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The Role of Double-Cylinder Insulation Technology in Ensuring the Quality of Bored Pile Concrete under Negative Temperature Condition

Ziying Liu[a], Tianlai Yu[a,*], Ning Yan[a], Zhihai Piao[b], Hongxiang Zhang[a]

[a]*College of Civil Engineering, Northeast Forestry University, Harbin150040, China*

[b]*Research and Development Center, Longjian Road and Bridge Co., LTD,Harbin 150090, China*

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Abstract

In this paper, the cement concrete with low heat of hydration was prepared by adding fly ash, and then used in the double-cylinder insulation technology. Based on heat dissipation test, thermal conductivity test and low temperature strength test of the prepared concrete, the growth law of concrete strength under negative temperature condition was studied. The strengths of three concrete test piles at the corresponding temperature were measured by ultrasonic method, and the influence law of double-cylinder insulation technology on the change of concrete strength was studied. The results show that the curing temperature dropped from 20□C to -3□C, -5□C and -7□C on the 28th day. Compared with the standard curing temperature, the strength loss was 29.7%, 31.7% and 42.8%, respectively. There were similar rules on the 60th day and 28th day. In the first 7 days, the temperature of low hydration heat concrete was 1. ~2.8°C lower than that of ordinary concrete. From the 7th day to the 28th day, the temperature of low hydration heat concrete was 0.5°C higher than that of ordinary concrete. After applying the double-cylinder insulation technology to the concrete, the temperature was increased by 7.9°C, 7.3°C and 4.8°C in 0~3rd day, 3rd~7th day and 7th~28th day, respectively. Compared with strength on the 28th day, the strength of low-hydration heat concrete was 2.15% higher than that of ordinary concrete. After applying polyurethane insulation layer, the strength of the low-hydration heat concrete increased by 18.6% compared with that of the low-hydration heat concrete without insulation layer.

Keywords: negative temperature, concrete, low heat of hydration, heat preservation, temperature of foundation pile, strength;

1. Introduction

Daxinganling belongs to the seasonal permafrost area, and bridges generally use bored pile foundations [1, 2]. The average ground temperature of frozen soil is basically 0 ~ -3.5°C [3, 4]. The cast-in-place pile concrete is in a low temperature environment for a long time, which will cause the hydration rate of the concrete to decrease obviously, and the hydration heat release is to be reduced significantly under the same period. Although the lower hydration heat release will reduce the disturbance of temperature rise to the frozen soil and shorten the frozen soil's refreezing time, it will cause a series of problems such as slow growth of the strength of the cast-in-place pile concrete itself, inadequate hydration and even insufficient strength [5]. Therefore, it is necessary to carry out experimental research on early mechanical properties of concrete under negative temperature conditions, and to grasp the law of concrete strength growth under negative temperature conditions, which has practical significance for the design and

* Corresponding author e-mail: tianlaiyu@126.com.

At present, the strength growth of concrete under negative temperature has been studied abroad. Michel Pigeon [6] and others believe that when the change of gas content could no longer improve the freezing resistance of high-strength concrete, the different types of cement, aggregates and curing periods have certain effects on the freezing resistance of small-water-binder ratio concrete. Through experiments, Nurse has found that the compressive strength of concrete increases as the product of temperature and time increases [7]. The research committee of natural environment concrete performance in Japan has studied the development law of concrete strength under natural cold and hot weather [8-12].

The research on the strength growth of concrete under negative temperature mainly focuses on the influence of antifreeze on concrete. Yang Yingzi and Ba Hengjing [13, 14] and others believe that after the completion of stirring, there are more water molecules around the coarse aggregate, after condensation hardening, it is loose porous, forming the interface transition zone, and they also think that the region is the weakest link, it has a significant impact on the mechanical properties and durability of concrete. The antifreeze is mainly to improve the microstructure of the negative temperature interface, so that the frost heaving stress in the transition zone is reduced, thus reducing the internal structural damage. The addition of antifreeze has different effects on the negative temperature concrete. When the appropriate amount of antifreeze is added, it mainly reduces the freezing point of water in concrete and accelerates the formation of early structure effectively; when the antifreeze mixed is in excess, due to the large amount of salt in the antifreeze, it will cause different degrees of damage to the pore structure of the concrete. Tian Limei, Lu Weina[15] and others have studied the strength development of C35 concrete under naturally changing negative temperature. Li Fen and Yang Yongpeng [16] have studied the development law of compressive strength of concrete within C40 strength grade under negative temperature.

By summarizing the research contents of available literature, we can find that there are still some problems in the study of negative temperature concrete compressive strength, mainly including:

1. Under the condition of protecting permafrost, there are few studies on the strength variation rule of low heat of hydration mixed with fly ash under the condition of negative temperature.
2. In the ice rich area, there are few studies on the strength variation of concrete under the condition of negative temperature combined with actual engineering.
3. In the drilling pile construction, the double protective cylinder heat preservation plan is used, and the growth law of concrete strength is lack of study.

2. Study on low hydration heat concrete

In seasonal frozen soil areas, as the environmental temperature changes, liquid water and solid ice transform between each other and form complex physical and mechanical characteristics of frozen soil [17-20]. Therefore, how to reduce the thermal disturbance to the permafrost around the pile and ensure the concrete strength to meet the design requirements has become the main problem to be solved in the study of project construction in the frozen soil region. In order to solve this problem, this paper proposes to adopt low hydration heat concrete to replace conventional concrete and take necessary insulation measures.

2.1. The Selection of raw materials

In this paper, "Mengxi" P • O 42.5 ordinary silicate (low alkali) cement was selected, its properties are shown in Table 1; Coarse aggregate is composed of 10-20 mm and 16-31.5 mm single-grain grade gravelmixing in proportion, the former proportion accounts for 72% and the latter 28%. After mixing, it basically conforms to 5~31.5 mm continuous grading. River sand was adopted as the fine aggregate, which is smooth, hard, and well graded. It has fineness modulus of 2.51, which belongs to medium sand. Grade II fly ash from Qiqihar, KMSP water reducing agent, KMSP-14 antifreeze and drinking water were used in this work.

Table 1. The properties of cement

normal consistency	security /mm	setting time /min		compressive strength / MPa		flexural strength / MPa	
		Initial setting	Final setting	3d	28d	3d	28d
29.2	0.5	254	360	27.8	49.6	5.1	8.0

2.2. The influence law of fly ash on hydration heat

The hydration heat was measured by SHR-16S test instrument, and the measurement system of hydration heat of cement can be seen in Figure 1. According to the test method stipulated in GB/T 12959-2008, the hydration heat at different fly ash contents and different period were tested.

Figure 1. Hydration heat test instrument

In order to study the effect of fly ash on hydration heat, seven groups of experiments were carried out; group one was pure cement. In groups 2 to 7, the fly ash content was 20%, 22.5%, 24.8%, 27.0%, 29.0% and 31.1%, respectively. The experimental ages of hardening were 1d, 3 d, 7 d, 14 d and 28 d. The results of the experiment are shown in Figure 2.

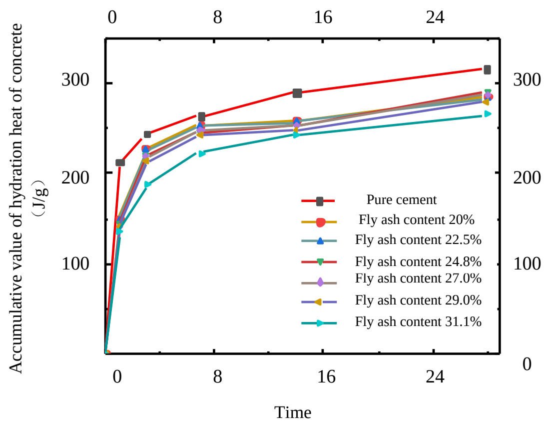


Figure 2. The curve of concrete hydration heat changing with time

Figure 2 shows that in the period of 0~3rd day, 3~14th day 14~28th day, pure cement in the hydration reaction of concrete released 243.2 J/g, 289.8 J/g, 315.8 J/g heat accumulatively. With the increase of fly ash content, the heat released by the concrete that falls into the fly ash gradually decreased. The amount of fly ash content increased from 20% to 31.1%, and the amount of heat released from hydration reduced from 228.4 J/g, 258.4 J/g, 285.7 J/g to 187.5 J/g, 243.2 J/g, 265 J/g, respectively.

It can be found that the hydration heat of pure cement in different ages of hardening is greater than that of different proportions of fly ash, and the greater the proportion of fly ash content, the smaller the hydration heat of cementing materials in each age of hardening was. Theoretically, the smaller the hydration heat of cementing material, the lower the temperature rise of the hydration heat of concrete will be, so the thermal disturbance to the soil around the pile foundation is much smaller. Combined with the relevant regulations in “Technical Specifications for Construction of Highway Bridges and Culverts” JTG / T F50-2011, in a freeze-thaw environment, the fly ash content should not exceed 30%, so 29% of cement material is selected.

2.3. The influence of cement content on hydration temperature

The concrete adiabatic temperature rise tester (HJW-3) was used to test the adiabatic temperature rise, and the influence of cement content on hydration temperature was studied. The instrument precision ≤±0.05°C, Temperature change of 50 L water at 72 hours ≤±0.05°C, as shown in Figure 3.

Figure 3. The laboratory concrete adiabatic temperature rise tester

The cement contents were 380 kg, 312 kg, 303 kg, 294 kg and 278 kg, respectively. The initial temperature was controlled at 20°C (error ± 0.5 °C). The content of admixture KSMP was 1.5%, and the antifreeze KM-14 was 5.0%, and the fly ash content was 29%. The shift test of adiabatic temperature rise is shown in Figure 4.

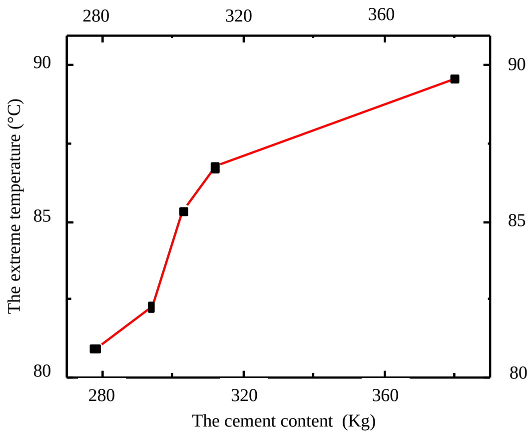


Figure 4. The influence of cement content on hydration temperature

As can be seen from Figure 2 to Figure 4, the adiabatic temperature increased continuously with the increase of concrete content. There was a nonlinear relationship between concrete content and adiabatic temperature rise. This was mainly due to that with the increase of cement content, the amount of water decreased, resulting in this uneven situation. Combined with the “Technical Specifications for Construction of Highway Bridges and Culverts” JTG / T F50-2011, the minimum concrete content of C30 concrete in severe cold areas cannot be less than 300 kg/m^3, so the final cement content was set to 303 kg/m^3.

2.4. Low hydration heat concrete mix ratio and slump test

According to section 2.3, 2.2, the mixing ratio of low hydration heat is, cement: fly ash: sand: gravel: water = (1:0.41:3.011:3.673:0.619). The mixing ratio of ordinary concrete is cement: fly ash: sand: gravel: water = (1:0.290:2.762:3.373:0.545). In order to meet the workability and water retention requirements of the construction process, slump test tests of cohesioness and water retention were added. In order to meet the workability and water retention required by the construction process, tests such as slump test, cohesion and water retention were conducted. The test results are shown in Table 2, which can meet the needs of the construction of bored pile project.

Table 2. The workability of low hydration hot concrete (mm)

Initial slump	Initial slump	slump after 60 min	cohesiveness	water retention
240	650×600	200	good	no bleeding

3. The influence of negative temperature on concrete strength

In order to study the strength growth law of bridge bored pile concrete in the frozen soil area under the low negative temperature curing environment, refer to literature [21-22], the proposed concrete mix ratio is seen in section 2.4. According to the method stipulated in*GB/T 50081—2002*, the curing temperature shall be conducted at 20°C (standard curing), -3°C, -5°C and -7°C, respectively. The compressive strengths of concrete specimen 150×150×150 mm at the 7th day, 14th day, the 28th day and the 60th day of hardening under different curing conditions were tested. The test data are shown in Figure 5.

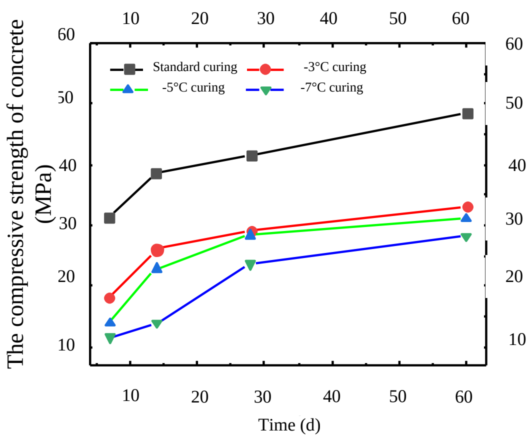


Figure 5. The summary chart of compressive strength of concrete

The data in Figure 5 show that at the same age of hardening, the strength of concrete decreased as the curing temperature decreased. When the age of hardening was 7 day, the concrete strength under -3°C curing only reached 43.4% of strength at the 28th day, under 20°C curing, and reached 75.8% under 20°C curing. When the age of hardening was 14 day, the concrete strength under -3°C curing only reached 62.8% of strength at the 28th day, under 20°C curing, and reached 93.0% under 20°C curing.

At the 28th day, the curing temperature was reduced from 20°C to -3°C, -5°C and -7°C, respectively. Compared with standard curing, the strength as reduced by 29.7%, 31.7% and 42.8%, respectively. The 60th day and 28th day of hardening showed similar rules, that is, the lower the curing temperature was, and the higher the strength loss was.

The higher the curing temperature was, the faster the strength of concrete developed in later period, that is, the 14th day- the 60th day strength. When the age of hardening was 60 d, the concrete under -3°C curing only reached 79.7% of the strength at the 28th day under 20°C curing and reached 117.4% under 20°C curing.

In order to ensure the strength of concrete under negative temperature, on the one hand, the temperature of the bored pile concrete must be increased, and on the other hand, the concrete strength level should be high. According to the research results of the temperature field of the concrete pile body, the curing temperature after concrete pouring was -2 ~ -3°C. Taking C30 concrete as an example, the strength loss under -3°C at the 28th day was 29.7%. At this point, it should be configured according to C43 to ensure that the concrete strength reaches C30.

4. Study on heat insulation effect of adding polyurethane between double-layer steel protective cylinders

4.1. The experimental site

The study was based on the bridge bored pile construction project of Jingmo highway. The site is located in an island-shaped permafrost area in the hilly and low mountains of Mohe County, Daxinganling area, Heilongjiang Province, with an average altitude of 550 m [23-24], the permafrost thickness in this area is 50-100 m [25], and the average annual ice age is 7 months [26]. Site I is located near pile 11 of K424+380 frozen soil bridge. Site II is located between Piers 15-16 of K425+290 frozen soil bridge. The depth of frozen soil on both sides of the piles is 11.5m. The soil layer on the pile side is shown in Table 3-a, Table 3-b.

4.2. Test pile materials and construction

1. Insulation scheme and materials

Polyurethane material was added between double cylinder for insulation. The polyurethane foam was used as insulation material, which has the advantages of low thermal conductivity and good insulation performance. The materials of protective cylinder is q235 steel, which has good plasticity and welding properties, and is convenient for construction.

2. Test pile construction

Three test piles were constructed by means of percussion drilling. Test pile 1# and 2# were located in site I, and the distance between them was 6m. Test pile 3# was located in site II. The concrete mix ratio is shown in section 2-4. Specific plans are shown in Table 4.

Table 3-a. Soil distribution of the site I

The serial number of soil layer	Name of the soil layer	The types of frozen soil	Soil thickness /m	Depth from the surface /m
1	Cumulosol	Ice layer containing soil	2.1	2.1
2	Ice layer	Pure ice	1.3	3.4
3	Cumulosol	Ice layer containing soil	1.6	5.0
4	Mucky soil	Ice layer containing soil	1.3	6.3
5	Roundstone	ice-rich permafrost	2.4	8.7
6	intense weathering tuff	Permafrost with much ice	2.8	11.5

Table 3-b: Soil distribution of the site II

The serial number of soil layer	Name of the soil layer	The types of frozen soil	soil thickness /m	Depth from the surface /m
1	Cumulosol	Ice layer containing soil	0.9	0.9
2	Silty clay	Permafrost with less ice	0.7	1.6
3	Silty clay	ice-rich permafrost	4.4	6.0
4	mucky soil	Permafrost with much ice	1.5	7.5
5	Roundstone	Permafrost full of ice	2.2	9.7
6	Pebble	Permafrost with much ice	1.8	11.5

4.3. The monitoring scheme of temperature field

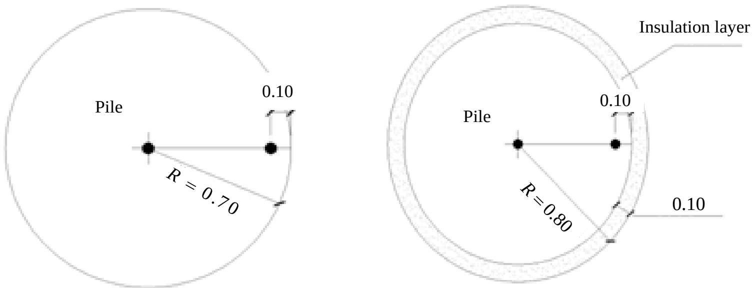
In each test pile, a temperature measuring line was arranged at y of pile core and pile wall, and the numbers are A and B respectively. The lateral arrangement of thermometer hole is shown in Figure 6. In each thermometer hole, 13 to 14 measuring points were arranged along the depth of the rock and soil layer. The location of the measuring points should consider the boundary of the soil layer. The distance between the sensors in the same soil layer was 0.2-1.3 m, as shown in Figure 7.

The temperature sensor is resistive temperature sensing element DS18B2. Temperature collection range is -55 ~ +125°C, and the accuracy is ±0.2°C. JMWT-64RT system is adopted for automatic collection. The system is powered by batteries in winter and solar energy in summer.

The temperature of the concrete throughout the pouring process was monitored. The temperature before concrete pouring was studied; the temperature data every 4 hours after concrete pouring until 24 hours were collected; afterwards, temperature measurement data every 3 days, 7 days, 14 days and 28 days were collected; After 28 days of concrete curing, temperature data was collected every 15 days.

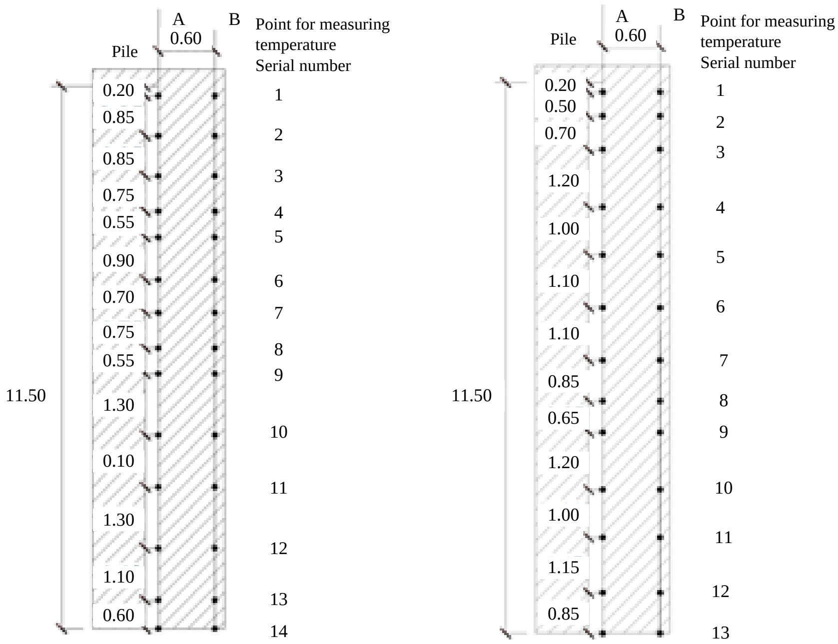
Table 4. Comparison table of test pile scheme (m)

Pile number	site	Pile diameter	pile length	Cement type	The type of protective cylinder	Pouring time
1#	I	1.4	11.5	C30ordinary cement concrete	Single layer steel protective cylinder	2017.10.31 11:20
2#	I	1.4	11.5	C30low hydration heat cement concrete	Double-layer steel protective cylinder, adding 10 cm polyurethane foam between layers	2017.11.04 11: 03
3#	II	1.4	11.5	C30low hydration heat cement concrete	Single laer steel protective cylinder	2017.10.22 14: 00



(a) 1# 3#test pile (b) 2#test pile

Figure 6: Horizontal layout of thermometer hole (m)



(a) 1# and 2# test pile (b) 3# test pile

Figure 7: Longitudinal layout of thermometer hole (m)

4.4. Study on temperature variation of pile foundation concrete

At the same age of hardening, the lower the curing temperature, the lower the compressive strength was. In the whole temperature field of pile foundation concrete, the temperature of pile wall was the lowest temperature. Therefore, the change law of pile wall temperature can better illustrate the effectiveness of low-hydration heat concrete integrating insulation layer. See the details in Figure 8-Figure 9 as below.

In Figure 8, the temperature field of the three test piles is unevenly distributed within a depth of 4.1 m from the surface, which was mainly due to the interference of external low temperature. In order to study the effect of low hydration heat concrete and the addition of insulation layer, only the temperature field below 4.1 m from the surface was considered in the analysis.

In the soil layer below 4.1 m, the temperature of the test pile 3 # was significantly lower than that of test piles 1# on the 1st day and 3rd day, which shows that the use of low hydration heat concrete reduced the early heat release of concrete and effectively reduced the thermal disturbance to the soil around the pile foundation. In the period of the 1st-28th day, the temperature of the test pile 2# was higher than that of the test pile 2#, indicating that the insulation effect of polyurethane material was better; The temperature of test pile 2# was obviously more uniform than that of test pile 3# and 1#, which indicates that the adding polyurethane between the two cylinders made the curing environment of pile foundation concrete more uniform. This provides a condition for the formation of the overall strength of pile foundation concrete and reduces the occurrence of too low local strength.

With the deepening of depth, the wall temperature gradually decreased, and the lowest temperature appeared at 11.5 m at the bottom of the pile. Based on Figure 9, the change of temperature with time was analyzed.

In the period of 0~3rd day, all the piles showed phenomenon of temperature rise, and in the 3th day, and test piles 1#, 3#and 2# had a maximum temperature of 11.2°C, 8.4°C and 16.3°C, respectively. In the 3rd~7th day, the temperature of each pile began to decrease, the average temperatures of test piles 1#, 3# and 2# were7.5°C, 6.3°C and 13.8°C, respectively. In the 7th-28th day, the average temperature of test piles 1#, 3# and 2# were 1.6°C, 2.1°C and 5.9°C, respectively. In the 28th~60th day, the temperature of all the piles reduced to -0.4 ~ -1.1°C.

In summary, the temperature of low hydration heat concrete was 1.2°C~2.8°C lower than that of ordinary concrete in the 0-7th day. In the 7th~28th day, the temperature of low hydration heat concrete was 0.5 C higher than that of ordinary concrete. This is because the low hydration heat concrete contained more fly ash content, which delayed the hydration process of the concrete. After adding the insulation layer in the same kind of concrete, the temperature of concrete improved by 7.9°C, 7.3°C and 4.8°C in the 0~3rd day, 3rd~7th day and 7th~28th day, respectively. The increase of curing temperature can directly enhance the strength of pile foundation concrete and reduce the loss of strength.

5. The quality verification of pile concrete

5.1. Monitoring scheme and data arrangement

In order to verify the quality of concrete, ultrasonic wave method was used to test the strength of three test piles at different ages of hardening. The sounding pipe was pre-buried in the concrete pile. Two sounding pipes were used to form a detection surface with a measuring point spacing of 100 mm. The cumulative height difference between the transmitting and receiving transducers of each measuring point did not exceed 2 cm. The test instrument is HC-U86 concrete ultrasonic detector. Figure 10 (a), (b) show the test principle, test instrument and test site for testing the concrete strength by ultrasonic method on site.

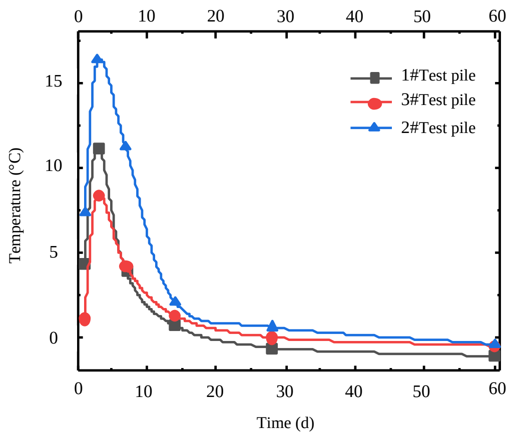


Figure 9. The change of pile bottom temperature with time (m)

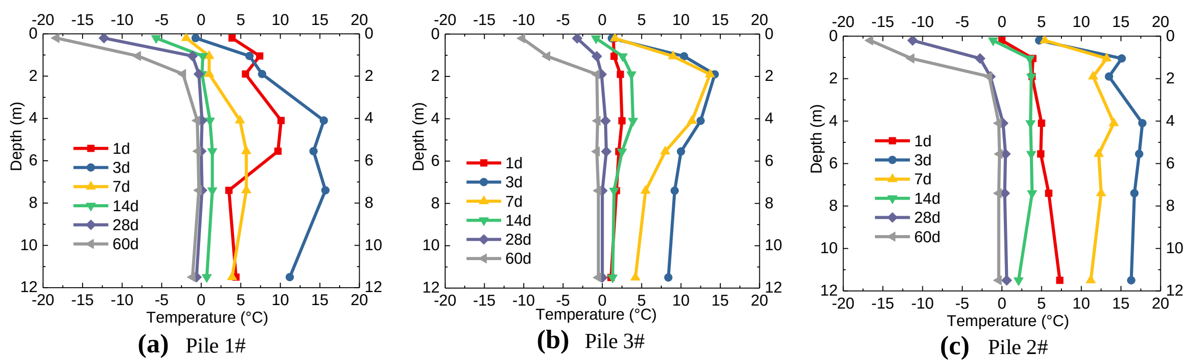
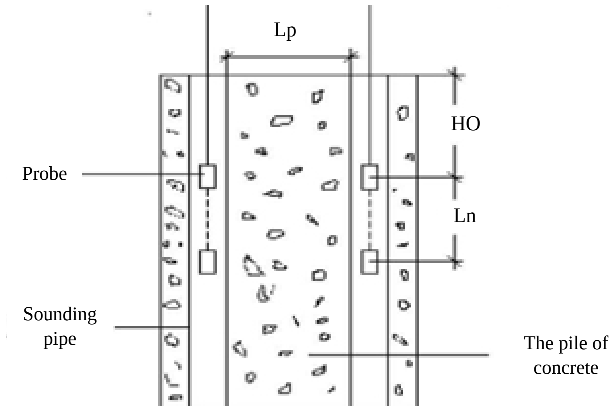


Figure 8. The curve of temperature changing with depth of test pile at each age of hardening (m)



(a) Schematic diagram of field strength measurement

(b) HC-U86 concrete ultrasonic detector

Figure 10. Ultrasonic on-site measurement of concrete strength

The measured data of strength and sound velocity of concrete sample on the 28th day under negative temperature environment were fitted, and the results showed that the strength increased exponentially with the sound velocity, as shown in equation (1).

$$f_{cu} = 0.035 \cdot v^{4.437}, \quad R^2 = 0.989 \tag{1}$$

The correction coefficients of concrete strength for the 7th day and 14th day of curing are shown in equation (2) and equation (3) respectively.

$$\lambda_7 = 0.669 + 0.022 \cdot T - 0.001 \cdot T^2, \quad R^2 = 0.934 \tag{2}$$

$$\lambda_{14} = 1.087 + 0.049 \cdot T - 0.003 \cdot T^2, \quad R^2 = 0.969 \tag{3}$$

5.2. Pile quality analysis

In the study of pile quality, the law of compressive strength of concrete at a depth of 11.5 m changing with time was analyzed. In Section 4-4, the lowest temperature of each test pile appeared at a depth of 11.5 m. Through analysis of the compressive strength at this depth, the advantages of low hydration heat concrete with adding insulation layer can be reflected.

In Figure 11, the strength of test pile 2# at each age of hardening was greater than that of pile 1#and pile 3#. At the 28th day, there was not much difference in the strength of pile 1# and pile 3#, and the compressive strength of pile 2# was 18.2% higher than that of pile 3#. It shows that the method of adopting double cylinder insulation technology with addition of insulation layer can keep the pile in a relatively high curing temperature, which has an obvious effect on the growth of concrete strength.

6. Conclusions

1. In the indoor low temperature curing test, when the age of hardening was 28 day, the curing temperature dropped from 20°C to -3°C, -5°C and -7°C. Compared with the strength of standard curing, the strength was decreased by 29.7%, 31.7% and 42.8%, respectively. In order to ensure the strength of concrete under negative temperature, on the one hand, the temperature of bored pile concrete should be raised, on the other hand, the strength grade of concrete should be higher.
2. In the first 7 day, the temperature of low hydration heat concrete was 1.2°C~2.8°C lower than that of ordinary concrete. In the period of the 7th-28th day, the temperature of low hydration heat concrete was 0.5°C higher than that of ordinary concrete.
3. After applying double-cylinder insulation technology to the concrete, the temperature of concrete improved by 7.9°C, 7.3°C and 4.8°C in the 0~3rd day, the 3rd~7th day and the 7th ~28th day, respectively. Compared with the strength of concrete on the 28th day, the strength of concrete after adding polyurethane material between double cylinders was increased by 18.2% than that of low hydration heat concrete. This indicates that double cylinder insulation technology with addition of polyurethane material can increase the quality of concrete pile.

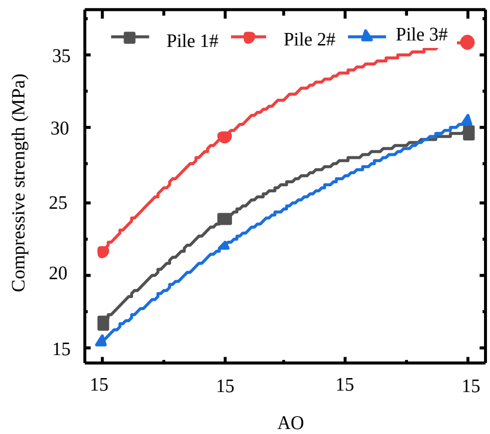


Figure 11. The curve of compressive strength of pile foundation concrete changing with time

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