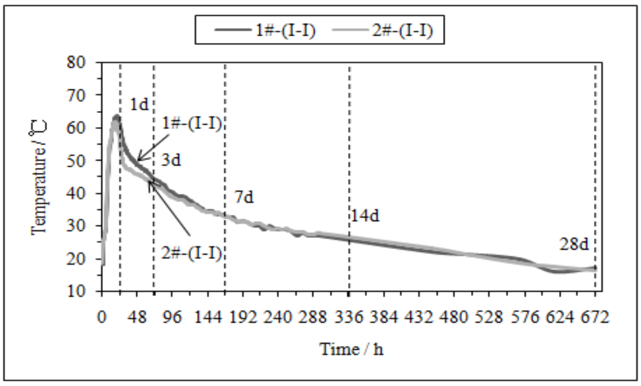

Fig. 4. The I-I shaft wall temperature at the curing age of 0-28 days

The initial temperature of the 3# and 4# sensors were 18.03℃ and 16.78℃ respectively.

Temperatures of the M-I shaft wall rose quickly because of concrete hydration heat. With the continuous accumulation of hydration heat, the temperature arrived at peak value 75.65℃ and 75.31℃ respectively at the age of the 22th hour, which was significantly higher than the temperature of the I-I shaft wall. Later temperatures started to decrease, similar to the I-I shaft wall, shown in Figure 5.

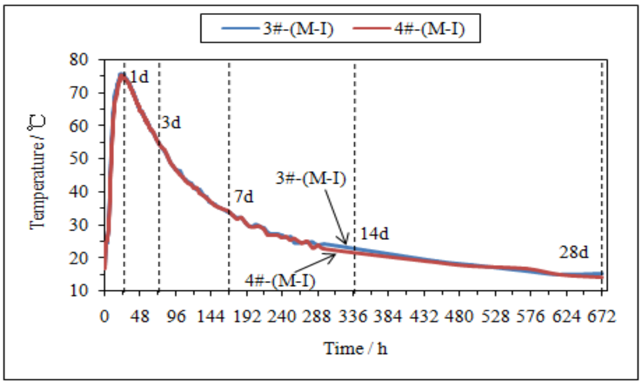

Fig. 5. The M-I shaft wall temperature at the curing age of 0-28 days

The 5#, 6# and 7# sensors, which were fixed on the O-I shaft wall, had the same trend of temperature change as the 3# and 4# sensors.

However, under the influence of low temperature of the outer and freezing wall, the 5#, 6# and 7# sensors were arriving at their peak temperature 47.51℃, 54.87℃ and 53.41℃ at the 34th hour, 28th hour and 33th hour respectively, almost 10 hours later than the 3# and 4# sensors, shown in Figure 6.

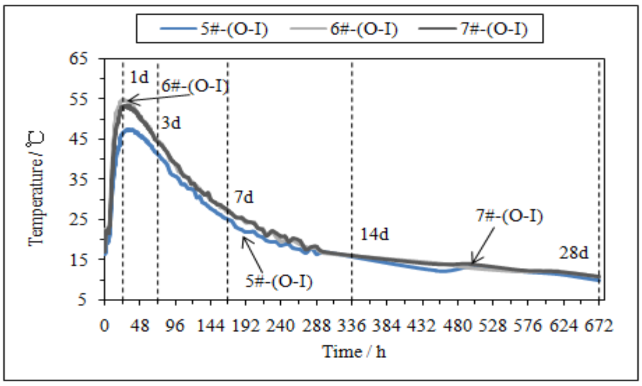

Fig. 6. The O-I shaft wall temperature at the curing age of 0-28 days

The temperature then began to descend. The peak temperature of each monitoring spots is shown in Table 3.

TABLE III
PEAK TEMPERATURE OF THE INNER SHAFT WALL IN MONITORING LOCATIONS

Temperature/℃	1#-(I-I)	2#-(I-I)	3#-(M-I)	4#-(M-I)	5#-(O-I)	6#-(O-I)	7#-(O-I)
Initial	18.35	18.64	18.08	16.78	16.56	17.42	17.00
Peak	63.61	61.73	75.65	75.31	47.51	54.87	53.41
The 28th day	17.43	16.47	15.35	14.13	9.93	10.89	10.73

B. The Time Course Analysis of the Inner Shaft Wall Concrete Temperature

The inner, middle and outside concrete of the inner shaft wall presented regular characteristics, which were influenced by the temperature of the wellbore cross-ventilation, strong concrete hydration heat and freezing temperature. The analysis of the data of 0-28 days indicates that the temperature duration curve of the inner shaft wall could be divided into 5 stages, shown in Figure 7.

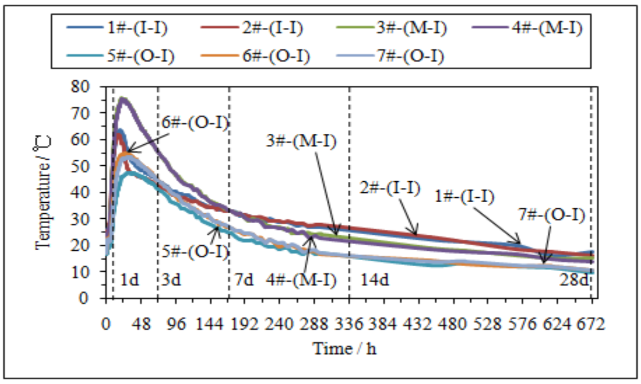

Fig. 7. Temperature duration curve of the inner shaft wall

1) In the first stage (0-1 day), temperature increased sharply. After a large volume of high-strength concrete was poured into forms, the hydration of concrete released a great deal of hydration heat, leading to the temperature rapid increase inside the concrete. All the monitoring spots successively reached to their peak value 20 hours after concrete had been poured into the mold. In the meantime, the outer peak temperature posed less than the inner peak temperature that was less than the middle peak temperature.
2) In the second stage (1-3 days), temperature descended quickly. Affected by the decrease of concrete hydration heat releasing, the heat exchange of the surface of the inner shaft wall and cross-ventilation in wellbore, the minus-temperature of freezing wall, and the concrete temperature formed an inflection point at the peak value and dropped rapidly.
3) In the third stage (3-7 days), temperature dropping slowed down. With the gradual completion of the cement maturing process, the release of hydration heat and the descending speed of temperature gradually reduced, and the temperature of the I-I and the M-I shaft walls got gradually consistent. The throughout temperature field came into being from the inner to outer side of inner walls.
4) The fourth stage (7-14 days) was the transitional stage of the temperature dropping rate. Continually influenced by the minus-temperature of freezing walls, the high temperature position changed with the formation of the throughout temperature field. The cross-ventilation of the inner surface of wellbore temperature and the minus-temperature gradually replaced the concrete hydration heat and played a dominant role in this stage. The temperature of the M-I shaft wall became lower than that of the I-I shaft wall, suggesting the outer temperature of the inner shaft wall less than the middle temperature of the inner shaft wall that is in turn less than the inner temperature of the inner shaft wall.
5) In the fifth stage (14-28 days), the descending speed of temperature became steady. The inner wall temperature decreased steadily and the descending rate of all the measuring spots became close, until the temperature of the monitoring spot became lower than the initial value at the cuing age of the 28th day.

Due to the effect of strong hydration heat, the temperature of the concrete in the M-I shaft wall rose rapidly and reached to the peak value in 20 hours, which was 2-4 days earlier than normal massive concrete.

According to the temperature time course curve of the inner shaft wall, there were two maximum temperature differentials of the inner wall at the curing age of 0-28 days. Firstly, at the 15th hour the temperature of the M-I shaft wall rose to 70.6℃ with strong hydration heat, the temperature of the O-I shaft wall was only 38.97℃, and the temperature differential was 31.63℃. Secondly, after the pouring of concrete lasting for 33 hours, the temperature of the M-I shaft wall was dropping slightly but still up to 72.86℃, while the temperature of the inner surface of the wellbore and the inner shaft wall dropped rapidly by cross-ventilation with the temperature differential being 25.39℃.

IV. MONITORING RESULTS AND THE ANALYSIS OF OUTER AND FREEZING SHAFT WALLS

A. Monitoring Results

In the 0-10 hours after concrete pouring into the inner wall forms, the outer shaft wall temperature stayed at about 5℃. From the 11th hour, the concrete hydration heat of the inner

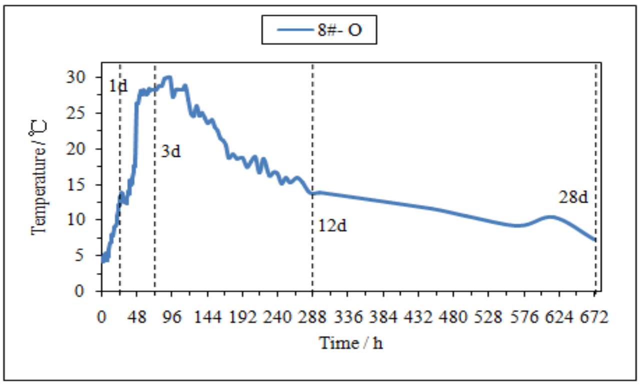

Fig. 8. The outer shaft wall temperature at the age of 0-28 days

shaft wall gradually conducted to the outer shaft wall, and thereby the outer wall temperature rose dramatically and rapidly arrived at the peak value of 29.88℃ at the 89th hour for the first time. During 89-288 hours, the temperature showed a fluctuation downward trend and after the 288th hour, the descending speed of temperature became steady till the 28th day, shown in Figure 8.

During 0-24 hours, the temperature stayed below about 0℃. After the 24th hour, hydration heat was gradually conducted to the freezing wall via the outer wall. The monitoring spot area of the freezing wall melted quickly and the temperature increased rapidly to the peak value at the 109th hour. During 109-288 hours, the temperature began to show a fluctuation downward trend, and after the 288th hour, the temperature descending rate became steady until the 28th day, shown in Figure 9.

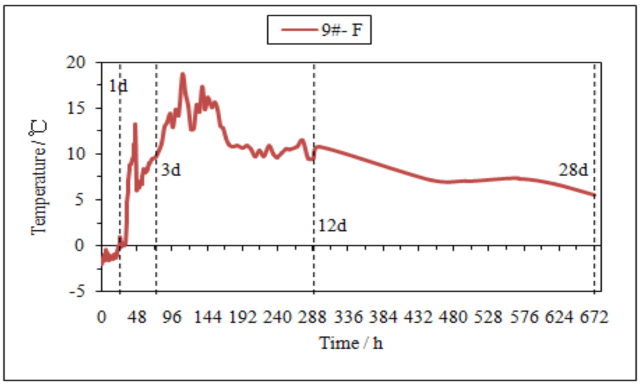

Fig. 9. The freezing shaft wall temperature at the age of 0-28 days

The peak temperature of outer and freezing shaft walls can be seen in Table 4.

TABLE IV
THE PEAK TEMPERATURE OF OUTER AND FREEZING WALLS

Temperature/℃	8#-Outer shaft wall	9#-Freezing shaft wall
Initial	4.74	-2.02
Peak	29.88	18.72
The 28th day	7.35	5.57

B. The Temperature Variation Analysis of Outer and Freezing Shaft Walls

Influenced by the hydration heat of the inner wall concrete, the initial temperature field of the outer and freezing shaft walls changed greatly. The temperature time-history curve is shown in Figure 10.

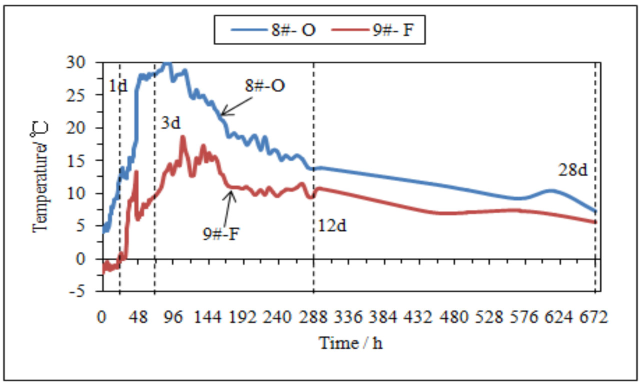

Fig. 10. The temperature duration curve of outer and freezing shaft walls

According to the temperature duration curve data, the temperature of outer wall between 0-10 hours and freezing wall in the 1st day did not significantly changed because the freezing temperature played a dominant role. At the 20th hour, the temperature of the M-I shaft wall was up to 74.71℃ while the temperature of outer wall was 9.65℃ and the freezing wall down to -0.6℃, as the temperature differential were 65.06℃ and 75.98℃.

The hydration heat replaced the freezing temperature to occupy the most powerful and influential position under the continual work of hydration reaction. The temperature of the outer and freezing shaft wall was changed dramatically. The temperature of outer and freezing shaft walls then rose to about 25℃ and 20℃. The temperature variation of the freezing shaft wall was slower than the outer shaft wall in that the freezing shaft wall monitoring spot area location was far from the center of the hydration heat. The original temperature field of the freezing shaft wall melt rapidly for a short time, which would transform the original stress field of freezing wall and little wonder that the changing of freezing stress could have great effects upon the structure strength of shaft wall.

V. THE TEMPERATURE GRADIENT ANALYSIS

At the age of 0-28 days, the radial temperature gradient curves along the shaft walls of the inner, outer and freezing shaft wall is shown in Figure 11.

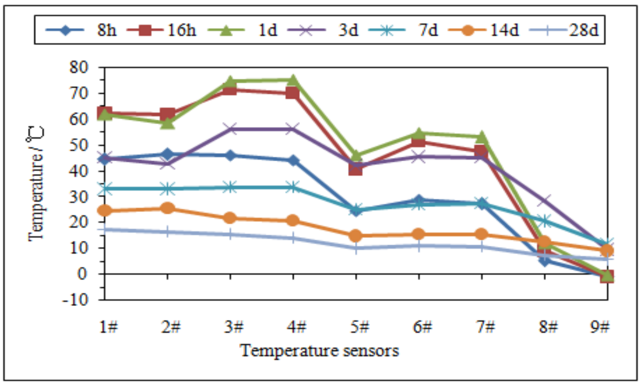

Fig. 11. Curves of temperature gradient

The curing age of 0-8 hours were the beginning of the hydration heat process. The curve presented nearly 4 temperature gradients (the temperature from high to low is: M-I shaft wall, O-I shaft wall, the outer shaft wall, the freezing wall, and the temperature of the I-I shaft wall is approximately equal to the M-I shaft wall). The temperature differential between the middle and outer sides of the inner wall was up to 18℃ as the temperatures of the outer and freezing walls were 4.93℃ and -1.17℃.

At the age of the 16th hour, 1st day and 3rd day, the middle concrete temperature of the inner wall reached to the peak value rapidly, and the gradient curve changed significantly, which presented 5 temperature gradients (the temperature from high to low is: M-I shaft wall, I-I shaft wall, O-I shaft wall, the outer shaft wall, the freezing wall). The maximum temperature differential between the M-I shaft wall, the outer wall and the freezing wall were detected in this stage as the maximum temperature differential emerged between the M-I shaft wall and the I-I shaft wall, also the difference between the M-I shaft wall and the O-I shaft wall.

At the age of the 7th, 14th and 28th day, with the release of hydration heat and the gradual consistence of the temperature of the inner and middle sides of inner walls, the throughout temperature field came into being from the inner to outer side of inner shaft walls as temperature gradients were presented similar to an inclined straight line.

VI. Conclusion

The concrete in the middle of the inner shaft wall reached to the peak temperature 75.65℃ in 20-24 hours, which was 2-4 days earlier than normal massive concrete. Due to the strongly continuous hydration heat of the inner shaft wall concrete, the temperature differential between the outer side of inner wall and the outer wall was up to 42.49℃ and 42.42℃ at the curing age of the 16th hour and 1st day. Affected by strongly continuous hydration heat of inner shaft wall concrete, the overall temperature of the outer and freezing shaft walls increased by, respectively, 25℃ and 20℃. The freezing shaft wall melt rapidly in a short period of time, which would transform the original stress field of frozen wall. In the wake of it, little wonder that the changing of frozen stress field could have great effect upon the structure strength of shaft wall.

The analysis of the data of 0-28 days during the massive concrete construction of the inner shaft wall reveals two maximum temperature differentials of the inner wall at the curing age of 0-28 days. (1) At the 15th hour when the temperature of the middle of inner shaft wall rose to 70.6℃ with strong hydration heat, the temperature of the outer side of inner shaft wall was only 38.97℃ with the temperature differential being 31.63℃. (2) The temperature of the middle of inner shaft wall was dropping slightly but still up to 72.86℃ at the curing age of the 33th hour while the temperature of the inner side of the inner shaft wall dropped rapidly by cross-ventilation in wellbore with the temperature differential being 25.39℃. The strongly hydration heat and huge temperature difference will make concrete shrinkage and crack at early-age, which will affect the working reliability of the shaft wall.

At the curing age of 0-7 days, the maximum temperature gradient came into being through the inner, outer and the freezing shaft wall. At the early stage of 0-20 hours, the middle of the inner shaft wall temperature rose to 74.71℃ while the temperature of the outer shaft wall and freezing shaft wall still stayed at, respectively, 9.65℃and -0.6℃, due to freezing temperature. Such a larger temperature gradient would pose great danger to the intensity growth of the massive concrete of the shaft wall at its early stage, thus seriously affecting the compactness and completeness of concrete.

The first approximate 10 hours after the concrete had been poured into the inner shaft wall is the crucial period in which the concrete from initial set to strength growing till it formed final strength. Dramatic changes in temperature accompany the concrete deformation and temperature stress, which will largely prevent strength development of the shaft wall at early-age, and it could be the reason why the natural service of shaft wall will susceptible to damage. The current codes have yet to regulate the ways of how early-age concrete temperature informs the curve shaft walls of massive concrete. Therefore, it can be suggested that, in the future work of production, a general monitoring survey of the temperature fluctuation needs conducting over massive concrete of the shaft wall at the curing age and some effective measures should be taken to decrease hydration heat and temperature difference of the shaft wall so as to avoid its cracking and damage in the intensity growth of massive concrete.

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