

EXPERIMENTAL STUDY AND EMPIRICAL MODEL ON THERMAL PROPERTIES OF REMOLDED LOESS

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Thermal conductivity—indispensable for assessing loess heat transfer and stability—was analyzed in saturated/unsaturated states under varying moisture, density, and temperature using a Netzsch HFM 446. Results show unsaturated remolded loess exhibits moisture-dependent conductivity increases, with water content being the dominant factor. A predictive model integrating moisture, dry density, and mineral composition demonstrated high accuracy, validated through experimental data and published literature.

Keywords: Remolded loess, thermal conductivity, dry density, water content, predictive model.

1. Introduction

Loess, as a critical engineering material, exhibits thermal properties vital for geothermal energy exploitation and underground engineering. Thermal conductivity — a pivotal parameter for assessing the thermal behavior of compacted loess — is governed by hygrothermal factors such as moisture content and dry density, with targeted regulation of these variables enhancing thermal stability. This study focuses on loess from Heifangtai, Yan'an, and Chanhe, employing the heat flow meter method to measure the thermal conductivity of remolded soil specimens. We analyze moisture-density influence mechanisms and develop a generalized geometric mean predictive model, validated against published experimental datasets. The results deliver essential parameter benchmarks for engineering applications in loess-dominated regions.

2. Materials and Methods

2.1 Materials sampling

Experimental loess specimens were systematically collected from three representative sites across China's Loess Plateau, each exhibiting distinct geotechnical characteristics: (i) Chanhe Site, Located on the third fluvial terrace of the Chanhe River in eastern Xi'an (34°21'N, 109°00'E), this engineering profile contains typical loess deposits at 1-8 m depth. The sampled material demonstrates natural moisture contents ranging from 10.1% to 14.7% with in-situ dry densities of 1.35-1.52 g/cm³. (ii) Yan'an Site, Situated in the northern engineering section of Yan'an New District (36°39'N, 109°29'E), the loess stratum extends 2-10 m below ground level. Laboratory analysis revealed elevated moisture parameters (12.9-16.2%) compared to Chanhe samples, accompanied by higher dry density values (1.49-1.62 g/cm³). (iii) Heifangtai Site, Occupying the fourth terrace sequence in Yongjing County, Gansu Province (36°05'N, 103°18'E), this 2-10 m thick profile exhibits remarkable hydro-physical properties. The aeolian deposits demonstrate exceptional aridity with natural moisture contents as low as 3.0-4.8%, correlating with reduced dry density measurements of 1.31-1.37 g/cm³. Laser granulometry

(Mastersizer 2000) classified all samples as silt/silty clay, dominated by 0.005–0.075 mm particles (see *Table 1*).

Table 1. Particle Size Distribution Analysis Results of Three Loess Samples

Physical Properties		Chanhe	Yan'an	Heifangtai
Particle size distribution	Sand 75-2000 μm	27.39	13.89	9.71
	Silt 5-75 μm (%)	71.95	79.4	77.64
	Clay<5 μm (%)	0.66	6.71	12.65

Three sites were used to prepare remolded specimens, respectively: natural loess was air-dried, crushed with a rubber mallet, and sieved through 2 mm. Target moisture was achieved incrementally via a spray method, with thorough mixing and minimal aggregate crushing using a pestle (Zhan et al., 2014). The soil was sealed for 48 hrs to homogenize moisture, then statically compacted at a constant rate into 17 \times 17 \times 35 mm square molds. Pressure was held for 30 mins after reaching target height to stabilize structure. Specimens were wrapped in plastic film, stored in a humidity chamber, and tested per protocols in *Table 2*.

Table 2. Experimental Scheme for Remolded Loess

Control moisture content(%)	Control dry density (g/cm^3)
6, 10, 14, 18	1.35, 1.45, 1.55, 1.65, 1.75

2.2 Testing Apparatus

The thermal conductivity of loess was measured using a Netzsch HFM 446 heat flow meter. With an accuracy of $\pm 1\%$ – 2% and plate temperature range of -20°C – 90°C , the test involved placing the soil sample between two plates maintaining a temperature gradient. Two high-precision heat flux sensors on the plates measured heat flux entering and exiting the specimen. Prior to testing, supplemental thermocouple measurement points were secured at the specimen's upper and lower surface centers using aluminum foil tape, followed by silicone gasket installation and 2.0 kPa pressure application to ensure optimal contact. The instrument first entered a coarse adjustment phase, transitionally to fine-tuning when plate temperatures approached preset values and heat flux stabilized. Testing concluded when steady-state conditions meeting standard criteria were achieved through iterative adjustments, with detailed process data subsequently exported.

3. Results and analysis

3.1. Analysis of variation law of thermal conductivity in remolded loess

Figure 1 illustrates the correlation between dry density and thermal conductivity in three remolded loess types under constant moisture content. All samples demonstrate increasing thermal conductivity with higher dry density, consistent with findings from Wang et al. (2007), Tang et al. (2015), and related studies. This trend occurs because soil particle compaction reduces porosity and enlarges interparticle contact areas at fixed moisture levels (Yu et al., 2015), enhancing heat transfer through solid particle conduction. While all soils follow this pattern, conductivity variations exist: At 18% moisture and 1.75 g/cm^3 density, Chanhe loess records the lowest conductivity ($1.8703 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), followed by Yan'an ($2.0576 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and Heifangtai loess ($2.3615 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$). These differences likely stem from inherent textural variations among the soil types.

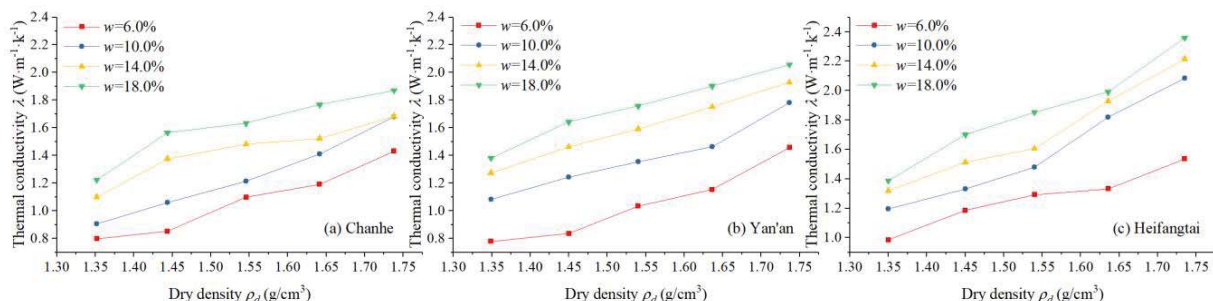


Figure 1. Relationship between thermal conductivity and dry density

Figure 1 also demonstrates how thermal conductivity in three remolded loess samples (constant dry density) increases with moisture content, particularly below 10% saturation. This rapid growth phase (6-10% moisture) shows heightened sensitivity to water content changes, followed by reduced progression rates at higher saturation levels. Multiple studies confirm this moisture-thermal conductivity correlation across Chinese loess regions (Wang et al. 2012; Zhen et al. 2019). Three mechanisms drive this phenomenon: 1) Phase replacement: Water (higher thermal conductivity than air) displaces pore air, creating thermal bridges between soil particles. 2)

Surface hydration: Silt-rich loess develops thicker water films at particle contacts, accelerating thermal transfer through enhanced surface interactions. 3) Saturation threshold: Beyond critical moisture levels, conductivity increases slow as hydration films stabilize, leaving only residual air-water replacement effects. This dual-phase response pattern aligns with findings from soil thermal dynamics research (Xiao et al. 2008; Dong et al. 2015), highlighting moisture's nonlinear impact on heat transfer in porous geomaterials.

3.2. Empirical relationship of thermal conductivity of remolded loess

Based on 60 thermal conductivity tests of remolded loess, the study proposes a predictive model:

$$\lambda = (c \log w - b) \cdot 10^{(a\rho_d^{-1})} \quad (1)$$

where parameters a , b , and c are surface-fitting variables, w represents moisture content (%), and A_d denotes dry density (g/cm^3).

Results demonstrate thermal conductivity increases proportionally with both dry density and moisture content (Figures 2a-c). Surface fitting correlations for Chanhe, Yan'an, and Heifangtai loess yielded coefficients of 0.915, 0.968, and 0.967 respectively, while combined regional data showed a 0.856 correlation (Figure 2d). Validation using published datasets demonstrated strong correlations: 0.939 (Wang et al. 2007), 0.866 (Wang et al. 2012), 0.926 (Tang et al. 2015), 0.964 (Ye et al. 2017), and 0.954 (Zhen et al. 2019). The consistent positive correlation between thermal conductivity and both variables persists across studies, though regional variations in soil texture, mineral composition, and testing protocols may explain reduced fitting accuracy in some cases.

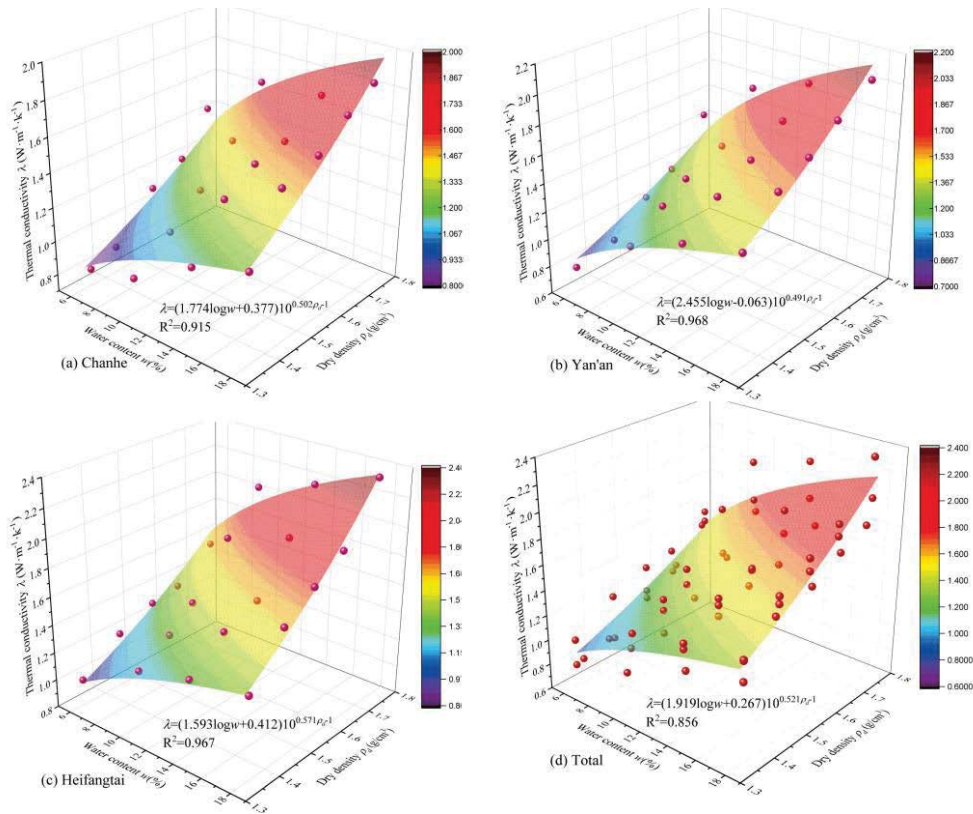


Figure 2. empirical relationship between dry density, moisture content and thermal conductivity

3.3. Model Validation

We evaluated the predictive accuracy of a thermal conductivity model for three remolded loess samples by comparing measured values with calculated predictions. Model performance was quantified using root mean square error (RMSE) and bias:

$$\text{RMSE} = \sqrt{\frac{\sum (\lambda_m - \lambda_p)^2}{m}} \quad (2)$$

$$\text{bias} = \frac{\sum (\lambda_m - \lambda_p)}{m} \quad (3)$$

Where, m is the sample capacity; λ_m and λ_p are measured and predicted thermal conductivity respectively. Lower RMSE indicates better alignment between experimental and predicted values.

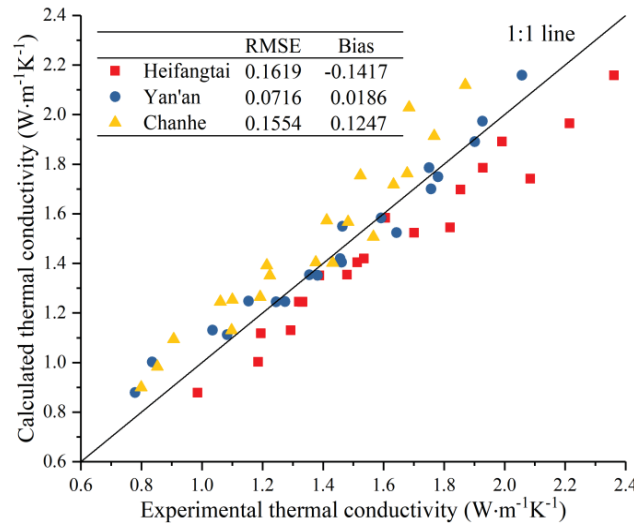


Figure 3. Consistency verification of measured and predicted thermal conductivity

Figure 3 demonstrates that thermal conductivity values derived from density-moisture correlations cluster evenly around the 1:1 equivalence line, showing strong agreement between empirical model predictions and laboratory measurements. This distribution pattern confirms the model's reliability in characterizing loess thermal conductivity variations under different density and moisture conditions. We compare the measured values of thermal conductivity of three remolded loess with the predicted values of the calculation model. The root mean square error (RMSE) and bias (bias) of the predicted values were calculated to evaluate the performance of the model in predicting the thermal conductivity of loess

4. Conclusions

The thermal conductivity of remolded loess correlates with its dry density and moisture content. At a fixed moisture level, higher dry density enhances structural compactness and thermal conductivity. While both increased moisture and density universally boost conductivity across three tested loess types, variations exist due to differences in mineral composition, particle size distribution, and restructuring during remolding.

An empirical model demonstrates strong predictive accuracy for loess thermal parameters, enabling practical applications such as temperature field reconstruction in disturbed Loess Plateau regions. This supports underground space development and frost-thaw hazard analysis.

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