Experimental Study on Key Design Parameters of Cast-in-situ Pile Foundation in Permafrost Regions

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Abstract. The freezing strength of pile foundation in contact with permafrost is the key parameter for calculating the bearing capacity and pull-out stability of foundation. The thermal physical parameters of concrete before initial setting under various conditions were measured by a thermal conductivity meter based on the transient method. The effects of water binder ratio and pouring temperature on the thermal physical parameters were analyzed. The results show that the ratio of water to binder increases from 0.4 to 0.6, the thermal conductivity and thermal diffusivity decrease and the specific heat increases correspondingly; the thermal conductivity is negatively correlated with the pouring temperature, while the specific heat and thermal diffusivity are not significantly correlated with the pouring temperature. Based on the above research results, it is suggested that the water binder ratio of 0.4-0.45 and the pouring temperature of 5-10°C should be adopted in the design of cast-in-place piles in permafrost regions.

1. Introduction

With the implementation of the national strategy of "the Belt and Road", the construction of an international channel for the "the Silk Road Economic Belt" and the further implementation of the plan for further implementation of the western development and the improvement of infrastructure in the western region in 13th Five-Year, the northwest and Northeast China will usher in the construction of a large regulatory infrastructure, including ±400kV DC, and Harbin-Dalian high-speed railway (built) and Beijing-Tibet highway (to be built) and other high-level projects. For engineering, permafrost is a kind of bad foundation soil, which is prone to frost heave and thaw settlement problems [1-2], causing certain damage to buildings. Pile foundation, especially cast-in-place pile foundation, has the advantages of high mechanization of construction and reliable quality of pile body, and is widely used as foundation form.

In this paper, the important influencing factors of freezing strength: water binder ratio and pouring temperature of concrete are studied. The thermal physical parameters of concrete before initial setting are determined by using QL-30 thermophysical parameter tester based on transient method at 5, 10, 15, 20 and 25°C, respectively. The thermal physical parameters of concrete before initial setting are 0.4, 0.5 and 0.6, respectively. Based on the compressive strength of concrete, the optimum water binder ratio and pouring temperature are proposed. The research results can provide important reference for temperature field study and foundation design of cast-in-place piles in permafrost region.
2. Determination Test

2.1 Test Material

(1) Cement: PO42.5 Portland cement from Lanzhou Gan Cao Cement Group, with fineness of 3.6, initial and final setting time of 80 and 130 minutes, density of 3025kg/m³, and other cement meet the requirements of the specification.

(2) Fine Aggregate: sand in Lanzhou Qingbaishi Material yard, fineness modulus 2.5, moisture content 3.8%, apparent density 2615kg/m³.

(3) Coarse Aggregate: Lanzhou Qing Baishi Material Field, the aggregate composition is sandstone, 5-30 mm gravel, apparent density 2915kg/m³.

(4) Water: laboratory tap water, meeting the requirements of "Water Use Standard for Concrete" [10] (JGJ63-2006) and "Hydraulic Concrete Construction Code" [11] (DL/T5144-2011).

(5) Air entraining agent: HAE-1 produced by Beijing Haiyan Concrete Admixture Co., Ltd. meets the requirements of "Specification for Mix Ratio Design of Ordinary Concrete" [12] (JGJ55-2011).

2.2 Test Conditions

In the test, the mix ratio of concrete is shown in Table 1 (mass/m³) and the aggregate gradation cumulative curve is shown in Figure 1.

| Strength grade | cement (kg) | Water binder ratio | Sand rate (%) | coarse: fine aggregate | Density (kg/m³) |
|----------------|-------------|--------------------|---------------|------------------------|-----------------|
| C30            | 380         | 0.4-0.6            | 41            | 7:3                    | 2400            |

Figure 1. Grain-size distribution curve of concrete aggregate

2.3 Test Methods and Instruments

Fifteen groups of specimens were made according to the test design scheme. The thermal physical parameters of pre-setting concrete were measured when the water binder ratio was 0.4, 0.5 and 0.6 concrete, respectively, cured in 5°C, 10°C, 15°C, 20°C and 25°C.

In order to avoid the influence of water migration on the determination process of concrete's import coefficient, the transient method was used to measure and analyze the concrete before initial setting. QL-30 based on hot wire method is a typical transient tester. It has been widely used. Its testing principle can be found in reference [13, 14]. It is not discussed here.

In order to stabilize each component in concrete at the test temperature, the whole process of sample preparation and determination is carried out in the temperature control curing box (Fig. 6). That is to say, each component is cured in the temperature control box for 48 hours before concrete mixing and thermal conductivity measurement.
3. Representational Analysis of Measured Values
The measured and contrasted values of the thermophysical parameters of concrete materials used in the test are shown in Table 2 (the contrasted values are from "Physics of Frozen Soil". Taking the most representative water and ice as an example, the thermal conductivity obtained by the experiment basically conforms to the range of the contrast value, but the deviation between the specific heat and the thermal conductivity is (+3.2%). Generally speaking, the QL-30 tester works normally and the test results are within the allowable range.

Table 2. Thermo-physical parameters

| Test Material                  | Source of Parameter | Thermal Conductivity $\lambda$ /W·m$^{-1}$·K$^{-1}$ | Specific Heat $C \times 10^6$ /J·m$^{-3}$·K$^{-1}$ | Thermal Diffusivity $\alpha \times 10^{-6}$ /m$^2$·s$^{-1}$ |
|-------------------------------|--------------------|--------------------------------|---------------------------------|--------------------------------|
| Cement                        | Measured Value     | 0.32                          | 1.07                            | 0.47                           |
| Coarse Aggregate              | Measured Value     | 3.51                          | 0.75                            | 3.05                           |
| Fine Aggregate                | Measured Value     | 1.32                          | 0.83                            | 2.13                           |
| Air Entraining Agent          | Measured Value     | 0.13                          | 1.16                            | 0.15                           |
| Concrete(before mixing)       | Measured Value     | 0.62                          | 1.31                            | 0.47                           |
| Water                         | Measured Value     | 0.521                         | 4.05                            | 0.46                           |
|                               | Reference Value    | 0.465–0.582                   | 4.18                            | 0.4–0.5                        |
| Ice                           | Measured Value     | 2.25                          | 2.14                            | 4.21                           |
|                               | Reference Value    | 2.21–2.326                   | 2.09                            | 4.46                           |

4. Analysis of Test Results

4.1 Effect of Water Binder Ratio on Concrete Compactness
According to the Standard of Testing Method for Mechanical Properties of Ordinary Concrete (GB/T50081-2002) [15], 15×15×15cm standard specimens were fabricated, and their compressive strength was tested by press. The experimental results are shown in Fig. 2.

Figure 2. Relation Curve between Dry Density and Water-binder Ratio of Concrete

From Figure 2, it can be seen that the density of concrete standard parts increases first and then decreases with the increase of water binder ratio, reaching the maximum of 2.35t·m$^{-3}$ at the water binder ratio of 0.45. The compressive strength is positively correlated with the density. Excessive or small water binder ratio is not conducive to the compressive strength, such as 0.35 and 0.6 water binder ratio compressive strength only 28.87 N·mm$^{-2}$ and 29.29 N·mm$^{-2}$, which are less than the standard value of 30 N·mm$^{-2}$. Therefore, 0.45 water binder ratio is the best water binder ratio, and the freezing strength is close to 0.45 water binder ratio.
4.2 Effect of Water binder Ratio on Thermophysical Parameters of Concrete

The relationship curves of thermal conductivity, specific heat and thermal conductivity with water binder ratio are shown in Fig.3.

![Figure 3. Relationship between thermophysical parameters and water binder ratio](image)

It can be seen from the result curve (fig. 3) that the thermal conductivity of concrete decreases with the increase of water binder ratio at various temperatures. The main reasons are as follows: 1) the thermal conductivity of coarse and fine aggregate is between 1.32 and 3.51 \( \text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1} \), which is much larger than that of water (0.521 \( \text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1} \)). With the increase of water binder ratio, the moisture content in concrete increases, thus reducing the thermal conductivity of concrete; 2) Under drying test conditions, the higher the water binder ratio, the larger the void and the conductivity of concrete. The smaller the thermal coefficient is. This is consistent with the research results of Liu Weidong [16] and Xiao Jianzhuang [17].

In addition, the thermal conductivity at different temperatures responds differently to the increase of water binder ratio. When the water binder ratio increases from 0.4 to 0.6, the slope of the descent curve increases from 2.95 to 5.8. It shows that 0.6 water binder is more sensitive to temperature change than concrete due to the increase of water action.

The specific heat increases with the increase of water binder ratio at various temperatures. The specific heat increases by 50.9%, 54.8% and 54.4%, at 5°C, 15°C and 25°C, respectively. This is because the specific heat of water is 4.18 \( \text{J} \cdot \text{m}^{-3} \cdot \text{K}^{-1} \), which is much larger than that of concrete aggregate (0.75-0.83 \( \text{J} \cdot \text{m}^{-3} \cdot \text{K}^{-1} \)). With the increase of water binder ratio of concrete, the specific heat increases.

We can see that the change of thermal conductivity is inversely proportional to the water binder ratio of concrete. Thermal diffusivity (\( \alpha \)) is a commonly used index to analyze the rate of change of temperature field and unstable heat conduction process. It is more different from the thermal conductivity. Thermal conductivity represents the parameters of thermal conductivity, while thermal conductivity reflects the ability of temperature variation within the object. It is closely related to its specific heat, and is related to its thermal conductivity (\( \lambda \)) and specific heat (\( C \)) [18]:
Previous studies on the thermal physical properties of concrete after final setting mainly focused on thermal conductivity, rarely involving thermal diffusivity. However, the specific heat of water greatly affects the thermal conductivity of concrete before initial setting, which is also a significant difference between concrete before initial setting and before.

4.3 Effect of Pouring Temperature on Thermophysical Parameters of Concrete

Fig.4 is the relationship curve between the thermal diffusivity, specific heat and thermal conductivity obtained from the test and the change of pouring temperature.

![Graph showing the relationship between thermophysical parameters and temperature](image)

**Figure 4.** Relationship between thermophysical parameters and temperature

In Fig.4, the thermal conductivity decreases with the increase of temperature in the range of 5-25°C under various water binder ratios. The thermal conductivity decreases by 19.9%, 38.8% and 58.16% respectively for 0.4, 0.5 and 0.6 water binder ratios.

Fitting the 0.4 water binder ratio which is commonly used in engineering, the thermal conductivity and temperature basically accord with the linear decreasing relationship (Formula 2), and also basically accord with the research results of foreign scholars [19,20]. Comparing with the relationship between thermal conductivity and temperature of concrete (Formula 3) by Li Engine et al. [21], it is found that they are in good agreement. The thermal conductivity of concrete decreases with the increase of temperature, which is caused by the change of molecular kinetic energy, that is, the increase of temperature, the increase of average molecular kinetic energy, and the loss of more energy when the thermal movement of molecules increases, which makes the thermal conductivity of concrete decrease. Because of the above reasons, the water content of 0.6 water cement concrete is nearly 8.9% higher than that of 0.4 water cement concrete, so when the temperature decreases in the range of 5-25°C, the rate of decline is higher than that of 0.4 water cement ratio by nearly 40%.

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\lambda = 2.991 - 0.0382T \quad 5^\circ C \leq T \leq 25^\circ C
\]  

(1)

The specific heat and thermal diffusivity have no obvious change with the increase of temperature,
which is mainly due to the presence of liquid water in concrete before initial setting. Because the specific heat of concrete does not change when the liquid water rises in the range of 5°C to 25°C, the specific heat and thermal diffusivity of concrete do not change significantly before initial setting.

5. Conclusion

(1) When the water binder ratio of concrete increases from 0.4 to 0.6 before initial setting, the thermal conductivity and thermal diffusivity decrease linearly with the increase of water binder ratio, and the specific heat increases with the increase of water binder ratio.

(2) Before the initial setting of concrete pouring temperature at 5°C to 25°C range increases, thermal conductivity and specific heat has a negative correlation with temperature. Thermal conductivity is the most sensitive to temperature change, and specific heat and thermal diffusivity are less affected by temperature. There is no significant correlation between the thermal diffusivity.

(3) 0.45 water binder ratio is the best water binder ratio. Combining with the results of this study, the water binder ratio is suggested to be 0.4–0.45, and the pouring temperature is 5–10°C.

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