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Research Article

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Effects of moisture content and dry bulk density on the thermal conductivity of compacted backfill soil

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Abstract: Soil backfilling and compaction are often involved in urban construction projects like the burying of power cables. The thermal conductance of backfill soil is therefore of great interest. To investigate the thermal conductivity variation of compacted backfill soil, 10 typical soils sampled in Zhejiang Province of China with moisture contents of 0%–25% were fully compacted according to the Proctor compaction test method and then subjected to thermal conductivity measurement using the thermal probe method at 20 °C. The particle size distribution and the chemical composition of the soil samples were characterized to analyze their effects on thermal conductivity. The results showed that the maximum thermal conductivity of fully compacted soils generally exceeds 1.9 W/(m·K) and is 20%–50% higher than that of uncompacted soils. With increasing moisture content, soil thermal conductivity and dry bulk density first increase and then remain unchanged or decrease slowly; the critical moisture content is greater than 20% in most cases. Overall, the critical moisture content of soils with large particle size is lower than that of those with small particle size. Quartz has the highest thermal conductivity in the soil solid phase, and the mass percentage of quartz for most soils in this study is more than 50%, while that for yellow soil is less than 30%, which leads to the thermal conductivity of the former being nearly twice as great as that of the latter in most circumstances. Based on regression analysis, with moisture content and dry bulk density as the independent parameters, the prediction formulae for the thermal conductivity of two categories of compacted backfill soils are proposed for practical applications.

Key words: Backfill soil; Compaction; Thermal conductivity; Moisture content; Dry bulk density

1 Introduction

Soil is an important part of the earth's surface system, as well as the material basis of human survival, production, and development. There are some differences in the cognition and research perspective of soil in different disciplines. Ecological and environmental scientists pay most attention to biodiversity, material circulation, energy exchange, and contaminant migration in soil. Agronomists mainly focus on soil properties affecting plant growth, such as moisture content, fertility, temperature, and specific heat capacity. Engineering experts regard soil as a base which can withstand high pressure or as a significant source of engineering materials (Huang and Xu, 2010).

Soil backfilling and compaction are often involved in practical projects, such as construction of roads (Han et al., 2018) and bridges (Le et al., 2021), burying of ground-source heat pumps (Kong et al., 2020; Tang et al., 2021), pipes (Alzabeebee, 2020; Wu et al., 2021), and power cables (Kim et al., 2014; Czapp and Ratkowski, 2021; Menaceur et al., 2021; Ocłoń, 2021), and carrying out thermal desorption for remediation of organic-contaminated sites (Zhao et al., 2019). Obviously, the mechanical properties of backfill soil, such as its bearing property and shear resistance, are of vital importance in engineering, because it must be compacted and have adequate strength to prevent subgrade collapse and to protect related underground infrastructures. Meanwhile, the thermal properties of backfill soil, such as thermal conductivity, specific heat capacity, and thermal diffusivity, have also attracted

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extensive attention in recent years, because they play an important role in understanding, prediction, and analysis of heat transport in soil (Lu et al., 2005a, 2005b; Leung and Chan, 2009).

Taking buried power cables as an example, the ampacity of cables is limited by the maximum allowable temperature of the core conductor because of the Joule heat generation during operation. According to the formulae developed by the International Electrotechnical Commission (IEC, 2006), the ampacity is affected not only by the cross-sectional area of the core conductor but also by the heat transfer ability of the surrounding backfill soil. In order to improve the ampacity, it is more economical to increase the thermal conductivity of the backfill soil around the cables than to increase the core diameter; this has become a consensus (Czapp and Ratkowski, 2021). Backfill soil with good heat transfer can shelter the cables from accidents due to the excessive temperature of the core conductor and can guarantee their long-term operation even at relatively high ampacity (Kim et al., 2014). Rerak and Ocłoń (2017) carried out a numerical study of ground power cables at a depth of 2 m by the finite element method and found that the temperature of the core conductor could be reduced from 64 to 48 °C when the thermal conductivity of the surrounding backfill soil increased from 0.5 to 1.0 W/(m·K). Similarly, for ground source heat pumps, ground pipes, and thermal desorption with remediataion only from controlling the thermal conductivity of backfill soil, we can analyze the temperature distribution of the sites and take targeted measures to enhance heat transfer or prevent heat dissipation, so as to ensure safety, improve efficiency, and reduce energy consumption. This is particularly significant in the context of the targets for “reaching the peak of emission of carbon dioxide” and “carbon neutrality” proposed by the Chinese government.

Soil is a porous material composed of solid, liquid, and gas phases and its thermal conductivity is affected by complex factors, including moisture content, bulk density, porosity, particle size, organic content, mineral composition, and temperature (Abu-Hamdeh et al., 2001; Xu XT et al., 2020; Ren et al., 2021). Researchers have proposed several prediction models of soil thermal conductivity based on theory or experimental data (Gemant, 1950; Johansen, 1975; Campbell, 1986; Chung and Horton, 1987; Côté and Konrad, 2005; Lu et al., 2007; Nikoosokhan et al., 2016). Gement (1950) deduced a theoretical formula of soil thermal conductivity with volumetric moisture content and particle size on the basis of the model that soil particles are spherical and water accumulates around the spherical surface, forming wedge rings. However, Gement’s model is not applicable when the volumetric moisture content is lower than 5% or higher than 20% (Gemant, 1950; Webb, 1956). Campbell’s model (Campbell, 1986) and Chung-Horton’s model (Chung and Horton, 1987) are both empirical formulae derived from experiments based on soil texture, density, and volumetric moisture content. However, some of the empirical parameters in Campbell’s model are difficult to obtain (Nikoosokhan et al., 2016). Johansen’s model (Johansen, 1975) is a classical normalized model for predicting the thermal conductivity of soil k according to the thermal conductivity of dry soil k_d, saturated soil k_s, and a dimensionless parameter Ke. k_d is related to dry bulk density, k_s is related to porosity, quartz content, and the thermal conductivity of water and various minerals, and Ke is related to saturation. Côté-Konrad’s model (Côté and Konrad, 2005) and Lu-Ren’s model (Lu et al., 2007) modified the formulae for k_d and Ke in Johansen’s model. Nikoosokhan et al. (2016) developed a relatively simple model for predicting soil thermal conductivity from some easily accessible parameters, such as sand content and dry density, from many experiments, which optimized the formula of k_s and k_d. However, none of them could satisfactorily predict soil thermal conductivity or stratum temperature distribution for a wide range of soil types and states (He et al., 2020). To some extent, it is also because the above three parameters, k_d, k_s, and Ke, are not completely independent (Zhang et al., 2018). Some researchers (de Lieto Vollaro et al., 2014; Salata et al., 2015) pointed out that the basic data of numerical simulation in engineering were mainly taken from traditional handbooks of thermal properties or classical models, but the simulation results usually failed to predict the actual situation accurately. Therefore, it is essential to obtain the thermal properties of soils through experimental measurement according to local conditions as the basic data of numerical simulation. This is more reliable than traditional handbooks or classical models. There have been plenty of studies on soil thermal conductivity, but only a few of them have paid attention to backfill soil under the fully compacted condition which is common in engineering.

To investigate the thermal conductivity variation of compacted backfill soils, 10 typical soils at a depth of 0.7–1.2 m in Zhejiang Province, China were sampled. Then, the particle size distribution and the chemical composition were characterized. Samples with moisture content (by mass fraction) of 0%–25% were prepared and fully compacted to simulate the practical situation of soil backfilling in engineering. The thermal conductivity of the soil samples was measured by the thermal probe method at 20 °C. Based on the experiment results, the effects of moisture content, dry bulk density, particle size distribution, and chemical composition on the thermal conductivity of compacted backfill soils were analyzed, and the prediction formulae for the thermal conductivity of compacted backfill soils were summarized.

2 Materials and methods

2.1 Soil sampling and characterization

Soils at a depth of 0.7–1.2 m, which is the typical depth of buried power cables (MOHURD, 2018), were sampled from 10 different districts, counties or county-level cities in Zhejiang Province, China. Then, the particle size distribution and the chemical composition were characterized. The determination of sampling sites, the appearance of soil samples, and the characterization methods are detailed in Data S1 of the electronic supplementary materials (ESM).

2.2 Experimental conditions and apparatus

The annual average temperature of the soil at the superficial layer in East China is around 20 °C (Yu, 2017), and the moisture content is no more than 25% in most cases (Ma et al., 2000). Therefore, the moisture contents of the soil samples prepared were 0%, 5%, 10%, 15%, 20%, and 25%, and the temperature was controlled at 20 °C. To make the research results relate to the engineering criteria, the samples were fully compacted through the Proctor compaction test (MOHURD, 2019); the relative compaction degree of each sample reached 100%. The definition of compaction degree is detailed in Data S2 of the ESM.

As shown in Fig. 1, the experimental apparatus mainly consists of a specially made stainless steel cylindrical container, an AP7LR-20-A12Y water bath case, a copper-constantan thermocouple connected to a temperature recorder, and a TR-1 stainless steel probe matching with a KD2 Pro thermal properties analyzer (DDI, 2016). The introduction of apparatus parameters and the procedures of the soil thermal conductivity measurement are detailed in Data S3 of the ESM. The original values and the standard deviations of the soil thermal conductivity measurement are shown in Data S4 of the ESM.

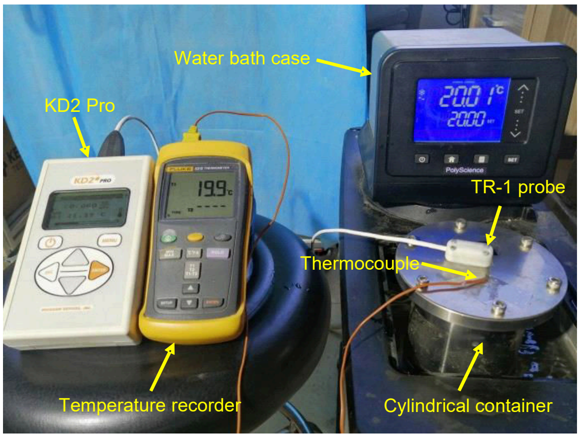


Fig. 1 Soil thermal conductivity measurement apparatus

3 Results and discussion

3.1 Effects of moisture content

The density of the gas phase in soils is very low, but its volume cannot be ignored. Therefore, the calculation of total soil mass generally involves only the solid and liquid phases, while the calculation of total soil volume involves all three phases. The definition of dry bulk density ρ_d is introduced in Data S2, while wet bulk density ρ_w refers to the ratio for the sum of the mass of the soil particles (solid phase) m_s and that of water (liquid phase) m_w to the total soil volume V.

As shown in Fig. 2, the maximum and minimum thermal conductivities of regosol (Fig. 2a) are 2.051 and 0.211 W/(m·K), respectively, and the former is nearly 10 times the latter. This is the maximum variation among the 10 fully compacted soils. Those of yellow soil (Fig. 2i) are 1.045 and 0.210 W/(m·K), respectively, and the former is only 5 times the latter, and is the minimum variation among the 10 soils. The maximum thermal conductivity of fully compacted soils in this study is about 20%–50% higher than that

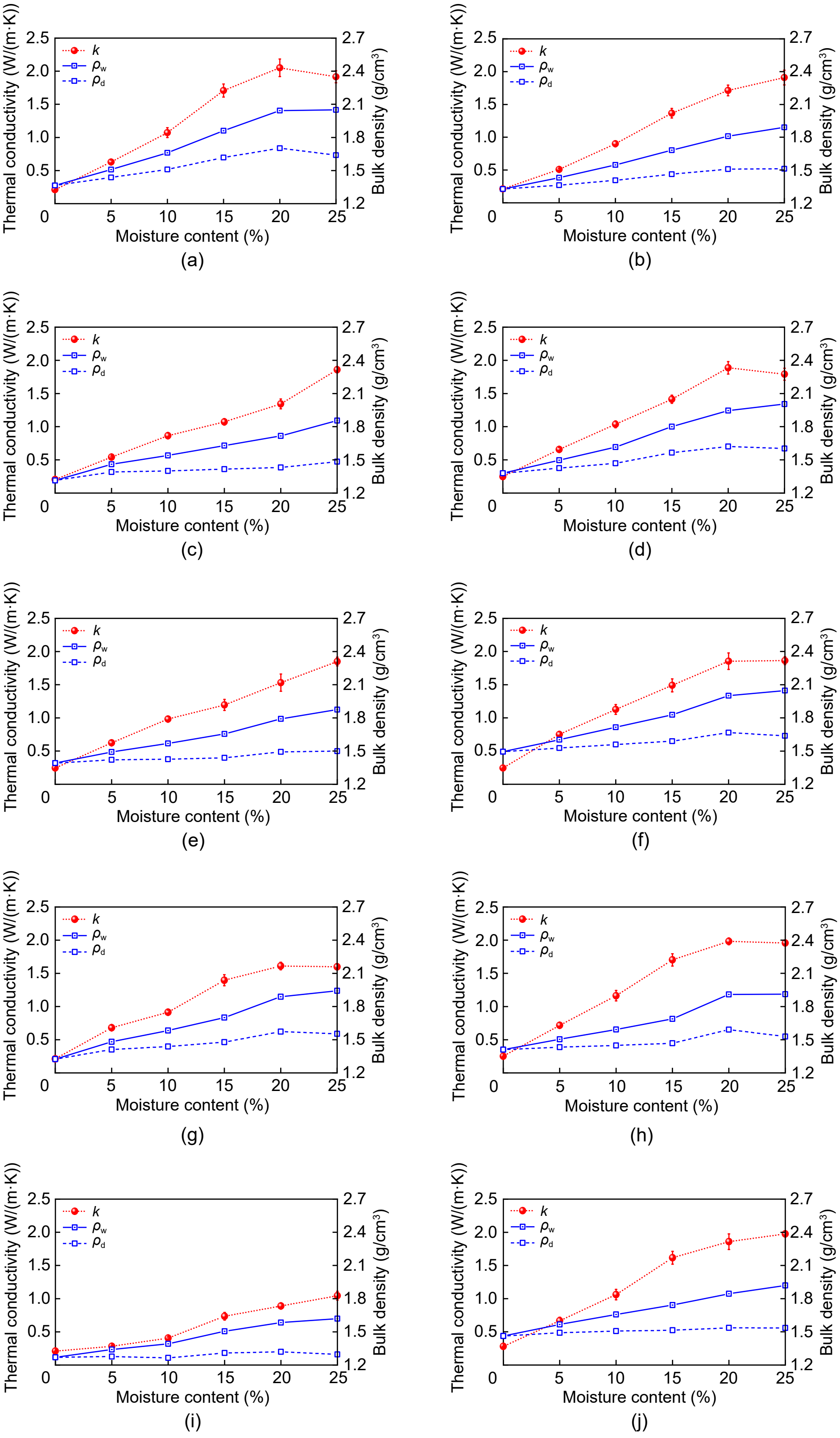


Fig. 2 Curves of dry bulk density, wet bulk density, and thermal conductivity against moisture content of soils: (a) regosol; (b) paddy soil; (c) red soil; (d) alluvial soil; (e) purple soil; (f) seashore solonchak; (g) brown clay; (h) limestone soil; (i) yellow soil; (j) mountain meadow soil

of naturally accumulated or uncompacted soils in other studies (Hiraiwa and Kasubuchi, 2000; Kong et al., 2020). Besides, with the increase in moisture content θ_m from 0% to 25%, the wet bulk density ρ_w of all the 10 fully compacted soils increases monotonically from about 1.25–1.50 g/cm^3 to about 1.60–2.05 g/cm^3, and the dry bulk density ρ_d and the thermal conductivity k increase overall, but not completely monotonically. Dry bulk density and thermal conductivity also increase monotonically when the moisture content varies from 0% to 20%, while the differences occur suddenly when the moisture content exceeds 20%. Specifically, when the moisture content exceeds 20%, the dry bulk density and thermal conductivity of paddy soil (Fig. 2b), red soil (Fig. 2c), and purple soil (Fig. 2e) still increase, while those of regosol (Fig. 2a), alluvial soil (Fig. 2d), brown clay (Fig. 2g), and limestone soil (Fig. 2h) start to decrease or remain basically unchanged. As for the other three soils, seashore solonchak (Fig. 2f), yellow soil (Fig. 2i), and mountain meadow soil (Fig. 2j), when the moisture content exceeds 20%, the dry bulk density starts to decrease or remains basically unchanged, while the thermal conductivity still increases. In other words, among the 10 typical soils, the variation of thermal conductivity of most soils is consistent with dry bulk density, while for only three soils it is consistent with wet bulk density. Therefore, in most cases, it is more reliable to predict the variation of the thermal conductivity for fully compacted soils by the variation of dry bulk density than by that of wet bulk density.

As shown in Fig. 3, there are still many pores inside dry soil because the solid particles have relatively strong resistance to deformation. The addition of water can enhance the attractive force among soil particles and make relatively small particles combine to form relatively large aggregates, which are more prone to deformation. In other words, an appropriate amount of water can reduce soil pores and make the solid particles arrange more tightly. In this case, the dry bulk density of the soil gradually increases. Meanwhile, the water in the soil gradually accumulates in films with good fluidity and occupies more space with the increase in moisture content. When the moisture content reaches a critical value, the dry bulk density of the fully compacted soil reaches a peak. As mentioned in Data S2, these two values are named optimal moisture content and maximum fully compacted dry bulk density, and are important in engineering. When the moisture content exceeds the critical value, the spacing of soil particles increases instead because a lot of the volume is occupied by the water films, which causes a decrease in dry bulk density.

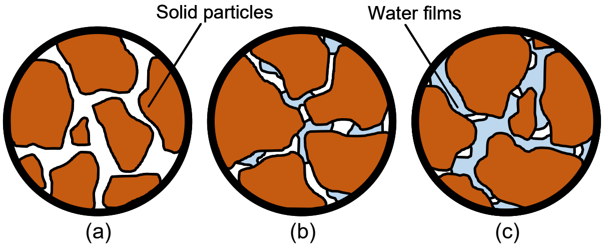


Fig. 3 Schematic of solid phase and liquid phase in soils: (a) dry; (b) below optimal moisture content; (c) above optimal moisture content

The average thermal conductivity of soil solid particles is about 2.930 W/(m·K), while the thermal conductivities of water and air are 0.594 and 0.026 W/(m·K), respectively (Duan, 2015). Thus, the solid phase plays the leading role in the overall soil thermal conductivity. When the moisture content is relatively low and then increases, the water, with its relatively high thermal conductivity, gradually replaces the air and occupies the soil pores. This reduces the contact thermal resistance and binds the solid particles more tightly. Therefore, in the stage of relatively low moisture content, thermal conductivity increases rapidly with the increase in moisture content. It can be seen from Fig. 2 that the thermal conductivity of most soils increases fastest within the moisture content range of 0%–15%. With the continuous increase in moisture content, the gas phase gradually decreases, which leads to the increase in thermal conductivity. However, when it exceeds the optimal moisture content, the dry bulk density begins to decrease, that is, the spacing of solid particles gradually increases, which leads to the reduction of soil thermal conductivity. Under the combined effects of these two factors, with the continuous increase in moisture content, soil thermal conductivity may increase at a relatively low speed, and then remain basically unchanged or decrease slowly. In the moisture content range of 15%–20%, the increase rates for the thermal conductivity of regosol (Fig. 2a), brown clay (Fig. 2f), limestone soil (Fig. 2h), yellow soil (Fig. 2i), and mountain meadow soil (Fig. 2j) slow down significantly. The thermal conductivity of each fully compacted soil will first increase with the increase in moisture content, and then remain basically unchanged or decrease. This is also confirmed by other experimental results based on compacted soils (Wallen et al., 2016) and uncompacted soils (Hiraiwa and Kasubuchi, 2000; Mengistu et al., 2017). However, the moisture content corresponding to the maximum dry bulk density or thermal conductivity of each fully compacted soil is different, and some of them may be higher than 25% (Wallen et al., 2016) or lower than 20% (Xu L et al., 2020). Last but not least, according to the analysis above, the corresponding moisture content of maximum thermal conductivity is generally greater than that of maximum dry bulk density for fully compacted soils. Curves in Fig. 2 indicate that the decline stage of thermal conductivity is later than that of dry bulk density for most fully compacted soils, which also confirms this conclusion.

3.2 Effects of texture and chemical composition

Soil thermal conductivity is related not only to moisture content and dry bulk density as mentioned above, but to its classification as well. It is common to classify soils by texture, which is also called mechanical composition or particle size distribution. According to the order of equivalent diameter from small to large, soil particles are divided into clay, silt, and sand. The classification of soil texture is determined by the mass percentage of the three kinds of particles.

In this study, soil texture was characterized, and then the 10 typical soils were classified into four categories according to the soil texture triangle proposed by the United States Department of Agriculture (USDA) (Fig. 4). The characterization and classification results are detailed in Table 1. To explore whether the variation trend of dry bulk density and thermal conductivity for the fully compacted soils with the same texture are similar, the curves of dry bulk density and thermal conductivity for the 10 typical soils were redrawn in Fig. 5 in terms of the order of particle size from small to large, that is clay loam (Fig. 5a), loam (Fig. 5b), sandy loam (Fig. 5c), and loamy sand (Fig. 5d).

As shown in Figs. 5c and 5d, the variations of dry bulk density and thermal conductivity for the three typical soils with relatively large particle size are quite similar. The two curves of sandy loam and loamy sand both increase with the increase in moisture content from 0% to 20% and decrease with the increase in moisture content from 20% to 25%. Besides, it can be noted that the thermal conductivity curves of regosol

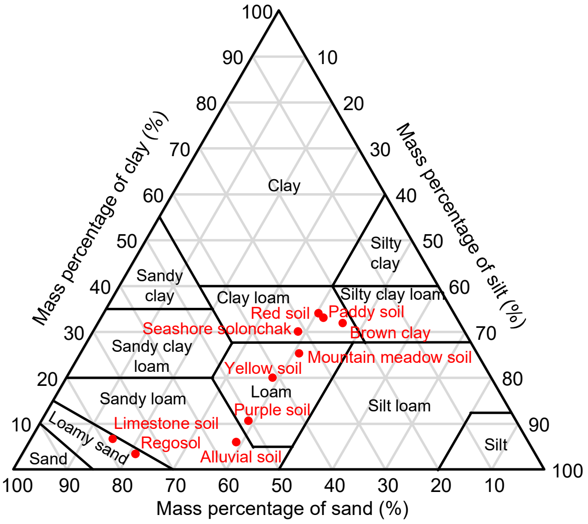
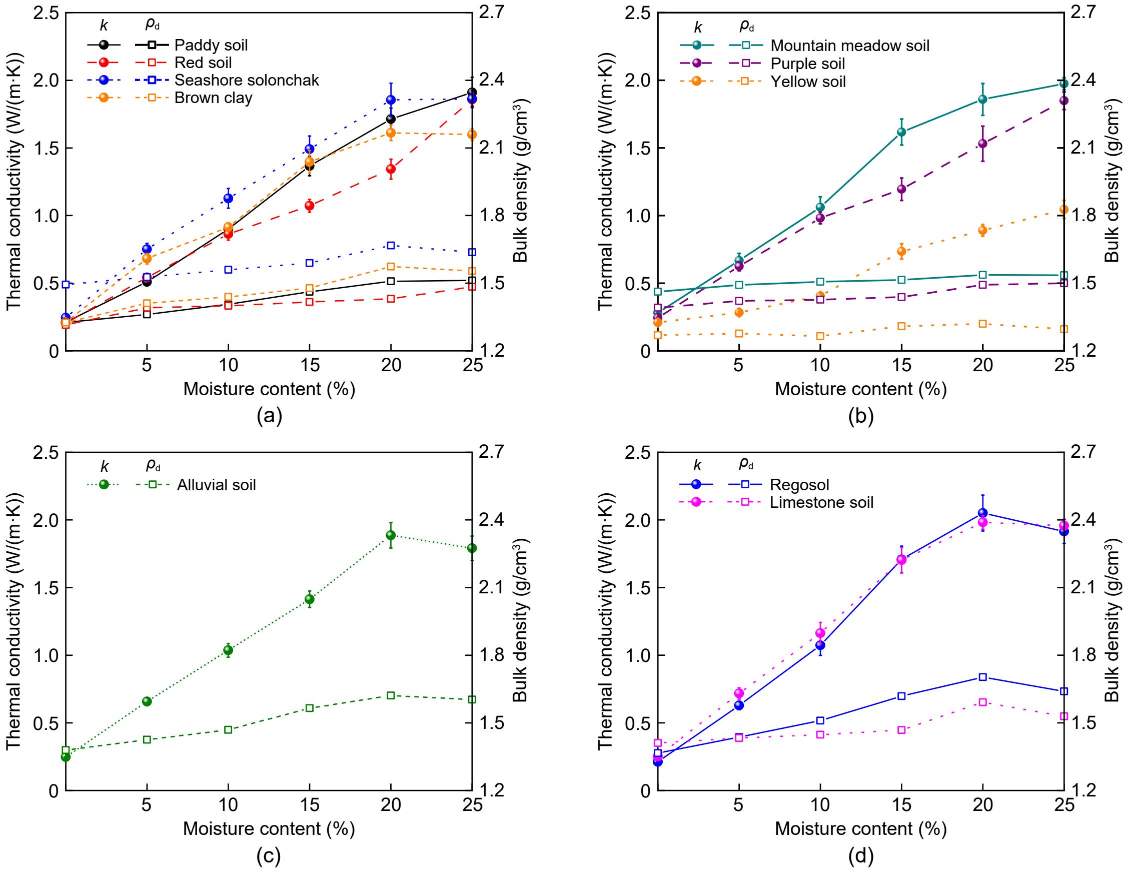


Fig. 4 Soil texture triangle (USDA NRCS, 2017)

Table 1 Characterization of soil texture

Soil type	Mass percentage (%)			Particle density (g/cm^3)	Texture classification
	Clay (<0.002 mm)	Silt (0.002–0.020 mm)	Sand (0.02–2.00 mm)		
Regosol	3.9	20.8	75.4	2.64	Loamy sand
Paddy soil	32.9	41.4	25.7	2.74	Clay loam
Red soil	33.8	40.4	25.9	2.70	Clay loam
Alluvial soil	6.0	38.7	55.3	2.68	Sandy loam
Purple soil	10.3	39.2	50.6	2.62	Loam
Seashore solonchak	29.9	38.8	31.3	2.69	Clay loam
Brown clay	31.9	46.3	21.8	2.72	Clay loam
Limestone soil	6.8	14.9	78.3	2.65	Loamy sand
Yellow soil	20.0	41.2	38.9	2.63	Loam
Mountain meadow soil	25.6	40.9	33.5	2.70	Loam



(a) (b) (c) (d)

Fig. 5 Curves of dry bulk density and thermal conductivity to moisture content of soils with different textures: (a) clay loam; (b) loam; (c) sandy loam; (d) loamy sand

and limestone soil almost coincide. However, the consistency for the two curves of clay loam and loam shown in Figs. 5a and 5b is relatively poor. For example, the two curves of paddy soil and red soil still increase when moisture content exceeds 20%, while those of seashore solonchak and brown clay decrease or remain basically unchanged, even though the four typical soils are all classified as clay loam.

Soil porosity generally decreases with the increase in the average particle size (Min, 2021). Therefore, the amount of water needed to completely fill up the soil pores with large particle size is less than that for those with small particle size, which may explain the phenomenon shown in Fig. 5 that the moisture content corresponding to the peak value for the dry bulk density curve and the thermal conductivity curve of fully compacted soil with large particle size is smaller than that with small particle size. It is worth noting that the thermal conductivity of yellow soil has obvious differences from the others. For instance, when its moisture content is 20%, the thermal conductivity of yellow soil is only 0.890 W/(m·K), while those of purple soil and mountain meadow soil are 1.531 and 1.859 W/(m·K), respectively, that is, about 1.7 and 2.1 times greater than that of yellow soil, respectively. This may be caused not only by the discrepancy in dry bulk density but also by differences in soil chemical composition, that is, the types and mass percentages of minerals and organic matter in the solid phase.

The characterization results of soil chemical composition are shown in Table 2. The mass percentage of quartz for most soils is over 50%. The only exception is for yellow soil, which also shows the smallest percentage of organic matter.

Among all the soil minerals, the thermal conductivity of quartz is 7.69 W/(m·K), and that of other minerals is in a range of 1.53–5.51 W/(m·K) (Xiao et al., 2007). Soil organic matter is mainly humus with an average thermal conductivity of about 1.26 W/(m·K) (Huang and Xu, 2010). Therefore, the increase in quartz generally has a positive effect on the increase in soil thermal conductivity, which is obvious from

Fig. 6. The formula of k_d in Johansen's model (Johansen, 1975) mentioned above also indicated that soil thermal conductivity increases with the increase in quartz content. Abu-Hamdeh and Reeder (2000) derived the same conclusion experimentally, namely that soil thermal conductivity increases with the decrease in organic matter content. However, there are few experimental studies on the effect of chemical composition on soil thermal conductivity at present.

Table 2 Characterization of soil chemical composition

Soil type	Mass percentage (%)		
	Quartz	Other minerals*	Organic matter
Regosol	65.2	26.9	7.9
Paddy soil	81.4	13.4	5.2
Red soil	73.0	23.8	3.2
Alluvial soil	60.9	31.8	7.3
Purple soil	57.2	22.6	20.2
Seashore solonchak	63.0	29.6	7.4
Brown clay	52.7	40.6	6.7
Limestone soil	66.9	19.6	13.5
Yellow soil	29.6	67.0	3.4
Mountain meadow soil	67.7	19.4	12.9

*Other minerals include orthoclase, anorthose, calcite, dolomite, hematite, ankerite, pyroxene, amphibole, mica, magnetite, and anatase

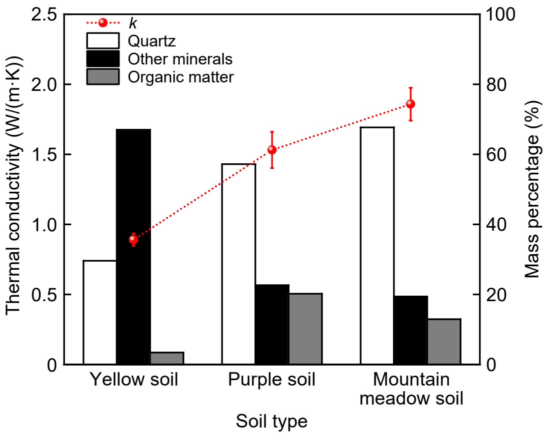


Fig. 6 Effects of chemical composition on soil thermal conductivity (moisture content: 20%)

3.3 Regression analysis and prediction formulae

It should be noted that, due to the complex composition of soils, it is difficult to predict the thermal conductivity of all types of soils accurately with any single formula. Therefore, it is necessary to propose different prediction formulae for different soil types. However, the parameters involved in the previous formulae are relatively complex and inconvenient to use in engineering. In view of this, besides exploring the effects of various parameters on soil thermal conductivity, this study also aims to propose prediction formulae of thermal conductivity for engineering projects involving soil backfilling.

As shown in Table 3, the prediction formulae for thermal conductivity of two categories of fully compacted soils are summarized through a binary linear regression analysis based on 1/2 power of moisture content ($\theta_m^{1/2}$) and 1/2 power of dry bulk density ($\rho_d^{1/2}$) as the independent parameters. The procedures and results of the regression analysis are detailed in Data S5 of the ESM. Although the prediction formulae in this study may still carry the same uncertainty level as others, they are relatively simple in form and convenient for practical application.

4 Conclusions

1. Overall, the maximum thermal conductivity of the 10 typical soils in a fully compacted state in this study is about 20%–50% higher than that of the soils in the natural or uncompacted state reported by others, which indicates the strong positive effect of dry bulk density on thermal conductivity.

2. Considering the three phases of soils, the density and thermal conductivity of the solid phase are the highest, while those of the gas phase are the lowest. Normal water content can make the solid phase contact closely, but excessive water will occupy the space and make the solid phase arrangement sparse. Therefore, with the increase in moisture content, the

Table 3 Prediction formulae for two categories of fully compacted soils based on binary linear regression analysis

Soil texture	Prediction formula	P-value of regression coefficient			R^2
		$\theta_m^{1/2}$	$\rho_d^{1/2}$	Intercept	
Clay loam & loam	$k=2.821\theta_m^{1/2}+3.773\rho_d^{1/2}-4.342$	6.54×10^{-15}	8.88×10^{-4}	1.08×10^{-3}	0.930
Sandy loam & loamy sand	$k=2.718\theta_m^{1/2}+4.958\rho_d^{1/2}-5.698$	2.46×10^{-5}	2.00×10^{-2}	2.16×10^{-2}	0.942

dry bulk density and the thermal conductivity of compacted backfill soils first increase rapidly and then slow down. When moisture content exceeds a critical value, dry bulk density and thermal conductivity remain basically unchanged or decrease slowly.

3. The variation of the thermal conductivity with moisture content for compacted backfill soils with the same texture classification is similar. Generally, the porosity of soils with large particle size is slightly lower than that of soils with small particle size; less water is required to fill up most pores of the former than that for the latter. Therefore, the critical moisture content of soils with large particle size is usually lower than that with small particle size.

4. Soil thermal conductivity is positively correlated with quartz content, which is extremely obvious when there is a great discrepancy in quartz content. The mass percentages of quartz for nine typical soils in this study are more than 50%, while only that for yellow soil is less than 30%, which leads to the phenomenon that the thermal conductivity of other soils is nearly twice that of yellow soil when the moisture content is 20%.

5. Under the condition that the significance level α equals 0.05, the absolute values of the correlation coefficients for moisture content and dry bulk density to thermal conductivity are more than 0.7, while those for particle size distribution and chemical composition to thermal conductivity are less than 0.3. Therefore, the prediction formulae for the thermal conductivity of two categories of compacted backfill soils are based on the binary regression analysis with moisture content and dry bulk density as the two independent parameters. The P-value of each regression coefficient in the formulae is less than 0.05, and the coefficient of multiple determination R^2 exceeds 0.9.

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Author contributions

Yu-hao WU: conceptualization, data curation, formal analysis, investigation, methodology, validation, and writing-original draft. Yan-hao FENG: data curation, investigation, and methodology. Li-wu FAN: conceptualization, methodology, project administration, and writing-review & editing. Qing WANG: investigation and writing-review & editing. Xin SONG: project administration. Zi-tao YU: writing-review & editing.

Conflict of interest

Yu-hao WU, Yan-hao FENG, Li-wu FAN, Qing WANG, Xin SONG, and Zi-tao YU declare that they have no conflict of interest.

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Electronic supplementary materials

Data S1, Data S2, Data S3, Data S4, and Data S5