Experimental investigation on heat transfer characteristics of soft clay at high temperatures

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ABSTRACT

Fire occurred in underground engineering such as tunnel will cause the change of the temperature field in the surrounding soil. The study on thermal conductivity of soils in fire environment is very important. This paper focuses on the experimental study on heat transfer characteristics of soft clay in Shanghai in high temperature environment over 100°C. The test results show that the change of internal temperature of initial saturated soils can be roughly divided into four stages, namely rapid heating stage I, constant temperature stage II, the second rapid heating stage III and the final constant temperature stage IV, when the drainage and exhaust are allowed in the high temperature environment. There is a peak value in the high temperature curve, the higher the temperature the bigger the peak value. According to comprehensive analysis of the heating curves under different temperature, high temperature has significant influence on thermal conductivity of soils and causes the increasing of thermal conductivity for wet soil and dry soil. The thermal conductivity of dry soil is relatively smaller than that of wet soil.

Keywords: high temperature environment, soft clay in Shanghai, thermal conductivity

1 INTRODUCTION

With the development underground engineering such as tunnels, more accidents were caused by fire in underground engineering (Yan, 2007; Qiang et al., 2006; Ulm et al., 1999; Carvel, 2004) and the fire will cause the changing of the temperature field in the soil around the structure. When the temperature field changes in the soil, the stress field, displacement field, and seepage field will change correspondingly. These changes influence each other and will do harm to tunnels and other underground structures in turn. Therefore, the temperature field in the surrounding soils of the structure has attracted scientific and technological workers’ attention. The thermal conductivity is an important indicator of soils to properly evaluate its thermal characteristics, which reflects the capacity of soils to conduct heat. Therefore, it is very important to study the thermal conductivity of soils in fire environment.

A lot of researches have been carried out on thermal characteristics of soils. DE Varies and Peck (1958), proposed the cylindrical probe method used to measure the thermal conductivity of soils in 1957; Johansen (1975) published Thermal Conductivity of Soils detailing the way of heat transfer in soils and methods of measuring thermal conductivity in 1975; Farouki (1986) published Thermal Properties of Soils describing in detail the transfer mechanism of heat in soils, and measuring methods, factors and computing method of thermal characteristics in 1981; Becker, Misra and Fricke (1992), studied the impact of the saturation and dry density on five types of soils and established a set of correlation empirical formula in 1992; Côté and Konrad (2005), studied thermal conductivity of several types of soils and established a generalized model for thermal conductivity of soils in 2005; Ludyna and Orman (2013), conducted macro and micro experiments of thermal conductivity of soils in 2013. Zhang (2004) studied the thermal conductivity of mixtures of sandy soils and soils in Eastern China and gave an experimental correlation; Lu (2009) studied thermal conductivity of rock-soils at various temperatures, and the results showed that the temperature significantly impacted the thermal conductivity of soils; Chen (2011) studied the thermal conductivity of the No. 4 soft silty clay in Shanghai, and analyzed the correlation between the thermal conductivity and void ratio.

These studies focused on thermal characteristics at temperatures below 100°C, and there were scarce researches on the influence of temperature on thermal characteristics of soil under fire conditions in which the temperature often were higher than 100°C (Xu, 2012). Therefore, it is meaningful to study the thermal conductivity of soils under high temperature above 100°C. Based on self-developed high-temperature heating equipment, experimental study was carried out...
on thermal characteristics of soils for temperatures above 100°C, and the law of thermal conductivity changing with temperature was obtained.

2 EXPERIMENTAL METHOD

2.1 Soil material

The soil samples used in this experiment was taken from an industrial plant located in east of Qishen Road, west of Wupo Road, south of Huxing Road, Minhang District, Shanghai. The site is in the leading edge of the estuary of the Yangtze River Delta, and its landform belongs to coastal plain which is one of the four major landforms in Shanghai. Soils was digged from 10m underground and was marine sediments of Holocene Q4. The soils belonged to warp clay with gray surface and was a main soil layer often crossed by subway tunnel projects in Shanghai. The basic physical properties of the natural soil samples are showed in Table 1.

![Fig.1. The temperature of soils heating experiment system of controllable pressure (part)](image)

Table 1 Basic physical properties of the mucky clay in Shanghai

| Water content (ω%) | Specific gravity (d<sub>s</sub>) | Unit weight (γ/kN/m³) | Plastic limit (W<sub>p</sub>/%) | Liquid limit (W<sub>i</sub>/%) | Void ratio (e) |
|-------------------|-----------------|----------------------|------------------------|------------------------|-------------|
| 46.4              | 2.74            | 17.0                 | 22.1                   | 41.0                   | 1.36        |

2.2 Experimental device

![Fig.2. The test principle of the internal temperature of soils](image)

The self-made pressure controllable multifunctional soils heating experimental system was used in this experiment (patented by State Intellectual Property Office of the R.P.C), which could achieve rapid heating with temperature controlled, as shown in figure 1. The experiment system consists a soil sample sealer placed in a temperature controlled heating furnace connected to a pneumatic valve at the upper. The interior dimension of sealer is 39.1 mm in diameter D and 80 mm in height H. In order to measure the temperature in the soil samples, three high precision probe type K-thermocouples were positioned at regular interval in the radius direction. The probe was 20 mm in length and 3 mm in diameter. High temperature wires are utilized for thermocouples. Three thermocouples were combined with data acquisition device called datataker at the same time, then data were outputted to a terminal computer. The test principle is shown in figure 2, in which TC represents thermocouples.

2.3 Test procedure

The natural soil samples were loaded in the soil sample sealer after drying and crushing. Saturated soil samples were prepared according to GBT 50123-1999 and were placed in a sealed container for later use. The water content of soil samples was 48.3%, and the weight density was 17.5 KN/m³.

The prepared saturated soil samples were loaded in the soil sample sealer as shown in Figure 2. The samples was prepared by the way of loading, vibrating and shaving in layers, instead of the method for triaxial test in GBT 50123-1999, in order to ensure the uniformity of soil samples (preparing steps of soil samples could be found in the literature by Chen (2015)). If using the method in GBT 50123-1999, the liquidity of samples was very poor, and the samples was uneven due to serious stratification. And if loaded in layers using compacting instrument and sleeve according to GBT 50123-1999, the viscosity of soils would make some or all of the soils adhere to compacting instrument. And the samples were still seriously stratified.

Permeable stones were covered and fixed at both ends of the sealer with soil samples, so that water and air could be exhausted from both ends of samples freely. Then the sealer was installed into the temperature controlled heating furnace, and began to be rapidly heated (10°C/min), the data acquisition system opened at the same time. The temperatures of soils were measured respectively for four hours at constant temperature of 105°C, 150°C and 200°C.
3 RESULTS AND ANALYSIS

3.1 The temperature change and heat transfer characteristic of soil

The experimental results are shown in Fig. 3 and Fig. 4, in which T, t and TC respectively represented temperature, time and thermocouple.

As can be seen from Fig. 3, the changing of temperature can be roughly divided into two stages, rapid heating stage I and constant temperature stage II. After four hours at a constant temperature, the temperature of soil samples still did not reach 105°C. The soil was completely saturated at initial conditions and the heat was conducted mainly through the mixture of soils and water, namely both water and soils acted as the bridge for conducting heat. At this time, the mixture of soils and water could be regarded as a uniform heat conductor as the soil particles were completely surrounded by water. Therefore, the interior temperature of samples rose quickly, namely rapid heating stage. As the temperature rose, the water vapor gradually increased, and with the escape of water vapor, the pore increased inside soils. Then the heat was conducted mainly through soil particles, water and steam, and the temperature of soils continued increasing. When the moisture in soil was completely evaporated, the heat in soils was conducted mainly through the steam and soil particles. At this time, the temperature of soils remained at about 100°C and would not rise due to the presence of water vapor, namely constant temperature stage in the Fig. 3. However, if the heating time was long enough, the water vapor in the soil would get out completely, then the heat would be conducted completely by the soil particles and the temperature would continue rising until the temperature of soils reach the heating temperature.

As can be seen from Fig.4, the change of temperature could be divided into four stages, namely rapid heating stage I, constant temperature stage II, the second rapid heating stage III and the final constant temperature stage IV. The mechanism of the first two stages in Fig.4 was similar to that in Fig.3, but there were two differences. First, there was a peak exceeding 100°C in rapid heating stage, and the higher the temperature the greater the peak. At ambient temperature of 105°C, the evaporation of water was relatively slow, the vapor bubble was less and impacted a little on conduction of heat. When the ambient temperature became higher, moisture was evaporated faster and the soil pores were filled with more bubbles of water vapor. The presence of water vapor bubbles obstructed the passage of heat conduction, resulting in the moisture evaporation delayed. Only the vapor bubbles were burst by higher temperature, could channel for heat conduction open, and could water become steam completely. The higher the temperature the greater the peak, due to that the temperature increased, the rate of producing of vapor bubbles became greater, the pore channels became more crowded, and more energy were required to burst steam bubble. This phenomenon was also found in the literature by Liu (2012). Second, the constant temperature stage is short. This was because the higher the temperature the faster the water evaporate. When water vapor was completely escaped, heat was totally conducted by solids granule, namely dry soil. Because TC3 was at out where soil firstly became dry and its temperature rose in advance. Then interior soil became dry. Because there was no moisture, the temperature of soil rose quickly again (second rapid heating stage) until the soil temperature was equal to heating temperature (final constant temperature stage).

Hence, for the initial saturated soil which was allowed to drain and exhaust, under the conditions of high temperatures for a long enough time, the changing of temperature inside soils could be divided into four stages, namely rapid heating stage I, constant temperature stage II, the second rapid heating stage III and the final constant temperature stage IV. In rapid
heating stage I, heat was conducted by wet soil mixed by soils, water and steam. In constant temperature stage II, heat was conducted by mixture of soils and vapor as water was completely evaporated. This stage temperature was maintained at about 100°C. The second rapid heating stage III was dry soil conducting phase. The final constant temperature stage IV was the phase when soil temperature was as same as environmental temperature.

3.2 The thermal conductivity of soils

It can also be seen from the Fig.4, the slope of second rapid heating stage III of heating curves at 150°C and 200°C were less than that of rapid heating stage I, namely \( k_{III} \leq k_I \). It was more evident in the heating curve at 150°C, which shows that the thermal conductivity of dry soil was less than that of wet soil.

It can also be seen from the Fig.4 that the slope of the rapid heating stage I of heating curve at 150°C was less than that at 200°C, namely \( k_{II}^{150°C} \leq k_{II}^{200°C} \). In fact, the slope of the rapid heating stage I of heating curve at 105°C was apparently less than that at 150°C, namely \( k_{I}^{105°C} \leq k_{I}^{200°C} \). This shows that the thermal conductivity of wet soil increased with temperature rising, and this result was consistent with experimental results of Nikolaev et al (2013). When studying Ottawa sands and Richmond Hill fine sandy soils at temperature of 2°C - 92°C, Nikolaev et al found that, the effect of temperature on the thermal conductivity of soils became obvious at temperature higher than 40°C, and the thermal conductivity increased as temperature rose. However, it can be seen from Fig.4, heating rate performed different when the soils begin to be heated. It shows that thermal conductivity were different at different temperatures and just were not pronounced below about 40°C. Because the amount of vaporization of water was small at low temperatures, and the movement of water vapor conducted little heat. At this time the heat conduction of soils depended mainly on soil particles. But when the temperature was higher than 40°C, the amount of vaporization of water got larger, and water vapor conducted heat significantly, resulting in an increment of the effective thermal conductivity of the soil. Therefore, the heating rates were significant difference.

It can also be seen from the Fig.4, the second rapid heating stage of heating curve at 150°C lagged more significantly behind that at 200°C, and the difference of the slope was obvious, namely, \( k_{III}^{150°C} \leq k_{III}^{200°C} \). This shows that the thermal conductivity of dry soil increased significantly as the temperature rose. And this conclusion was consistent with the thermal conductivity of dry soil at temperature of below 100°C.

4 CONCLUSIONS

(1) It can be inferred from the analysis of temperature changes and heat transfer characteristics of the soil that, for the initial saturated soil which was allowed to drain and exhaust, under the condition of high temperature for a long enough time, the change of temperature inside the soil could be divided into four stages, namely rapid heating stage I (heat conducted by wet soil mixed by soils, water and steam), constant temperature stage II (heat was conducted by mixture of soil and vapor as water was completely evaporated, and the temperature was remained at about 100°C), the second rapid heating stage III (dry soil conducting phase) and the final constant temperature stage IV (soil temperature was equal to environmental temperature).

(2) At high temperature of 150°C and 200°C, there was a peak value in the heating curve, and the higher the temperature the greater the peak.

(3) The high temperature environment had a significant influence on thermal conductivity of soils from the differences of heating curve at temperature of 105°C, 150°C and 200°C. With the temperature rising, thermal conductivity of both wet soil and dry soil increased, and thermal conductivity of wet soil was greater than that of dry soil.

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