Engineering Geology 204 (2016) 14–22

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

# Experimental study on physical properties of soft soil after high temperature exposure

Zhengfa Chen [a,b], Hehua Zhu [a], Zhiguo Yan [a,*], Li Zhao [a], Yi Shen [a], Anil Misra [c]

[a] State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, 200092, China
[b] School of Architectural Engineering, Shandong University of Technology, Shandong, Zibo 255049, China
[c] Department of Civil, Environmental and Architectural Engineering, The University of Kansas, Kansas 66045, United States

ARTICLE INFO

*Article history:*
Received 24 November 2014
Received in revised form 18 January 2016
Accepted 22 January 2016
Available online 23 January 2016

*Keywords:*
Tunnel fire
High-temperature
Soft soil
Physical property
Microstructure

ABSTRACT

The temperature effect induced by tunnel fire is important in geotechnical engineering. Due to the difficulties of extinguishing a fire in a tunnel, the fire duration time could be more than 120 min and after the heating the temperature of the soil around the tunnel could exceed 100 °C. However, the physical and mechanical properties of soils exposed to temperatures in the range of 100 °C to 200 °C have been rarely explored. A custom high-temperature apparatus was developed for measuring soft clay specimens with variations of mass, moisture content, dimensions and temperature distributions exposed to high temperatures of 105 °C, 120 °C, 150 °C and 200 °C for 150 min and 240 min, respectively. These measurements are performed after high-temperature exposure, and the water in both liquid and vapor phases are allowed to escape the specimens when the pore pressure exceeds 100 kPa during the heating process. The results show that the volume change, saturation and dry density of the specimens vary nonlinearly with the ambient temperature and are affected by the exposure time. The results also show that the variation of temperature within the specimen may be divided into four stages characterized by a rapid temperature rise stage followed by a plateau at 100 °C with another rapid temperature rise and a final plateau corresponding to the ambient temperature. Finally, novel changes in particle agglomeration and cluster shapes of the exposed samples were observed using a Scanning Electron Micro-scope.



## 1. Introduction

In recent years, geotechnical engineering issues involving temperature effects have received increasing attention due to the emerging areas of energy storage in geotechnical structures, the energy of terrestrial heat and underground water, the underground storage of high-radioactive waste and the temperature variation of soil around the structure induced by fire Gens, 2010). Most of the current and previous research has focused upon the influence of temperatures below 100 °C on the physical and mechanical property of soils (Finn, 1951; Duncan and Campanella, 1965; Paaswell, 1967; Andersland and Akili, 1967; Becker et al., 1992; Fleureau et al., 2002). For example, Campanella and Mitchell (1968) have investigated the effect of temperature on volume variation and pore water pressure of cohesive soil with the highest temperature of 60 °C. Habibagahi (1977) studied the influence of heating on permeability of clayey soil. Since the 1980s, the thermal issues in geotechnical engineering have gained further significance (Demars and Charles, 1982; Mctigue, 1986; Horseman et al., 1987; Baldi et al., 1988; Eriksson, 1989), and large numbers of mathematical models considering thermo-hydro-mechanical–chemistry coupling of soils have been proposed (Hueckel and Borsetto, 1990; Thomas and King, 1991; Schrefler and Zhan, 1993; Gawin et al., 1995; Cui et al., 2000; Khalili and Loret, 2001; Gens et al., 2005; Gatmiri and Arson, 2008; Monfared et al., 2012).

However, in many cases, soils can be exposed to a temperature above 100 °C, such as in tunnel fires, a typical case is the fire of Gotthard Tunnel in Switzerland in 2000 (Vuilleumier et al., 2002). Due to the closed environment, disadvantaged conditions of thermal dissipation and smoke evacuation in tunnel, a tunnel fire features as high temperatures reaching above 1000 °C, rapid temperature increase (5 min to reach 1200 °C) and long-time duration (more than 120 min) (Yan et al., 2013). High temperature induced by fire can be transmitted rapidly to the soft soil surrounding the tunnel leading to the temperature of soil increasing distinctly for a shield tunnel with a cast iron segment or a steel segment assembled in the soft soil. For example, in the fire test experiment in the Gelsenkirchen Subway Tunnel (361 m in length, 6.29 m in diameter, assembled with ST52-3 steel segments) the temperature of the soil 3 cm and 30 cm outside the lining reached 122 °C and 59 °C, respectively (EL-Arabi et al., 1992; Haack, 1992). In addition, the tunnel lining structure experiences direct damage through spalling, desquamation, crack, and mechanical degradation in fire (Yan et al., 2012, 2015, 2016), and diffused high temperature can bring prominent changes in soil mechanical properties, which results in the change of loading (Liu, 2012).

* Corresponding author.

http://dx.doi.org/10.1016/j.enggeo.2016.01.014
0013-7952/

Numerous findings on the effects of fire on soil properties are available in the literature (Certini, 2005). However the investigations of the effects of temperatures above 100 °C on the physical and mechanical behavior of soil surrounding tunnel structures in which the soil bear a certain pressure are rare. Morin and Silva (1984) studied the variation of thermal conductivity, permeability and thickness of the double electric layer as temperature changes for four ocean sediments over a wide temperature range from 22 °C to 220 °C, and the results indicated that the thermal conductivity of clayey soil particles is independent of the temperature variation. Hueckel and Baldi (1990) performed isotropic consolidated drained triaxial compression tests on Pontida silty clay in a range of temperature from 18 °C to 115 °C of temperature, which indicated that shear strength and hardness of Pontida silty clay decreases with increasing temperature. By heating two different clay powders (MC Kaolin and Western Bentonite), Wang et al. (1990) found that the specific gravity of soils under 400 °C remains constant with temperature and there was a sudden drop in the specific gravity of Kaolin occurs at temperatures above 400 °C, however, no major changes in the specific gravity of Western Bentonite occurred for temperatures up to 600 °C. Soil with Bentonite as the dominant mineral shows considerable reductions in the liquid limit and the plastic index with heating, whereas the consistency indices of Kaolin based clays are less likely to change for temperatures up to 400 °C. Towhata et al. (1993a, 1993b) investigated the variation of the liquid and plastic limits of soil in a temperature range from 22 °C to 200 °C and found that results are similar to those presented by Wang et al. (1990). Graham et al. (2001) reported that irreversible change of illite clay minerals can occur in a temperature range from 100 °C to 140 °C and irreversible change of montmorillonite occurs above 150 °C. Certini (2005) discussed the effects of fire on five aspects of the properties of forest soils and found that generally, the mineralogical assemblage is not altered to any great extent by fires because the first step of disruption of most minerals-dehydroxylation occurs for temperatures over 500 °C. More detailed discussion on forest fire was presented by Cerdà and Robichaud (2009) from three sections, fire effects on soil, rehabilitation and restoration strategies and regional strategies. More recently, Verma and Jayakumar (2012) and David et al. (2014) have investigated the influence of high temperature on the ecological environment of surface soil undergoing forest fire.

Alongside this study, a temperature control test device was developed to investigate the physical and mechanical properties of soils exposed to temperatures above 100 °C. The device was used to obtain the physical property indices of mass, moisture content and volume of soil samples and the variation of temperature in the soil samples exposed to high-temperature environments of 105 °C, 120 °C, 150 °C and 200 °C for durations of 150 min and 240 min for each temperature. The Scanning Electron Microscope (SEM) was used to examine and assess the microstructure evolution of the exposed soil samples.

## 2. Experimental test program

### 2.1. Test specimens

The soil tested in the experiment was taken from an engineering plant in Shanghai. The site was located in the southeastern front edge of Yangtze River delta entrance, where landform belonged to a type of coastal plain among four landform units in Shanghai area. Soil samples were taken from underground at a 10-meter distance from the site, which belongs to Holocene $Q_4^2$ ocean sediment. The subsurface geological profile is shown in Fig. 1. The soil is muddy clay with a gray surface. The physical properties of the natural soil are indicated in Table 1. The mineral composition of soil was determined, as presented in Table 2, the main ingredients of the soil are kaolinite, illite and montmorillonite, along with a small amount (2% – 4%) of organic matter.

The natural soil was pulverized with a grinder after air drying to a water content 5.06% and then the pulverized soil was let through the sieve with diameter 0.5 mm according to the Chinese *Test method of soils for highway engineering* (*JTG E40-2007*) (hereinafter referred to as E40). In accordance with the method in E40, the vacuum saturation method was used to prepare the remolded saturated soil. The water content and density of the remolded saturated soil were 48.3% and 1.75 g/cm$^3$ respectively, and it was stored in the sealed container before testing.

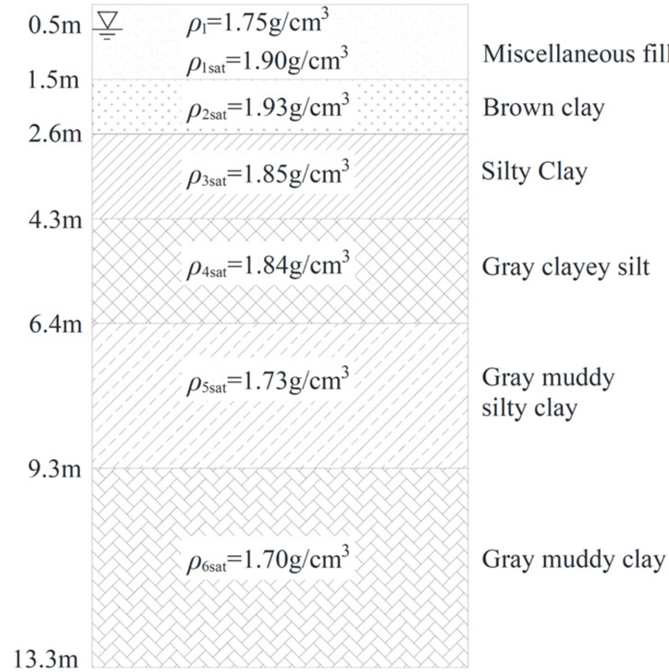


**Fig. 1.** Geological profile.

### 2.2. Test set-up

A high-temperature soil heating test apparatus (HSHTA) was designed utilizing the available heating and pressure control techniques in order to investigate soil behavior after exposure to high temperature. As exhibited in Fig. 2, the developed HSHTA includes the following equipment: heating oven, sealed soil samples container, pressure gauge, condenser pipe, measuring system of condensate water, gas analyzer and data acquisition system. The soil samples can be heated to the target temperature using the heating oven and its internal pressure is controlled at a constant target value using a pressure valve and a pressure gauge. From the air–steam mixture expelled from the soil samples, the water vapor liquefies to liquid water after flowing through the condenser pipe and then flows into a condensate water test system. The remaining gas, which is insoluble in water, is transferred into the gas analyzer. The data acquisition system gathers and processes the analysis results of the condensate water and the gas in real time. The moisture content and saturation of soil samples are determined through the measurement of the condensate water. The phase transition of the soil sample at high temperature such as the decomposition of organic matter, and the escape of gas dissolved in water is obtained by analyzing the results from the gas analyzer. Considering the feasibility of manufacture and application in a tunnel fire, the maximum allowable test temperature of the developed HSHTA is 300 °C, and the precision of temperature control is $\pm$1.5 °C.

As exhibited in Fig. 3, the sample sealed container is made of stainless steel of type 0Cr18Ni9 in China (similar to 304 of ASTM). This type of steel can resist high temperature and corrosion, with the steel withstanding temperatures of up to 870 °C. The linear thermal expansion coefficient of steel under 200 °C is approximately $12 \times 10^{-6}$/°C, so the swell-shrink effect of steel was not considered in the test. At both ends of the container, the rubber sealing rings with high temperature resistance were used, these rings can withstand temperatures of up to 320 °C. At the top end of container, a pressure gauge was set to control the pressure in the soil