Thermal properties of forest soil with different moisture content and dry density

Chen Chen, Daochun Xu, Wenbin Li, Lihong Yao

***Abstract*—**Thermal properties of forest soil have significant effects on heat transfer efficiency. Many factors can affect these properties, such as moisture content, porosity and dry density of soil. This contribution has measured thermal properties of forest soil with a novel piece of equipment (Hot Disk analyzer). The soil samples (35) were divided into several groups with different moisture content or dry density, such that there were samples with different moisture content but the same dry density and with different dry density but the same moisture content. The relationship between these properties (thermal conductivity and thermal diffusivity) and moisture content or dry density was discussed. The thermal conductivity and thermal diffusivity tended to increase with increased dry density, for the reason that quartz content of forest soil increased with increasing dry density. The thermal conductivity and thermal diffusivity first increased but then decreased with increased moisture content; 25% moisture content of soil were the inflection points of the thermal conductivity curves.

***Keywords*—**thermal properties, forest soil, moisture content, dry density.

I. Introduction

In recent years, precision forestry has seen rapid growth and wireless sensors have been used in a wide range of applications. However, the supply of electricity can become a significant problem and leads to limitations in the application of sensors in forest areas. Batteries, solar energy and wind energy have been used to supply electricity for precision forestry, but these solutions each have their own shortcomings[1]. Batteries need to be recharged within a regular period, and might lead to pollution in forests if not disposed of properly. Solar energy has limited application in forests because of forest crown closure, and the expense of equipment and variability of wind supply have limited the application of wind energy in forests[2].

Thermoelectric power generation has become an alternative option for the supply of electricity to precision forestry applications[3, 4]. Some thermoelectric power generators have been put forward and a few projects have been trialed[5]. One of the most promising options uses the temperature difference between the surface and the deep soil for thermoelectric power generation[6, 7]. Nevertheless, its generating capacity is tiny and the heat transfer efficiency in the soil has a significant influence on the generating capacity. Studies on soil heat transfer have shown that the thermal properties of soils are vital factors in the efficiency of this process[8]. Thus, acquiring detailed values of the thermal properties of soils is an urgent task.

Some experimental studies on the thermal properties of soils have also been conducted[9, 10]. Experimental approaches, such as the use of a heat pump[11] or thermal-probe method[12], etc., have various advantages and disadvantages for measuring thermal properties. In situ measurements, such as the heat pump methods, cannot obtain these results because it is difficult to control each variable factor individually. As for thermal-probe method, data for the thermal properties of forest soils might not be accurate enough.

The purpose of the experiments above was to explore the factors that affect the thermal properties of soils. These factors might include temperature[13, 14], moisture content[15], and porosity[16] and so on. Among these factors, forest soils might have different thermal properties related to changing dry density and moisture content, however, the specifics of these relationships have not been elucidated in detail in previous studies. Few studies have explored the thermal properties of forest soil below the dry density of 1 m, and the relationships between soil properties and moisture content or dry density have been explored but detailed descriptions are not found in the literature.

This paper has analyzed the thermal properties of soil at different moisture content and dry density, using a novel piece of equipment, the Hot Disk analyzer (TPS 2500S, produced by Hot Disk AB in Gothenburg, Sweden). The purpose of this study was to: (1) measure the thermal properties of forest soil with different moisture content and dry density, including thermal conductivity, specific heat, thermal diffusivity; (2) propose a new empirical model to calculate thermal properties based on moisture content and dry density; (3) give a reasonable explanation to the tendency of the thermal properties on moisture content and dry density.

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II. Materials and Methods

A. Study region

The Jiufeng National Forest Park, with a total area of 8.3204 km^2 and a maximum elevation of 1153 m a.s.l., is located in the northern region of the Haidian District of Beijing, China, spanning latitudes of 39°54′N, and longitudes of 116°28′E. The study area is located on the park's eastern hillside, between 500 m a.s.l. and 800 m a.s.l. Mean annual temperature at the site is 12.2 °C, and the mean annual precipitation is close to 700 mm. The precise location of the study region is shown in Fig. 1.

Fig. 1. Location of Jiufeng National Forest Park and the Study region

B. Soil samples

The soil samples taken from the study region were complex and complicated. As was previously shown, forest soils generally contained three layers: litter layer, subsoil layer and substrate layer, they were composed of silt, clay, sand and gravel [17, 18]. Soil samples with different moisture contents and dry density were prepared. First, all soil samples were dried evenly. Then the samples were sieved to 2 mm. Each soil sample was put into the standard soil corer with a volume of 100 cm^3. The corer containing sample was weighed immediately after the empty corer had been weighed. An electronic scale, with intervals of 0.01 g and span of 500 g was used. The soil bulk density was calculated by Eq. (1):

$$\rho_b = (m_1 - m_2)/v_2 \quad (1)$$

where ρ_b is the bulk density of samples (g/cm^3), m_1 is the weight of the corer containing sample, m_2 is the weight of the empty corer (m_2 = 97.95 g) and v_2 is the volume of the corer (v_2 =100 cm^3).

The dry density of soil was calculated by Eq. (2):

$$\rho = \rho_b/(1+\omega) \quad (2)$$

where ρd is the dry density of the sample, and w is the water content of the soil sample.

Dry density and moisture content of soil might have an influence on the thermal characteristics. To test this, soil samples with different moisture content but the same dry density and with different dry density but the same moisture content were prepared. First the dry density of dried soil were measured and all the soils were mixed to get the samples with the same dry density. In order to get samples with different dry density, the soils were mixed with six different combinations and the dry density was 1.21, 1.35, 1.41, 1.52, 1.61, 1.69 g/cm^3. Then samples were prepared with different moisture contents as follows:

(1) The initial moisture content of the dried soil was measured and found to be 2%.

(2) Soil samples with 5%, 10%, 15%, 20%, 25%, 30% and 35% moisture content were prepared by adding water evenly with a watering can. The quantity of water was calculated by Eq. (3)[19]:

$$m_\omega = m_m/(1+\omega_0)(\omega-\omega_0) \quad (3)$$

where mw is the weight of the added water (g), mm is the weight of the dry sample, w is the desired moisture content (w=5%, 10%, 15%, 20%, 25%, 30% and 35%) and w0 is the initial moisture content (2%).

(3) The soil samples that had been prepared as above were sealed and stored for 1–2 days before use in the following experiment.

Thirty-five soil samples with different moisture contents and dry density were prepared by the above means. The soil samples, with moisture content varying from 2% to 35%, were divided into three groups with dry density of 1.21, 1.41 and 1.69 g/cm^3, respectively (Fig. 2). And the other soils with different dry density were divided into two groups with moisture content of 2% and 10%.

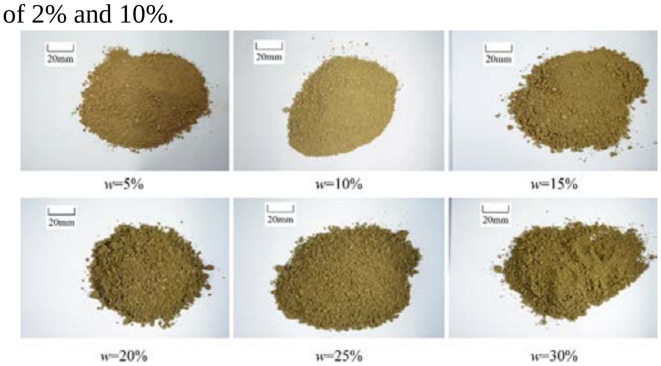


Fig. 2. Soil samples with changing moisture content (dry density 1.14 g/cm3)

C. Measurement on soil thermal properties

The Hot Disk thermal constant analyzer (TPS 2500) was used to determine soil thermal properties (Fig. 3). The thermal properties of soil samples were measured. The equipment was provided with an electric resistance measurement, a natural convection airflow oven, and a data program for thermal conductivity (λ, W·m^{-1}·K^{-1}) and thermal diffusivity (α, mm^2·s^{-1}). The thermal properties were determined at 20℃, 50 mg of soils were put into the sample pot and the Kapton probe was placed between the two samples; then, the containers and the probe were placed into the oven at an ascending heating rate of 5℃ from 20℃ to 750℃. After two hours heating, the temperature curve *T(t)* was obtained, and the thermal conductivity and thermal diffusivity could be calculated by Eq. (4):

$$T(t) = P_0/(\pi^{1.5} r\lambda)\cdot f(\tau) \quad (4)$$

where P_0 is the input power, t is the heating time, r is the probe radius, τ is the relative Fourier number to the sample and *f(τ)* is the a linear expression of thermal diffusivity,

$f(\tau) = \sqrt{t\lambda}/\alpha$.

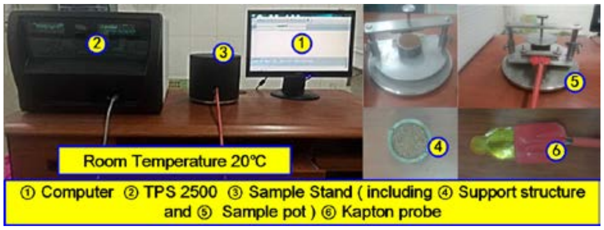
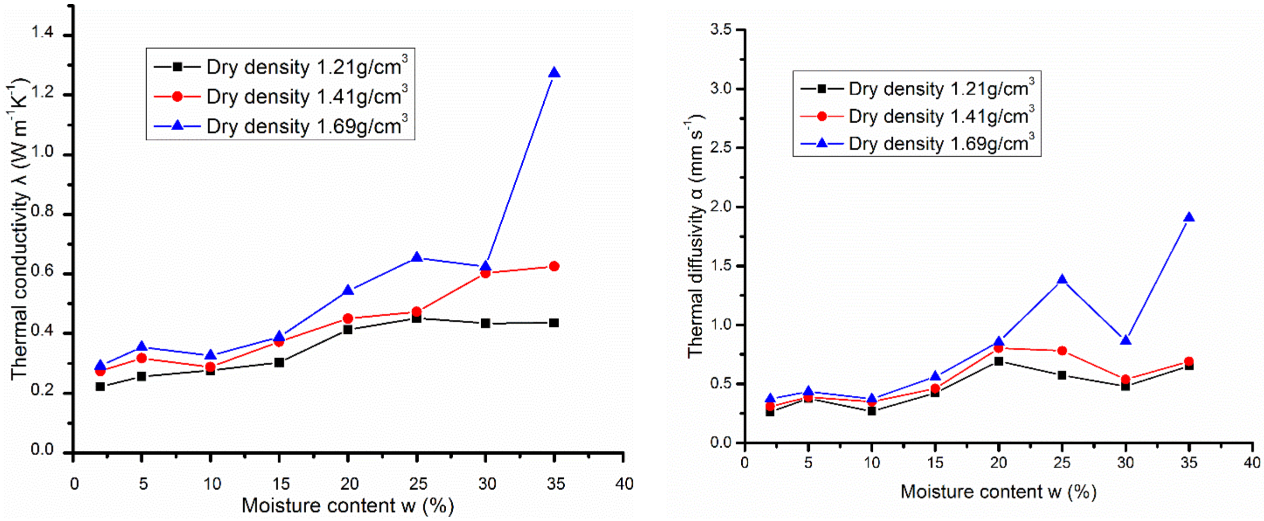


Fig. 3. Hot Disk thermal constant analyzer

III. Results and Discussion

A. Thermal properties of soil with changing moisture content

The thermal properties of soil samples with different moisture content were measured with the Hot Disk Analyzer. The thermal properties of soil, which include thermal conductivity and were measured and their values were collated into line charts (Fig. 4).



(a) Thermal conductivity (b) Thermal diffusivity

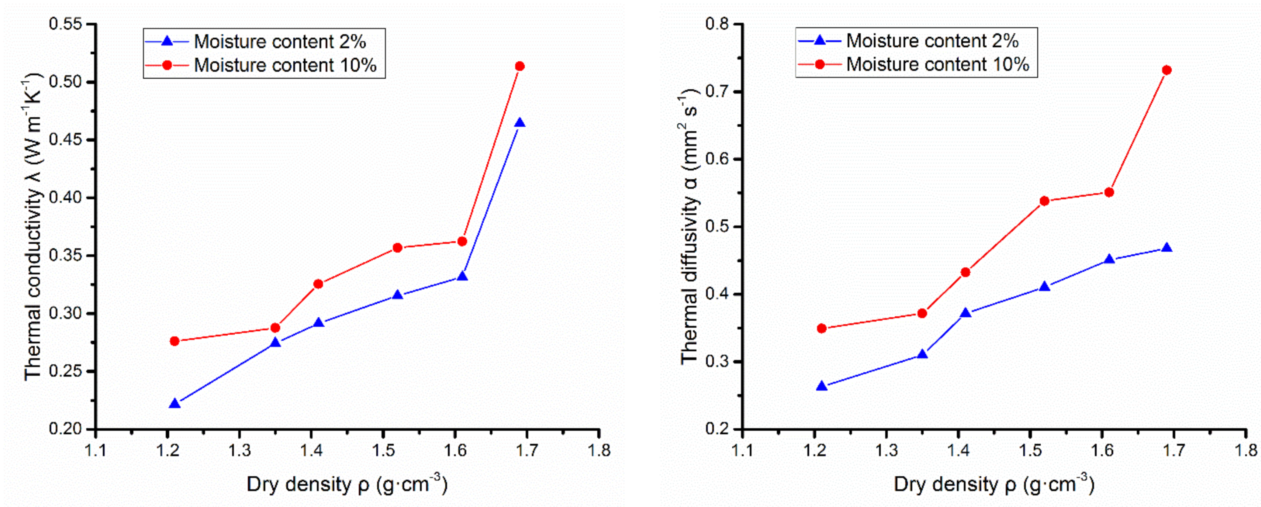
Fig. 4. Thermal properties of soil with changing moisture content

The thermal conductivity of soil increased with increasing moisture content (Fig. 4-a). Group 1 and Group 2, containing samples of the same dry density (1.21 and 1.41 g/cm3, respectively), tended to show an increase in thermal conductivity with increased moisture content from 2% to 25%; above 25% moisture content, the thermal conductivity tended to decrease slightly, so that 25% moisture content was the inflection point. Group 3, containing samples of dry density 1.69 g/cm3, showed a continuous increase in thermal conductivity with increased moisture content; above 30% moisture content, the thermal conductivity increased sharply.

The thermal diffusivity in the three groups was shown in Fig. 4-b. Thermal diffusivity tended to increase with increasing moisture content. Groups 1 and 2, containing samples of 1.21 and 1.41 g/cm3 dry density, respectively, had the same inflection point (25% moisture content). Below 25% moisture content, the thermal diffusivity increased, and after the inflection point, it tended to decrease. In Group 3, containing samples of dry density 1.69 g/cm3, the thermal diffusivity continuously increased except 30% moisture content; above 30% moisture content, thermal diffusivity increased substantially.

A. Thermal properties of soil with changing dry density

Before measuring the thermal properties of the soil, the samples were divided into two groups. The two groups had moisture contents of 2% and 10%, respectively. The thermal properties of soil samples are shown in Fig. 5.



(a) Thermal conductivity (b) Thermal diffusivity

Fig. 5. Thermal properties of soil with changing dry density

The thermal conductivity was shown in Fig. 5-a, which generally increased with increasing dry density, especially above the dry density of 1.61 g/cm^3. Despite the above results, it can also be seen the thermal conductivity of Group 2 (10% moisture) was more than that of Group 1 (2% moisture), thus confirming the conclusion obtained above from Fig. 4-a. In Group 1 (2% moisture) and Group 2 (10% moisture), the thermal diffusivity of soil tended to increase with increasing dry density (Fig. 5-b), especially above the dry density of 1.35 g/cm^3.

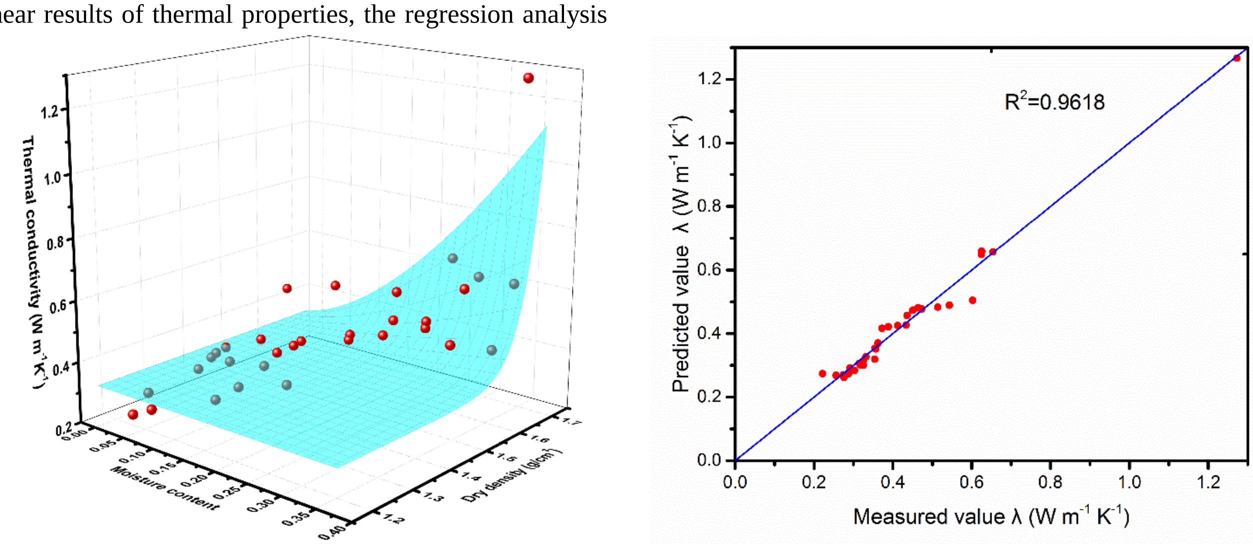
A. Regression analysis model on thermal properties of soil

In order to explore the relationship among moisture content, dry density and thermal properties of soil, the multivariate regression analysis model was calculated, and because of the nonlinear results of thermal properties, the regression analysis model was nonlinear. The multivariate nonlinear regression analysis model about moisture content, dry density and thermal conductivity could be calculated from Fig. 6-a. The measured values of thermal conductivity were collected and put into MATLAB, and the equation was obtained as Eq. (5):

$$\lambda = f(\omega,\rho) = 0.3435 + 2.2633 \cdot \mathrm{e}^{-8} \cdot \omega^{1.6099} \cdot \rho^{36.0806} \quad (5)$$

where λ is thermal conductivity, W/(m·K); ω is moisture content; ρ is dry density, g/cm3; e is natural logarithm.

The comparison between the measured values and predicted values was obtained (Fig. 6-b). The R-square was 0.9618, larger than the standard value (0.95), so the model about thermal conductivity of soil was reliable.



(a) (b)

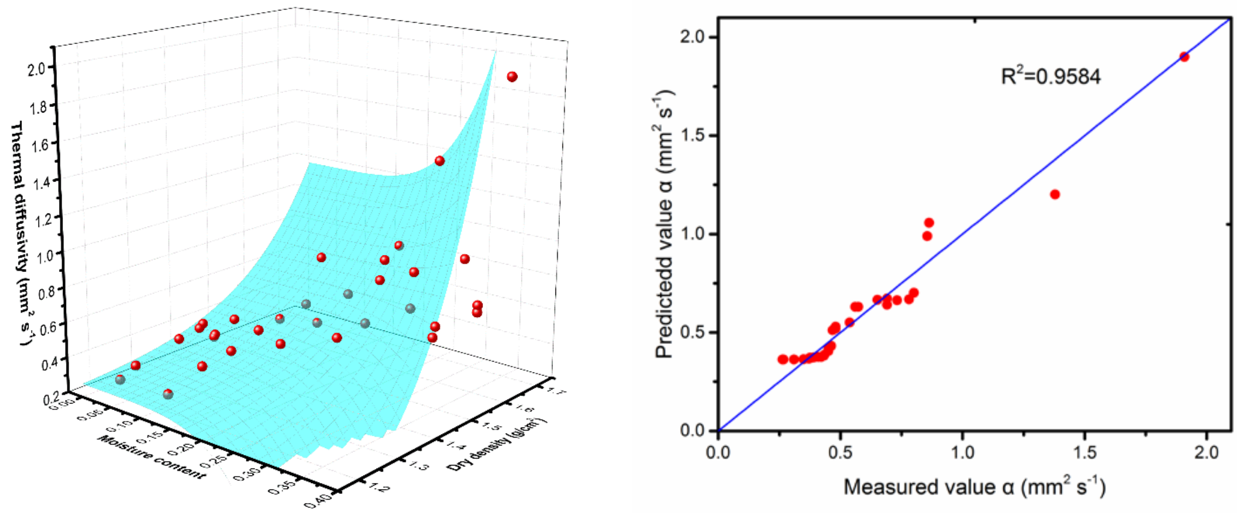
Fig. 6. Model on the thermal conductivity of soil (a. multivariate nonlinear model; b. model results)

The measured values about thermal diffusivity with different moisture content and dry density were analyzed in the same way, so the multivariate nonlinear model was obtained (Fig. 7-a), and the thermal diffusivity of soil could be calculated through moisture content and dry density by Eq. (6):

$$\alpha = f(\omega,\rho) = 0.2615 - 278.2507 \cdot \omega^{4.9434} + 0.0042 \cdot \rho^{9.5835} + 2.8394 \cdot \omega^{4.9434} \cdot \rho^{9.5838} \quad (6)$$

where α is thermal conductivity, mm2/s; ω is moisture content; ρ is dry density, g/cm3.

Similarly, Fig. 7-b has shown the comparison between the measured values and predicted values. The R-square was 0.9584, larger than the standard value (0.95), so the model about thermal diffusivity was believable.



(a) (b)

Fig. 7. Model on the thermal diffusivity of soil (a. multivariate nonlinear model; b. model results)

A. Discussion

This paper investigated the relationships between thermal properties of soil with the dry density and moisture content of forest soil. The results showed that the thermal conductivity and thermal diffusivity generally increased with increased moisture content and dry density. There were some explanations for the curves of the thermal properties with moisture content and dry density:

(1) The curves of thermal conductivity and thermal diffusivity with moisture content

Forest soil belongs to the porous medium, which consists of solid, liquid and air, and heat transfer in soils normally includes: 1.conduction in particles, 2.conduction in water, 3.conduction in air, 4.convection in water and 5.convection in air (Fig.8-A), and it is dominated by conduction rather than convection[16]. It is well known that the thermal conductivity and thermal diffusivity of the soil solids is higher than that of water, and these properties of water is higher than that of air (1>2>3). Thus it can be concluded that when the moisture content of soils increases, the conduction in air is replaced by the conduction in water in the heat transfer proceeding, so the thermal conductivity and thermal diffusivity increase with the increased moisture content. However, when the unsaturated soils become saturated, the conduction and convection in water become dominated in soil heat transfer with the increased moisture content (Fig.8-B), and the more water has broken the existed conduction in particles, so the thermal conductivity and thermal diffusivity of the saturated soils decrease with the increased moisture content. The curves at 1.21 and 1.41 g/cm3 dry density might be explained by this phenomenon, when the moisture content raises to 25%, soils are saturated. But the soil samples at 1.69 g/cm3 dry density, the saturation is larger than 25%, so the curve increases continuously.

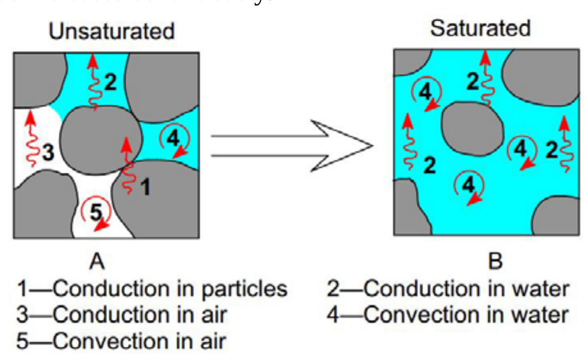


Fig. 8 Heat transfer in forest soils (A-unsaturated; B-saturated)

(2) The curves of thermal conductivity and thermal diffusivity with dry density

The conduction in particles, which is one of heat transfer formation, would increase in forest soils with the increased dry density, so the thermal conductivity and thermal diffusivity would increase. Besides, it is known that forest soils are consist of organic matters, quartz (SiO2), dolomite (CaMg(CO3)2) and other minerals. The thermal conductivity and thermal diffusivity of quartz are 13.8552 W/mK, 7.028 mm2/s, respectively, and quartz has the best thermal properties among the chemical compositions[20]. In all compositions, quartz has the most dry density, 2.65 g/cm3, thus with the increased dry density, the quartz content increase, so the thermal conductivity and thermal diffusivity increase of soils with increasing dry density.

Previous studies of thermal properties of soil have suggested that the moisture content of soil is proportional to the thermal conductivity [10, 16, 20]. This contribution has verified the correctness of these researches and gets agreement with previous studies. Besides, this contribution provides an empirical model to calculate thermal properties based on moisture content and dry density, which are shown in Eq. (5) and Eq. (6), thus when the moisture content and dry density of the forest soil are known, the above model can be used to obtain its thermal properties.

Ⅳ. CONCLUSIONS

In this contribution we have explored the detailed changes in the thermal properties of forest soil with moisture content and dry density. The conclusions from this experiment are as follows:

(1) Thermal conductivity and thermal diffusivity of soil tended to increase with increasing moisture content and dry density.

(2) Thermal conductivity and thermal diffusivity of soil increased with increasing moisture and then decreased, with an inflection point at 25% moisture content.

(3) The multivariate nonlinear regression models on thermal conductivity and thermal diffusivity with moisture content and dry density are presented and reliable.

(4) The explanations about the tendency of thermal conductivity and thermal diffusivity are given.

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