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Research Article

Experimental Study on Normal Frost-Heave Force Generated from Loess upon Freezing considering Multiple Factors

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An experimental study on the normal frost-heave force generated by loess was conducted by subjecting loess with various water contents and densities to different temperature conditions. The experimental results show that the interaction of the three factors has a significant effect on the normal frost-heaving force. Normal frost-heave force increases exponentially with an increase in dry density and linearly with a reduction in the freezing temperature or an increase in water content; of these factors, dry density has the greatest influence on frost-heave force, followed by water content then temperature. A frost-heave force model is developed that includes overall consideration of the interactions of water content, density, and temperature based on fitting of the test results. The value calculated with the model is in good agreement with values measured in verification tests, indicating that the model has high accuracy and can provide scientific guidance for engineering design in loess areas.

1. Introduction

Construction in loess areas suffers from major problems due to freezing damage [1–4]. A lack of scientific guidance on frost-heave force in the design of structures such as foundations, subgrade, tunnels, culverts, artificial freezing support, and other projects means that they experienced different degrees of deformation and cracking and even structural failure due to excessive frost-heave force in the soil mass, leading to serious security issues and causing great economic loss [5–11].

Few studies have yet been conducted on frost-heave force. Early studies on frost-heave force often took temperature as the main influencing factor. In terms of theoretical research, Penner et al. [12] proposed that due to the influence of the temperature gradient, the maximum frost-heave force appears at the top of the soil. According to another study by Penner and Walton [13], temperature is closely related to frost-heave force, and as the temperature decreases, frost-heave force increases linearly. Takashi et al. [14] obtained the relationship between frost-heave force and temperature by measuring the pore-water pressure of unfrozen water at different temperatures. Jiang et al. [15] studied the relationship between temperature and normal frost-heave force through an experiment on normal frost-heave force in low-liquid limit clay. Tang et al. [16] studied the relationship between temperature and frost-heave force through an indoor experiment on the frost-heave force generated by mucky clay. Gutkin [17] studied the influence of horizontal frost-heave force on an enclosing structure with finite stiffness. In addition to these theoretical studies, scholars have also performed numerous studies on frost-heave force under real-world working conditions. In tunnel engineering, Gao et al. [18] and Feng et al. [19] obtained an elastic-plastic analytical solution of the plastic region of tunnel-surrounding rock stress in cold regions. By considering the isotropy of tunnel temperature and the anisotropy of surrounding rock, Xia et al. [20] obtained an analytical solution for frost-heave force. In the study of frost heave of foundation and supporting structure, temperature is also regarded as an important factor affecting frost heave. On the basis of monitoring of the temperature and deformation of the foundation of a transmission line tower, Wen et al. [21] argued that the spherical stress at the base of the tower was closely related to temperature. Wang et al. [22] and Ji et al. [23] proposed that frost-heave force is related to the properties of the material restraining the frost-heave body and temperature. In the above studies, the frost-heave force calculated only considering the effect of temperature is quite different from the actual value of frost-heave force, which cannot accurately reflect the magnitude and variation of the actual frost-heave force.

With the further study of frost-heave force, it is found that soil properties (moisture content, dry density, etc.) also have an impact on frost-heave force. Xu et al. [24] studied the variation of cohesion and internal friction angle of loess samples with different water contents and dry densities after freeze-thaw cycles. It was found that the cohesion of loess after freeze-thaw cycles decreased with the increase of dry density and water content, while the internal friction angle of loess changed little after freeze-thaw cycles. Wang et al. [25] set up a prediction model of frost heave of cohesive soil considering the influence of temperature and optimized the hydraulic section of irrigation canal accordingly. Zhang et al. [26] studied the influence of water content and dry density on frost heave. He believed that when water content was 15~25% and temperature was −15~35°C, the settlement of the upper and lower boundary of the overlying permafrost layer decreased with the decrease of temperature and the increase of water content.

As can be seen from the above summary, the factors often considered in the study of frost-heave force are temperature, water content, and dry density. But, the process of generating actual frost-heave force is a multifactor coupled process. Change in any of the factors (density, water content, or freezing temperature) will change the ice content, unfrozen water content, pores between soil particles, and so on [27]. The influence of dry density, water content, and temperature on normal frost heaving should not be neglected.

However, there are few studies considering the effects of dry density, water content, and temperature on frost-heave force, and the interaction of these three factors is not considered. Therefore, this paper intends to systematically and quantitatively study the comprehensive influence of the three factors on frost-heave force. Moreover, considering that loess is a special kind of soil, its physicochemical and physicomechanical properties are particularly sensitive to changes in density and water content [28–30]. This study takes loess as the test soil sample and carried out an experimental study on the frost-heave force generated by loess, taking density, water content, and temperature into consideration. To quantitatively analyze the influence of these various factors on frost-heave force, the experiment was set as a closed unidirectional freezing test to avoid interference of other factors. The results reveal the laws governing the effects of three factors on normal frost-heave force, and a model for normal frost-heave force is established based on the experimental data that take the interactive effects of three factors into consideration. The results can provide a basis for the analysis of frost-heave force and a reasonable reference for the calculation of frost-heave force in loess soil.

2. Experimental Setup and Test Procedure

The loess used in the experiment is from a foundation pit in Fuping area, Shaanxi Province, China. The properties of the loess are shown in Table 1. Loess samples with different water contents and dry densities were prepared indoors.

Cutting-ring loess samples with identical dimensions of 79.8 mm × 20 mm were prepared. The loading device is a WG-type single-lever oedometer manufactured by Nanjing Soil Instruments, and the deformation monitoring device is a dial gauge with an accuracy of 0.01 mm to provide a reading accuracy meeting the test requirements. The testing devices are shown in Figure 1.

The temperature-controlled chamber was first cooled to the test temperature, and then the soil samples were placed in the chamber for testing. The soil samples were frozen under test temperature, and the loading device was used to apply a vertical load to restrain frost-heave deformation so as to guarantee that no frost-heave deformation occurred in the soil samples. The displacement is restrained during freezing, and the axial load is measured as the frost-heave force. Frost-heave force experiments were carried out on soil samples with different water contents and dry densities at different temperatures.

Under the action of temperature, the freezing of soil samples will occur over a period of time. Frost-heave force gradually increases with time; but after a certain period, the increment gradually decreases with time until the frost-heave force reaches a stable state. An increment of less than 0.5% of the measured frost-heave force in two consecutive hours can be regarded as the standard for a stable state.

In practical engineering, the dry density of loess varies over a large range. Considering the range of dry densities encountered in engineering contexts, the dry densities of the soil samples in this experiment were set within the range 1.30~1.70 g·cm^{-3}. Additionally, frost-heave force has a pressure-melting effect on soil. To study the effect of temperature change on pressure-melting effect, it was judged that the completion of soil sample freezing in the earlier stages should be guaranteed. Therefore, in the present experiment, the highest temperature value is the lowest temperature in the zone of severe phase transformation: −3°C. Because the average daily minimum temperature in the Loess Plateau in winter is −12°C, the range of temperatures in this experiment on the frost-heave force generated by loess is taken as −3, −7, and −12°C. Table 2 lists the parameter values for each group of soil samples in the present test, in which ρ_d is the initial dry density of a soil sample, w is the water content in the soil sample, T is the soil temperature, and P is the frost-heave force. A total of 60 groups of samples were tested. In this paper, three groups of parallel experiments were conducted in each group. The average value of the measured data was taken as the final data, and parallel experiments were carried out on individual points with abnormal test data.

3. Results and Analysis

Experiments on the frost-heave force generated by loess samples with different water contents and dry densities were carried out at different temperatures according to the experimental scheme outlined in Section 2. The results of the tests are analyzed below.

Table 1: Physical properties of loess.

w_1 (%)	w_p (%)	I_p	Particle content (%)		
			>0.05	0.05~0.005	<0.005
34.4	18.1	16.3	17	61	22

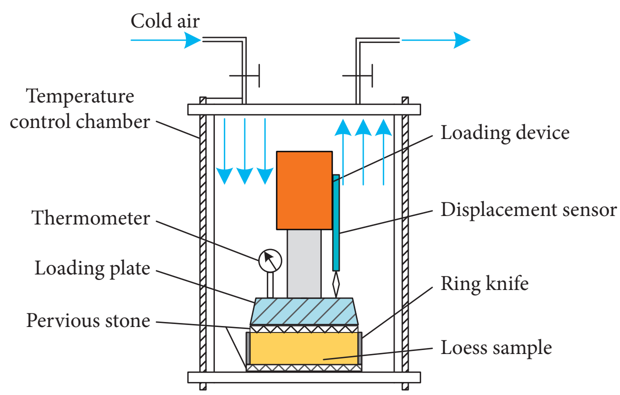

Figure 1: Testing devices.

Table 2: Parameter values for each group of soil samples tested.

Test numbers	ρ_d (g·cm^{-3})	w (%)	T (°C)	Test numbers	ρ_d (g·cm^{-3})	w (%)	T (°C)
1	1.3	−7	20	31	1.5	−12	20
2	1.3	−7	22	32	1.5	−12	22
3	1.3	−7	24	33	1.5	−12	24
4	1.3	−7	26	34	1.5	−12	26
5	1.3	−7	28	35	1.5	−12	28
6	1.4	−3	20	36	1.6	−3	20
7	1.4	−3	22	37	1.6	−3	22
8	1.4	−3	24	38	1.6	−3	24
9	1.4	−3	26	39	1.6	−3	26
10	1.4	−3	28	40	1.6	−3	28
11	1.4	−7	20	41	1.6	−7	20
12	1.4	−7	22	42	1.6	−7	22
13	1.4	−7	24	43	1.6	−7	24
14	1.4	−7	26	44	1.6	−7	26
15	1.4	−7	28	45	1.6	−7	28
16	1.4	−12	20	46	1.6	−12	20
17	1.4	−12	22	47	1.6	−12	22
18	1.4	−12	24	48	1.6	−12	24
19	1.4	−12	26	49	1.6	−12	26
20	1.4	−12	28	50	1.6	−12	28
21	1.5	−3	20	51	1.7	−3	20
22	1.5	−3	22	52	1.7	−3	24
23	1.5	−3	24	53	1.7	−7	20
24	1.5	−3	26	54	1.7	−7	22
25	1.5	−3	28	55	1.7	−7	24
26	1.5	−7	20	56	1.7	−7	26
27	1.5	−7	22	57	1.7	−7	28
28	1.5	−7	24	58	1.7	−12	20
29	1.5	−7	26	59	1.7	−12	24
30	1.5	−7	28	60	1.7	−12	26

3.1. Analysis of the Influence of Dry Density on Frost-Heave Force. According to Figures 2(a) and 2(b), normal frost-heave force generally increases with an increase in dry density, but it shows no significant increase with an increase in dry density at small dry density values. When dry density is less than 1.40 g·cm^{-3}, soil samples have large pores, and the normal frost-heave force generated by the soil samples is 0 kPa. This is because the initial water content in the soil

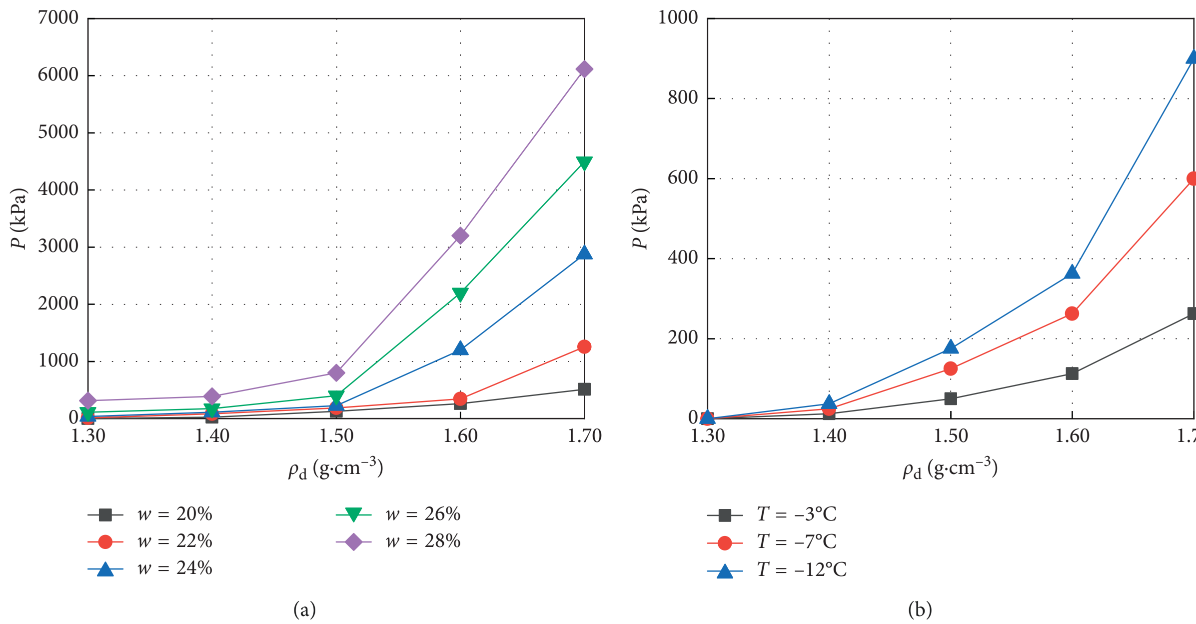

FIGURE 2: Relationship between dry density and frost-heave force. (a) $T = -7^\circ$C. (b) $w = 20\%$.

samples is very low, causing the ice content in the soil upon freezing to be too low to fill the pores. Moreover, ice has a limited improvement effect on the strength of cementation between soil particles. The soil mass itself suffers no frost-heave deformation, so no normal frost-heave force is generated. When dry density increases to 1.50 g·cm^{-3}, the increase rate of frost-heave force increases significantly.

3.2. Analysis of the Influence of Water Content on Frost-Heave Force. Figures 3(a) and 3(b) show the relationship between water content and normal frost-heave force when the dry density is 1.60 g·cm^{-3} and the soil temperature is −7°C. According to the figures, at a given soil temperature, a change in the initial water content of the soil samples has a significant influence on frost-heave force. At set values for dry density and freezing temperature, the normal frost-heave force produced in soil sample freezing increases approximately linearly with an increase in the initial water content in the soil sample. There is a minimum water content threshold: when the water content is lower than this minimum value, no frost-heave force is generated when freezing deformation of soil samples is restrained. For example, in Figure 3(b), among the soil samples with a dry density of 1.30 g·cm^{-3} and different water contents, the smaller the water content of the soil sample, the smaller the frost-heave force. When the water content was 20%, the force-heave force generated by the soil sample was 0 kPa.

3.3. Analysis of the Influence of Temperature on Frost-Heave Force. According to Figures 4(a) and 4(b), change in temperature has a significant effect on normal frost-heave force. When dry density and water content are held constant, the freezing temperature of the soil samples decreases; when frost heave of the soil samples is restrained, the normal frost-heave force generated increases. At a high temperature, normal frost-heave force increased more significantly with a decrease in temperature; with a decrease in the temperature, the amplitude of the increase in normal frost-heave force decreased. According to Figure 4(a), when the dry density is 1.50 g·cm^{-3}, the freezing temperature decreases from −3°C to −12°C and the frost-heave force increases by about three times, following similar trends at different water content levels. According to 4(b), when the water content is 24% and soil samples with different dry densities are considered, the frost-heave force increases by about 2.5 times as the freezing temperature decreases from −3°C to −12°C. Furthermore, with a decrease in the freezing temperature, normal frost-heave force is more sensitive to changes in dry density and water content. The lower the freezing temperature, the greater the increment of frost-heave force caused by an increase in dry density and water content.

3.4. Analysis of the Significance of the Influences of T, w, and ρ_d on Frost-Heave Force. In order to quantify the significance of the influence of the three factors on the frost-heave force, the orthogonal table was used to analyze the three factors. Take w as 20, 24, and 28%. Take ρ_d as 1.4, 1.5, and 1.6 g·cm^{-3}. Take T as −3, −7, and −12°C. Construct an orthogonal table of 3×3, as shown in Table 3. Among them, K_1, K_2, and K_3 represent the average value of indicators at each level of each factor. The value obtained by subtracting the smallest K from the largest K in each column is called R, which indicates the significant level of influence of each factor on the frost-heave force (see Table 3).

The magnitude of R can reflect the order of significance of factors (see Table 4). The values for the range, R, in the significance analysis are 800.00>662.333>520.883, and the corresponding order of significance is dry density>water content>temperature. In other words, among the factors

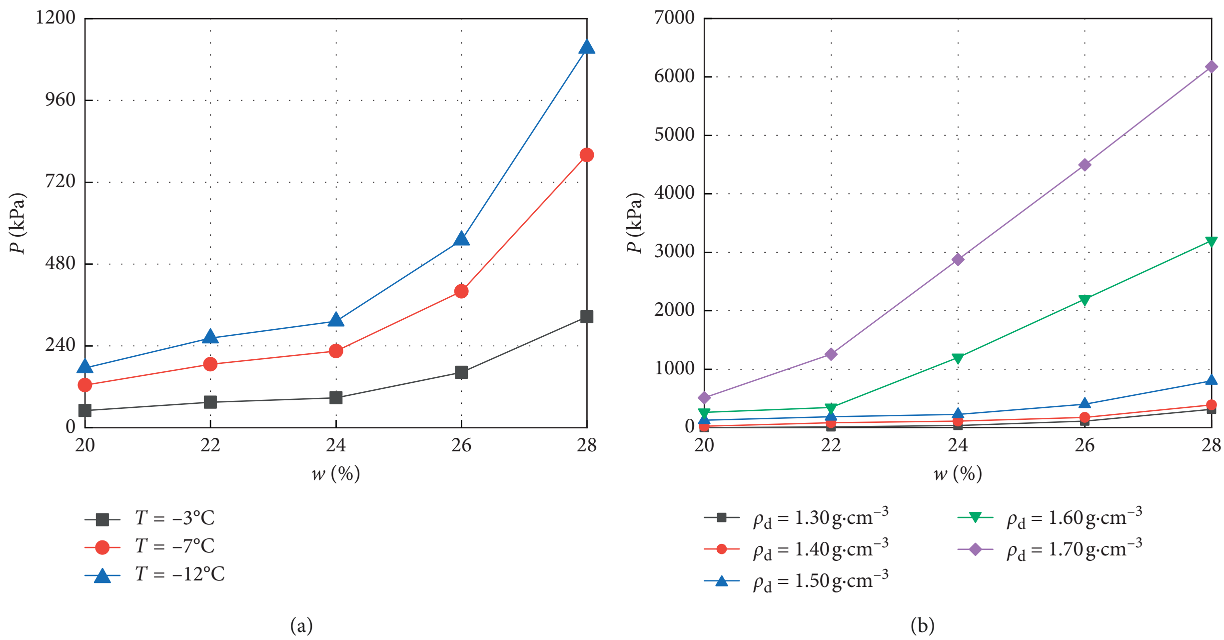

FIGURE 3: Relationship between water content and frost-heave force. (a) $\rho_d = 1.60\,\text{g·cm}^{-3}$. (b) $T = -7°\text{C}$.

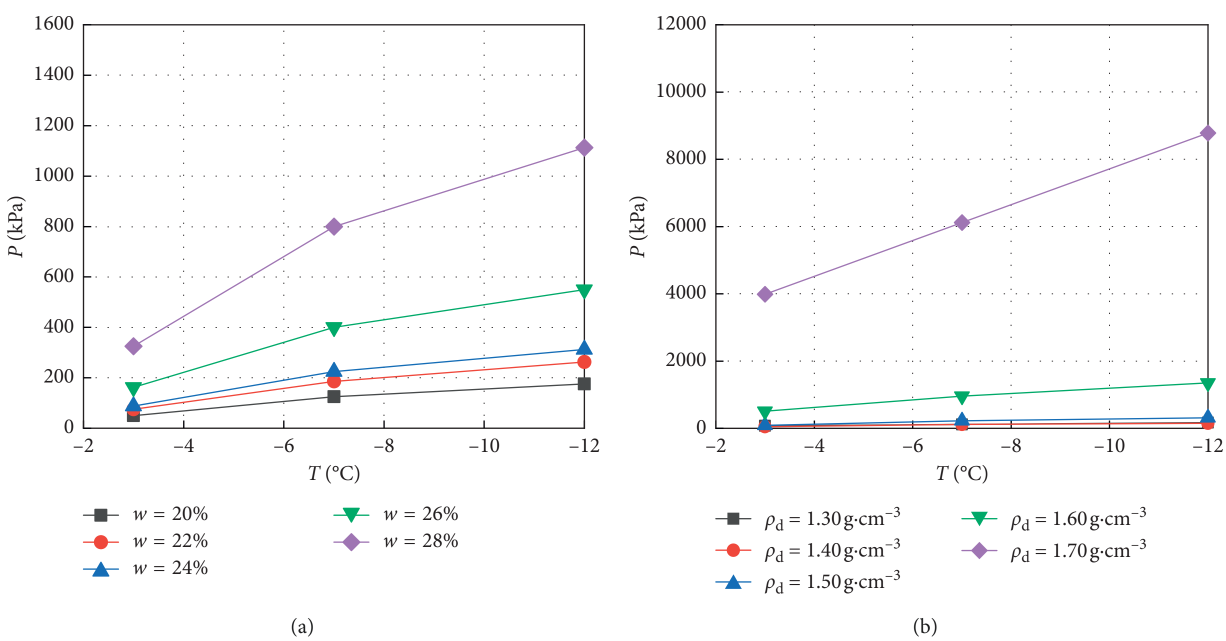

FIGURE 4: Relationship between temperature and frost-heave force. (a) $\rho_d = 1.50\,\text{g·cm}^{-3}$. (b) $w = 24\%$.

influencing frost heave in loess areas, dry density has the greatest influence, followed by water content and then temperature.

3.5. Forecasting Model of Frost-Heave Force. According to the significance analysis above, dry density has the greatest influence on normal frost-heave force in loess, followed by water content, and subzero temperature has the least influence. Therefore, the influence of a single factor, dry density, on normal frost-heave force is considered first. The forecasting model of normal frost-heave force is thus initially

$$P = a_1 \cdot \exp\left(a_2 \cdot \rho_d + a_3\right), \tag{1}$$

where P is the normal frost-heave force; ρ_d is the dry density; and a_1, a_2, and a_3 are coefficients.

Fitting is conducted on the test results for soil samples with different water contents and dry densities at different freezing temperatures. The values of a_2 and a_3 are 9.9 and

Table 3: Significance analysis.

i	w (%)	ρ_d (g·cm^{-3})	T (°C)	P_i (kPa)
1	20	1.50	−12	175.500
2	24	1.40	−7	112.500
3	28	1.60	−3	1275.000
4	20	1.40	−3	12.500
5	24	1.60	−12	1350.000
6	28	1.50	−7	800.000
7	20	1.60	−7	262.500
8	24	1.50	−3	87.500
9	28	1.40	−12	362.500
K_1	$(P_1+P_4+P_7)/3$	$(P_2+P_4+P_9)/3$	$(P_3+P_4+P_8)/3$	
K_2	$(P_2+P_5+P_8)/3$	$(P_1+P_6+P_8)/3$	$(P_2+P_6+P_7)/3$	
K_3	$(P_3+P_6+P_9)/3$	$(P_3+P_5+P_7)/3$	$(P_1+P_5+P_9)/3$	
R	$K_{max}-K_{min}$ (in this column)	$K_{max}-K_{min}$ (in this column)	$K_{max}-K_{min}$ (in this column)	

Table 4: Values of significance analysis.

K_1	150.167	162.500	629.333
K_2	516.667	354.333	391.667
K_3	812.500	962.500	912.500
R	662.333	800.000	520.833

−12.46, respectively. The values of a_2 and a_3 are only related to the dry density and do not change with a change in water content and freezing temperature. The correlation coefficients of the model consisting of a_1, a_2, and a_3 are all greater than 0.9, indicating that the calculated and measured values of the model are in good agreement. Table 5 shows some of the values of a_1 and the correlation coefficients of the model consisting of a_1, a_2, and a_3.

The influence of water content and freezing temperature on normal frost-heave force was investigated. Among a_1, a_2, and a_3, only the value of a_1 is related to w and T. Thus, when analyzing the influence of water content and freezing temperature on normal frost-heave force, fitting is conducted only on a_1. The influence of water content on normal frost-heave force is greater than that of freezing temperature, and therefore, the influence of water content on a_1 is considered first in the next section. The fitting formula is as follows:

$$a_1 = b_1 w + b_2. \quad (2)$$

The values of b_1 and b_2 in the formula are shown in Table 6. The correlation coefficient r for the values is high, indicating that fitting on b_1 and b_2 is reliable.

Considering the influence of freezing temperature, fitting is carried out when b_1 and b_2 are given. The fitting formula can be expressed as follows:

$$b_1 = c_1 T + c_2, \quad (3)$$

$$b_2 = c_3 T + c_4. \quad (4)$$

The values of c_1, c_2, c_3, and c_4 in the formula are shown in Table 7. By substituting formulas (3) and (4) and formula (2) into formula (2) and formula (1), respectively, a model can be obtained for normal frost-heave force that comprehensively considers the influence of dry density, water content, and freezing temperature.

$$P(\rho_d, w, T) = (-0.88Tw + 4.09w + 17.9T - 84.3) \cdot \exp(9.9\rho_d - 12.46). \quad (5)$$

Table 5: Values of a_1 and the correlation coefficients r of the model consisting of a_1, a_2, and a_3.

T (°C)	w (%)	Parameter	Values
−3	20	a_1	3.99
		r	0.942
	24	a_1	14.96
		r	0.965
	28	a_1	56.02
		r	0.987
−7	20	a_1	7.11
		r	0.953
	24	a_1	26.62
		r	0.944
	28	a_1	99.66
		r	0.976
−12	20	a_1	9.09
		r	0.969
	24	a_1	34.04
		r	0.933
	28	a_1	127.42
		r	0.981

Table 6: Values for the coefficients b_1 and b_2 and the correlation coefficient r.

T (°C)	w (%)	a_1	b_1	b_2	r
	20	3.99			
−3	24	14.96	6.23	−127.97	0.988
	28	56.02			
	20	7.11			
−7	24	26.62	11.14	−227.67	0.928
	28	99.66			
	20	9.093			
−12	24	34.037	14.25	−291.09	0.942
	28	127.416			

Table 7: Values for parameters c_1,c_2, c_3, and c_4 and the correlation coefficient r.

T (°C)	b_1	c_1	c_2	r	T (°C)	b_2	c_3	c_4	r
−3	12.52				−3	−15.24			
−7	22.28	−0.88	4.086	0.963	−7	−27.12	17.9	−84.3	0.964
−12	28.49				−12	−34.67			

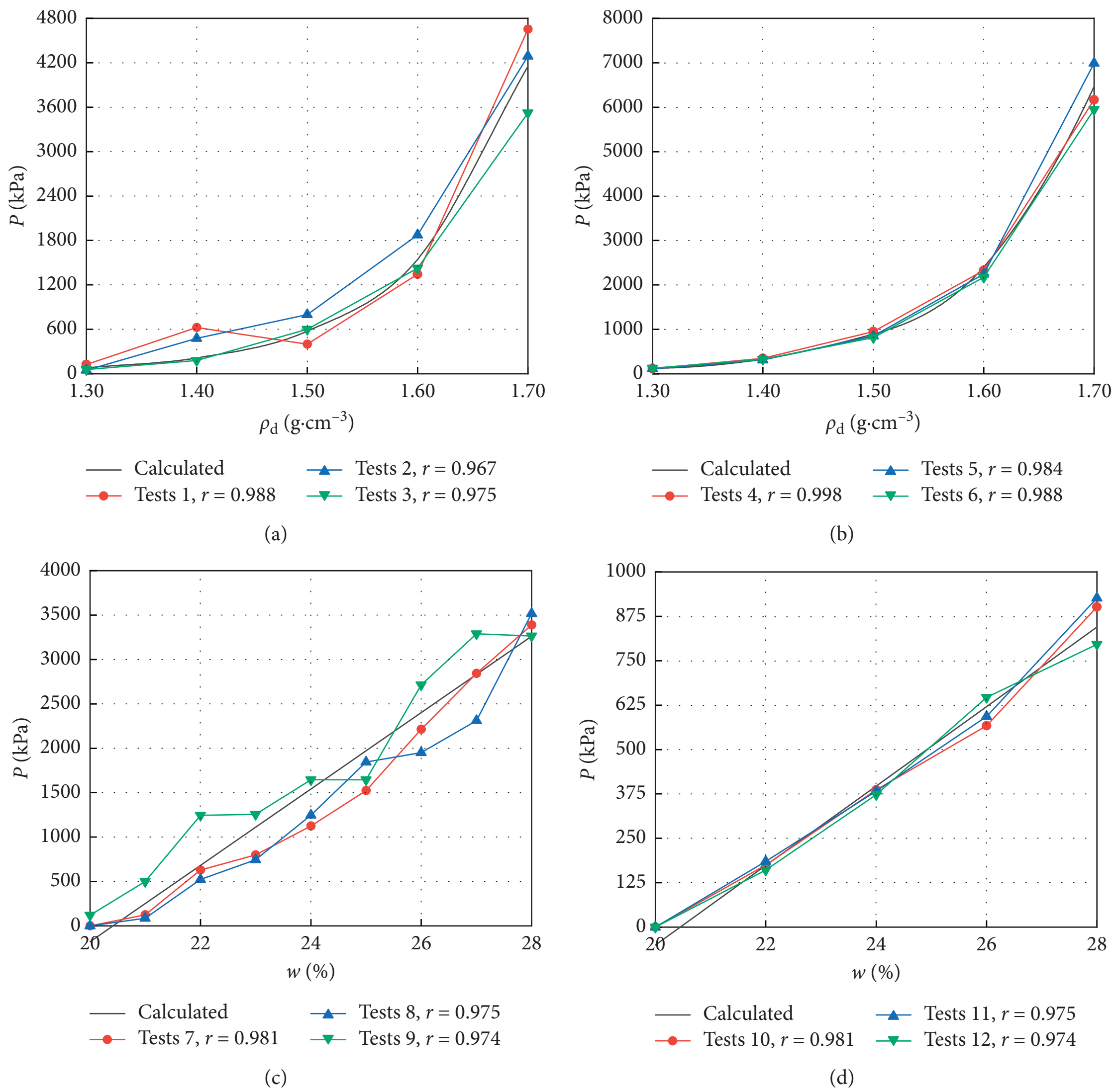

Figure 5: Continued.

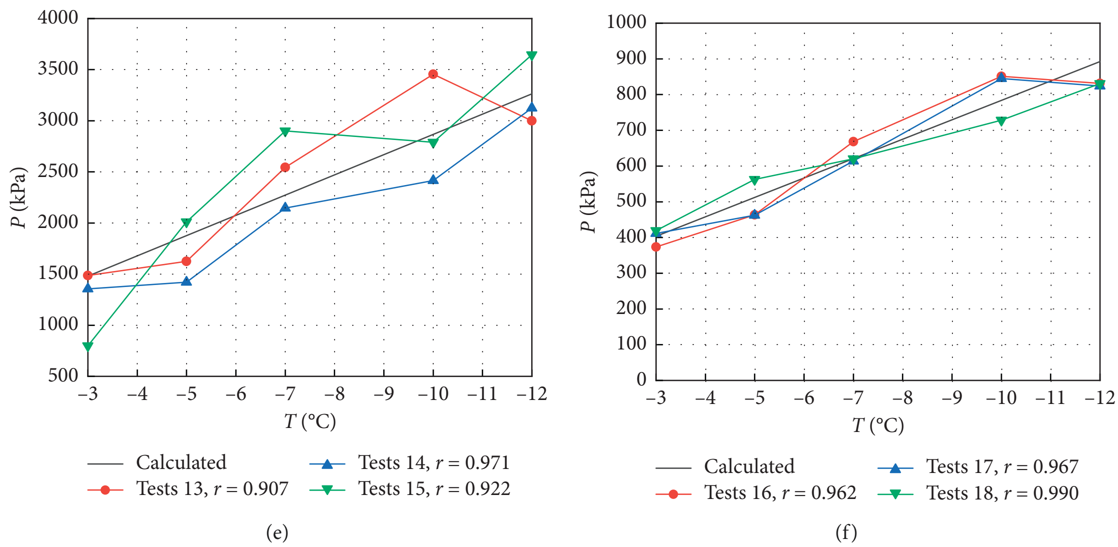

Figure 5: Comparison of the measured values and fitted values for frost-heave force. (a) $w = 24\%$, $T = -7^{\circ}C$. (b) $w = 26\%$, $T = -12^{\circ}C$. (c) $\rho_d = 1.60\ g{\cdot}cm^{-3}$, $T = -12^{\circ}C$. (d) $\rho_d = 1.50\ g{\cdot}cm^{-3}$, $T = -7^{\circ}C$. (e) $\rho_d = 1.60\ g{\cdot}cm^{-3}$, $w = 28\%$. (f) $\rho_d = 1.50\ g{\cdot}cm^{-3}$, $w = 26\%$.

In order to verify the rationality of the model, three groups of experiments were conducted with different water contents, dry densities, and temperatures, and three parallel experiments were conducted in each group. The measured data are compared with the calculated values of the model in Figure 5. It shows that the calculation results of frost-heave force are basically consistent with the data of verification test. The correlation coefficient (r) between them is close to 1. It shows that formula (5) has high reliability in describing the relationship between loess frost-heave force and the three factors, and the prediction error of frost-heave force is small.

4. Conclusions

(i) An experimental study was conducted on the normal frost-heave force generated by soil samples with different water contents and different densities at different freezing temperatures, revealing a close correlation between the normal frost-heave force generated by loess and the water content, dry density, and temperature of the soil. Normal frost-heave force increases exponentially with an increase in dry density, linearly with a decrease in freezing temperature, and also linearly with an increase in water content.

(ii) According to the significance examination, the impacts on frost heave in loess can be ranked dry density>water content>temperature.

(iii) By considering the interactive effects of the influencing factors of dry density, water content, and freezing temperature on frost-heave force, a model for the normal frost-heave force generated by loess in areas with seasonally frozen soil was established. The calculated values based on the model are in good agreement with the values measured in verification tests, indicating that the model is accurate and can provide scientific guidance for engineering design in loess areas.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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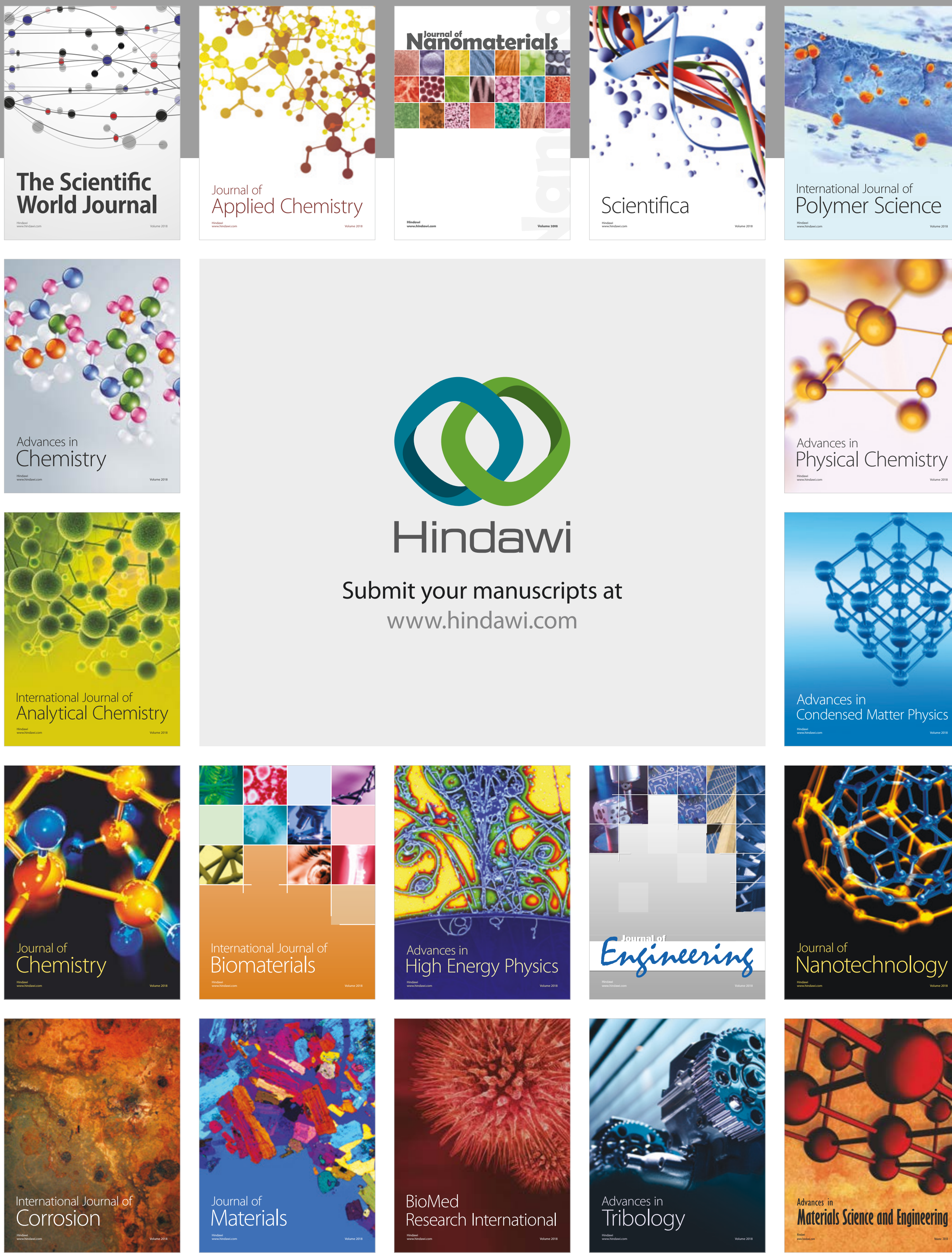
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