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Research Article

Research on Compressive Tests of Iron Tailing and Cement-Modified Earth Materials from Northwest China

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The strength of earth-modified materials is an important mechanical indicator of raw soil building materials. Iron tailings are a rich mineral waste resource with basic properties similar to river sand and can be used as a modified material for raw soil construction. To increase the utilization rate of iron tailings and improve the mechanical properties of earth materials, modification of earth materials were analyzed using iron tailings and cement. Through a single lattice theory design method, 10 different blending ratios of modified earth specimens were designed, with each group comprising six 100 mm cubic specimens. Earth specimens were used as the control group and compression tests carried out under standard curing conditions, with analysis of the failure mode, compressive strength, deformation, and load–displacement curve for each specimen. Also, the reasons for specimen failures were examined, including the influence of strength, dispersion, and implications of load–displacement curves. The optimal mix ratio of modified materials was determined using frequency domain analysis method. The results showed that the load–displacement curves of materials with different material ratios were basically similar and the slope and discreteness of the curves quite different. Increased tailings and cement content improved the compressive strength of earth materials and increased the discreteness of the material. Through frequency analysis, it was obtained that when the content of tailings was 12.1%–19.5%, cement content 13.9%–19.1%, and earth 65.5%–69.9%, there was a 95% of the guaranteed rate of compressive strength of iron tailings and cement-modified earth materials between 6 and 9 MPa. Iron tailings can, thus, be used as the preferred material for modifying earth materials; single lattice theory can be used as the design method for mixing experiments, and frequency domain analysis can be an effective calculation method for optimizing mixing design. Adding cement and iron tailings to modify the raw soil formula can provide reference for the selection of basic materials for raw soil construction.

1. Introduction

As one of the oldest building materials on earth, earth materials have been used for more than 10,000 years. Earth construction refers to buildings made of unbaked native soil as the main material [1–3]. Because of its many advantages, such as natural materials, adapted measures to local conditions, convenient construction, economical saving, low energy consumption, sustainable development, and superior thermal insulation performance, it has been widely used in rural areas in the northwest part of China [4–6]. However, the low strength of traditional earth materials also results in many restrictions on the use of earth materials.

To improve the mechanical properties of earth materials, researchers at home and abroad have done much work on earth modification. Earlier studies have indicated that the appropriate proportions of different grains in soil are generally 40%–70% for sand, 20%–40% for silt, and 10%–25% for clay by weight [7, 8]. In this study, mixed soils were obtained by mixing. Sattar Barati, a professor of Shiraz University from Iran, has studied the cement/bentonite stability testing of iron ore tailings. Test results show that the introduction of cement/bentonite to iron ore has a good effect, with the tailings needing a higher water content to achieve the best compaction effect and lead to a lower dry density. The unconfined compressive strength (UCS) of bentonite is little increased, while the strength of tailing cement mixture is greatly improved [9]. Based on the study of industrial waste fly ash and slag for modifying earth, Fanghui Han and Shaomin Song have found that the average compressive strength of raw adobe prepared by mixing the above two modification materials is greater than that of raw adobe mixed with a certain modifying materials alone. The maximum compressive strength of the green adobe obtained by mixing and blending can reach 5.25 MPa [10]. Emad et al. [11] have discussed the impact of the different grain sizes of sand on the ultimate stress of hand-mixed cement grouted sand modified with polycarboxylate ether-based polymer using two different test standards (ASTM and BS). Mohammed et al. [12] have discussed Vipulanandan constitutive models to predict the rheological properties and stress–strain behavior of cement grout modified with metakaolin. This geopolymer has been found to be useful for increasing soil strength and specimen water resistance when samples are enhanced by curing at high temperature. At the same time, researchers have also tried to modify and optimize earth material using sand and gravel. With decreasing sand and gravel resources, the equal substitution of materials has received extensive attention. The main chemical components of iron tailings are silicon dioxide and aluminum oxide (SiO_2 and Al_2O_3, respectively), which have the same physical and chemical properties as sand and appear today to be the best alternative building materials. In China, iron tailings have been used to manufacture iron tailing sand, iron tailing sand concrete, composite wallboard, and nonburning bricks [13].

According to statistics, the amount of iron tailings produced in China every year has reached more than 150 million tons, which occupies a lot of land and causes a certain burden on the environment and a waste of resources [14, 15].

In summary, a large amount of research both domestically and internationally has focused on using traditional building materials for hardening and modifying earth materials. There are few studies on the application of iron tailings to earth building materials. In this study, iron tailings and cement were used to modify earth materials. Using the single lattice theory, 10 different modified earth formulations mixed with cement and iron tailings were designed, with six specimens in each group and a total of 60 specimens. After the specimens were cured, compressive strength tests were conducted. Through analyses of compressive strength tests, failure modes, compressive strengths, and load–displacement curves of the modified material specimens, the effects of modified admixture content on material properties were examined. Also, frequency analysis was used to build a modified blending ratio to obtain the optimal formula, which might provide a reference for future engineering practice and theoretical research. A discussion was presented for the applicability of cement and iron tailings as earth modification additives and experimental and computational methods proposed for the selection of modified admixtures.

2. Materials and Methods

2.1. Test Materials. The loess used in these tests was taken from Chang'an District, Xi'an City, China. It was dried in a dryer and pulverized with a silt machine equipped with a 5-mm sieve, with large particles and impurities removed for later use. According to "The Standards for Geotechnical Experiment Methods," GBT50123-2019, China, 2019 [16], the plastic limit index of the soil sample was 14%, liquid limit index was 24%, and plastic index was 10. The ring knife method [16] was used to determine the most optimal moisture content of the soil sample, as $\omega = 19.08\%$ and maximum dry density at $\rho_\mathrm{d} = 2.03\ \mathrm{g/cm^3}$.

Figure 1: Iron tailings.

The iron tailings came from Daxigou Mining, Xiaoling Town, Zhashui County, Shangluo City, Shaanxi Province, the ore of which was soft in texture and mainly composed of quartz, hematite, albite, and amphibole. Before testing, iron tailings were grounded and screened by a pulverizer to produce iron tailing particles (Figure 1). The composition of iron tailings obtained by X-fluorescence elemental analyzer is shown in Table 1.

The cement used in these tests was the ordinary Portland cement with a strength grade of 42.5 of Qinling Brand and the mixing water was tap water.

2.2. Experimental Formula Design. Using the single lattice theory [17], there were three components in this experiment, namely iron tailings (Z_1), cement (Z_2), and earth (Z_3). The {3,3} simplex lattice design was adopted, and the number of experimental points was 10 [18]. According to the data, the iron tailing content in the test should not be <10%, cement should not be <5%, and earth, as the main material, should not be <65%. The restrictions of this formula were shown as follows:

$$Z_1 + Z_2 + Z_3 = 1,\ Z_1 \geq 0.1,\ Z_2 \geq 0.05,\ Z_3 \geq 0.65. \quad (1)$$

The specific formula design is shown in Table 2 and, among them, X_1, X_2, and X_3 represented the coding representative values of iron tailings, cement, and earth, and Z_1, Z_2, and Z_3 represented the actual percentages of iron tailings, cement, and earth, respectively (Figures 2 and 3). The specific conversion of X_i and Z_i is shown in Equation (2), expressed as follows:

Table 1: Composition percentage of iron tailings.

SiO_2	Al_2O_3	Na_2O	MgO	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Other
65.58	9.87	1.59	3.34	0.21	3.10	2.95	0.12	0.25	7.59	5.40

Table 2: Test ratio design of modified soil materials.

Test marshalling	Coding component			Experimental mix ingredients		
	X_1	X_2	X_3	Z_1	Z_2	Z_3
TS1	1	0	0	0.3	0.05	0.65
TS2	0	1	0	0.1	0.25	0.65
TS3	0	0	1	0.1	0.05	0.85
TS4	1/2	1/2	0	0.2	0.15	0.65
TS5	0	1/2	1/2	0.1	0.15	0.75
TS6	1/2	0	1/2	0.2	0.05	0.75
TS7	2/3	1/6	1/6	0.23	0.08	0.68
TS8	1/6	2/3	1/6	0.13	0.18	0.68
TS9	1/6	1/6	2/3	0.13	0.08	0.78
TS10	1/3	1/3	1/3	0.17	0.12	0.72

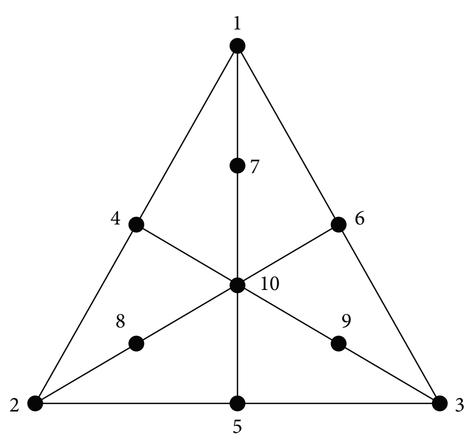


Figure 2: Restricted area.

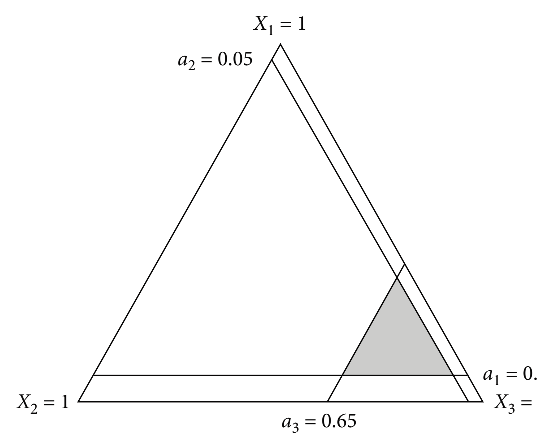


Figure 3: Test site.

$$Z_i = \left(1 - \sum_{j=1}^{3} a_j\right) X_i + a_i, \quad (2)$$

with a_1, a_2, and a_3 representing the minimum percentages of the three components. Substituting $a_1 = 0.1$, $a_2 = 0.05$, and $a_3 = 0.65$ into Equation (2) yields:

$$Z_1 = 0.2X_1 + 0.1; Z_2 = 0.2X_2 + 0.05; Z_3 = 0.2X_3 + 0.65. \quad (3)$$

2.3. Preparation and Maintenance of Specimens. According to the actual mixing ratio (Table 2), there were 60 specimens in total, divided into 10 groups of six each, with six pure earth specimens were produced as a control group. The experiment was carried out on the basis of the production method, maintenance conditions, and test method of previous studies by this research group [17]. This method can be used to press earthen bricks, which can be scaled up as an industrial brick production process. The method for making test specimens was as follows: The cube test model was first laid flat on the counterforce frame, and then lubricating oil applied to the cube test mold containing the same amount of soil. The sample was then loaded in three replications, with the thickness of each layer at 50 mm. The jack moved at a rate of 0.5 mm/s, and the control compaction load at 18–20 kN. After one layer was pressed, it was left stagnant for 3–5 min and the pressure plate then lifted. When the subsoil sample was added, the contact surface of the subsoil sample was roughened. After compaction, the height of the soil beyond the top of the test mold was <5 mm. The upper surface of the specimen was grounded with a soil-dressing

(a) (b)

Figure 4: (a) Fabrication device. (b) Molding specimen.

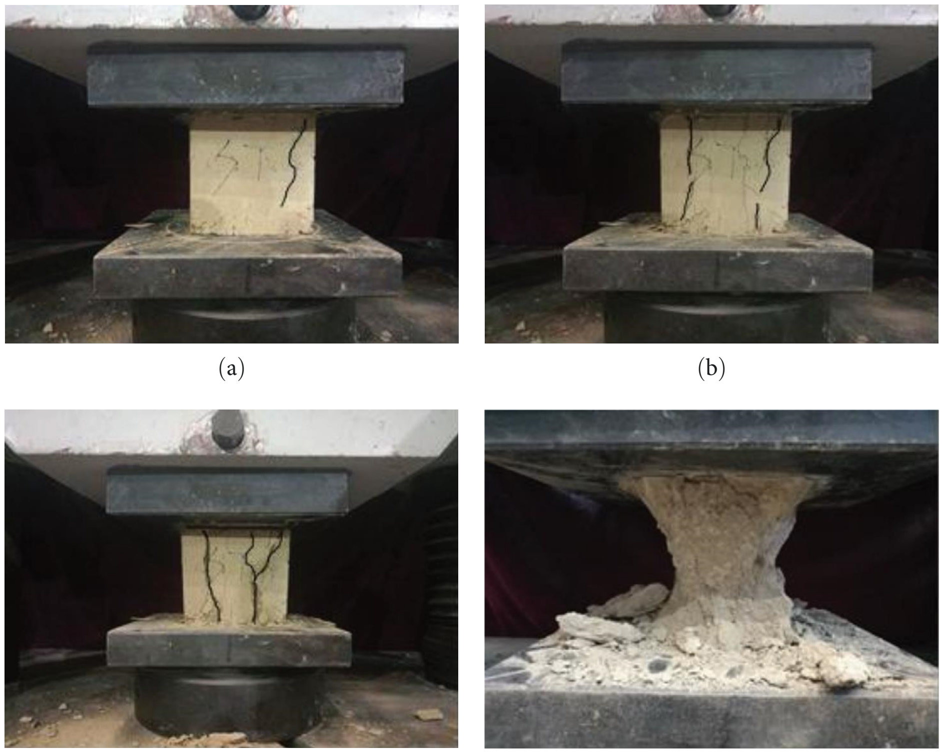
Figure 5: YDL1000 testing machine.

knife and the die removed. This sample-making process is shown in Figure 4, including the test piece fabrication device and a completed test piece. After fabricating the test pieces, they were placed in a room with a relative humidity of 30%–40% at 25–30°C for 28 days [17].

2.4. Compressive Strength Tests. These experiments were carried out in the Construction Engineering Structural Laboratory of Chang'an University. The pressure testing machine was a YDL1000 electrohydraulic servo universal testing machine, which can automatically output the relationship between the displacement and load during a test (Figure 5). Before a test, the flatness of the specimen was checked with a spirit level and ground if necessary. Then, the specimen was centered and place horizontally on the ball-spinning support. Loading was controlled by displacement and the loading rate set at 2 mm/min. When the load reached 70% of peak load, the test was considered to be ended. Following the test, the experimental data were used to construct a σ–ε curve, with σ as the longitudinal axis and ε as the transverse axis (specimen deformation/height 100 mm). The σ and ε data were collected after the peak load was reached and these data were used to construct a second curve. Before formal measurements, the system was prepressure tested to ensure that the press ran normally and in close contact with the specimen before starting the experiment.

3. Test Process and Phenomenon

3.1. Test Process and Phenomenon of Earth Specimens. In the initial stage of loading, no cracks appeared on specimen surfaces. As pressure increased, cracks first appeared at specimen weak corners and corner cracks expanded downward from oblique and vertical cracks. The cracks were wide in the upper part and narrow in the lower part and there are many bifurcated and small cracks around the main cracks, which developed and extended from different directions. At the same time, a number of cracks gradually appeared on the upper end of the specimens and gradually extended downward and the soil skin between the cracks gradually fell off. When the pressure reached about peak load, a number of small cracks began to sprout at the lower end of the specimen and developed vertically or obliquely upward. These finally connected with the downward-developing corner cracks and the middle crack at the upper end of the specimen, forming two to three main through-reaching cracks, which divided the specimen into three to four parts. These cracks were gradually separated from each other, with the specimen, thus, in the shape of being large at the top and narrow at the bottom and, finally, the specimen seriously damaged. By peeling off the soil blocks around the test piece, the failure mode of the test piece was observed to be an "hourglass type" (Figure 6).



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

Figure 6: Experimental process of soil specimens. (a) Crack generation. (b) Crack propagation. (c) Specimen failure. (d) Hourglass-shaped failure.

3.2. Test Process and Phenomenon of Modified Earth Specimens. Compression tests of modified specimens were basically similar to those of earth specimens. The difference was that, after the specimen cracked, crack development was dominated by vertical crack development, supplemented by oblique development. At the same time, there were very few small cracks around the main crack and there were no small cracks at all. When the load reached the ultimate load, the main cracks linked up to each other and, for some specimens, there were some transverse cracks between the main cracks. The damage also showed an "hourglass shape" (Figure 7).

4. Test Results and Analysis

These compressive strength of each group of specimens was calculated according to Equation (4) and the average compressive strength of each group taken as the final compressive strength of each group (Table 3).

$$P = F/A, \tag{4}$$

where P is the compressive strength, MPa; F is the ultimate load borne by a specimen, kN; and A is the cross-sectional area of the specimen, mm^2.

4.1. Destruction Form. The failure forms of earth and modified earth specimens were basically similar. Cracks mostly started at the corners of specimens or where specimen edges were weakly stressed and the cracks gradually expanded to penetrate and fail as tests progressed. Destruction was in the form of an "hourglass type," the reason for which was that specimens were subjected to a "restraint effect" by the upper and lower bearing plates of the test instrument during the compression process. During experiments, modified earth specimens were found to have better compressive performance than the plain soil specimens. Except for TS1 and TS3, the ultimate load of modified raw soil samples was higher than that of plain soil samples and the compressive performance of these samples improved.

4.2. Compressive Strength. The average compressive strength of the earth samples was 1.69 MPa (Table 3). Except for TS1 and TS3, the average compressive strengths of the other earth samples modified by iron tailings and cement were significantly higher than the average compressive strength of earth samples. The compressive strength was 1.55–5.62 times of the average compressive strength of the earth specimens.

Comparing TS3, TS6, and TS1, when the cement content was 5% and tailing content varied from 10%, 20%, and 30%, the compressive strengths of specimens were seen to be 1.35, 1.77, and 1.13 MPa, respectively. The compressive strengths showed a trend of increasing at first and then decreasing. Comparing TS9 and TS7, when the cement content of both was 8% and tailing content changed from 13% to 23%, the compressive strengths of specimens were seen to be 2.62 and 3.71 MPa, respectively, and the compressive strength showed

FIGURE 7: Test process of partial modified soil specimens. (a) Crack generation. (b) Crack propagation. (c) Specimen failure. (d) Hourglass-type failure.

TABLE 3: Test results of each group.

Specimen grouping	Peak load mean (kN)	Peak displacement mean (mm)	Mean value of limit displacement (mm)	Compressive strength		
				Mean value (MPa)	Standard deviation	Coefficient of variation
Earth	16.87	3.19	4.61	1.69	0.19	0.11
TS1	11.27	2.65	3.44	1.13	0.23	0.21
TS2	94.97	4.06	6.05	9.5	1.98	0.21
TS3	13.48	3.66	5.13	1.35	0.05	0.04
TS4	72.45	3.38	4.32	7.25	0.79	0.11
TS5	63.38	3.58	5.24	6.34	0.36	0.06
TS6	17.68	2.9	3.76	1.77	0.31	0.17
TS7	37.07	3.41	4.32	3.71	0.54	0.15
TS8	48.33	4.12	5.22	4.83	0.42	0.09
TS9	26.23	3.14	3.98	2.62	0.54	0.21
TS10	27.89	2.78	3.65	2.79	0.81	0.29

an increasing trend. When the cement content was constant, the reasonable content of tailings should be between 15% and 20% and, when the tailing was <20%, the compressive strength of specimens generally increased with tailing content, increasing with increased tailing content.

Comparing TS2, TS3, TS5 or TS4, TS6 or TS8 and TS9, it can be seen that, when the content of iron tailings was constant, the compressive strengths of specimens were seen to increase with increased cement content.

Taking the X-axis as the iron tailing content, Y-axis as cement content, and Z-axis as compressive strength, a scatter diagram of the modified material content and compressive strength was created (Figure 8). This showed that the content of iron tailings and cement directly affected the compressive strength of the modified earth specimen (Figure 8 and Table 3). When tailing iron content was low and cement content was large, the compressive strengths of specimens were maximum. Among them, the influence of cement was

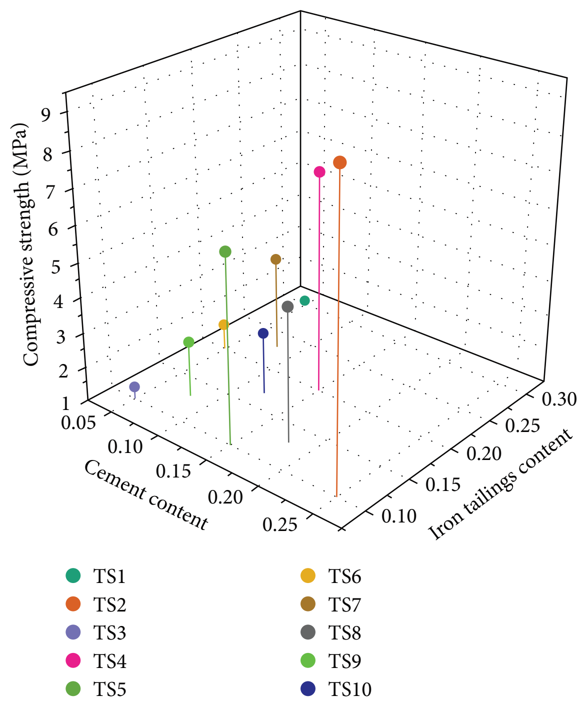


Figure 8: Scatter diagram of modified material contents and compressive strength.

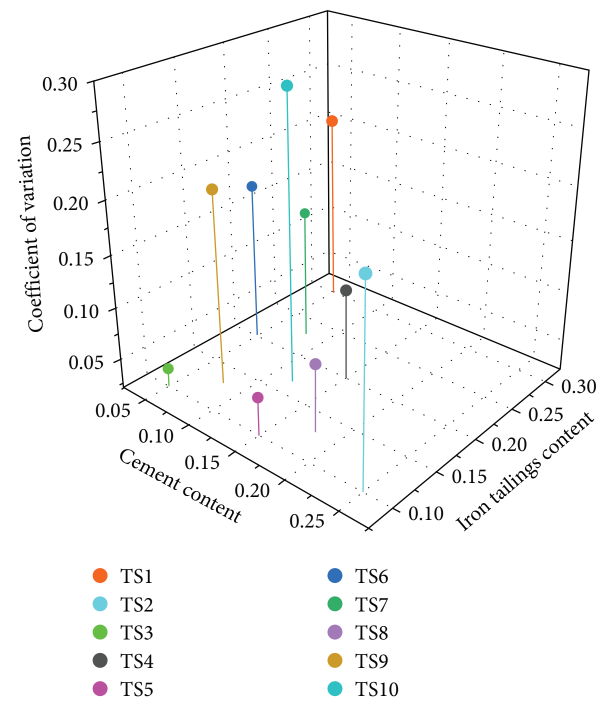


Figure 9: Scatter diagram of variation coefficient of iron tailing and cement content and compressive strength.

the most significant but, considering the environmental protection factor, the amount of cement in the modified specimen should not be too large and iron tailings should be used to the maximum extent. Thus, the suggested tailings content should be 20% and cement content should be 15%, such that TS4 formula appeared the most reasonable.

4.3. Compressive Strength Dispersion. Earth specimens were a complex system and the addition of admixtures changed the composition, structure, and properties of the specimens, which led to different changes in the compressive strengths of modified specimens. Therefore, studying the variation trends of the dispersion degree of compressive strength under each admixture was a guiding role for the selection of the content of each admixture.

Taking the X-axis as the iron tailing content, Y-axis as cement content, and Z-axis as coefficient of variation of compressive strength, a scatter diagram of the content of modified material and the coefficient of variation of compressive strength was drawn (Figure 9). This showed that, when the cement content was constant, the coefficient of variation of TS3, TS6, TS1, and TS5 and TS4 gradually increased with increased iron tailings content.

With the content of iron tailings constant, the coefficient of variation of compressive strength of TS3, TS5, and TS2 increased with increased cement content, while the coefficient of variation of compressive strength of TS9, TS8, and TS6 and TS4 increased with increased cement content and decreased with increased cement content (Figure 9).

4.4. Load–Displacement Curves. Stress–strain curves of earth and modified earth materials under each group of formulas were drawn and the curves under each formula observed to be basically similar (Figure 10). Also, the stress–strain curves were divided into two parts: ascending and descending sections. The ascending section was subdivided into three substages, namely the specimen compression stage, approximate elastic stress stage, and inelastic stress stage. The descending section involved the failure stage of the specimen.

Comparing the stress–strain curves of TS3, TS6, and TS1, it was seen that, when the cement content was 5% and tailings content was 10%, 20%, and 30%, the slopes of the three groups of curves showed a steeper slope. After increasing, they decreased, with the TS1 group having the lowest slope. The six curves in the TS3 group were closely arranged and the ultimate load of each curve mainly concentrated around 1.4. In addition, the ultimate strain displacement concentrated around 0.04, indicating that the degree of dispersion of the specimens in this group was small. However, the six curves in TS1 and TS6 groups were sparsely arranged and the limit stress and limit strain between the curves varied greatly, indicating that the two TS1 and TS6 groups possessed large dispersion. When the cement content was constant, increased tailing content was concluded to accelerate dispersion of modified materials.

Comparing the stress–strain curves of TS3, TS5, and TS2, when the content of iron tailings was 10% and cement content was 5%, 15%, and 25%, the slope of the curves and ultimate stress increased, with the increase in TS2 the largest. The curves of these three groups also showed that increased cement content had little effect on strain under ultimate stress of the modified material, with the strain under ultimate stress of the three groups of curves concentrated around 0.04. The compactness of the six curves in TS5 and TS2 groups

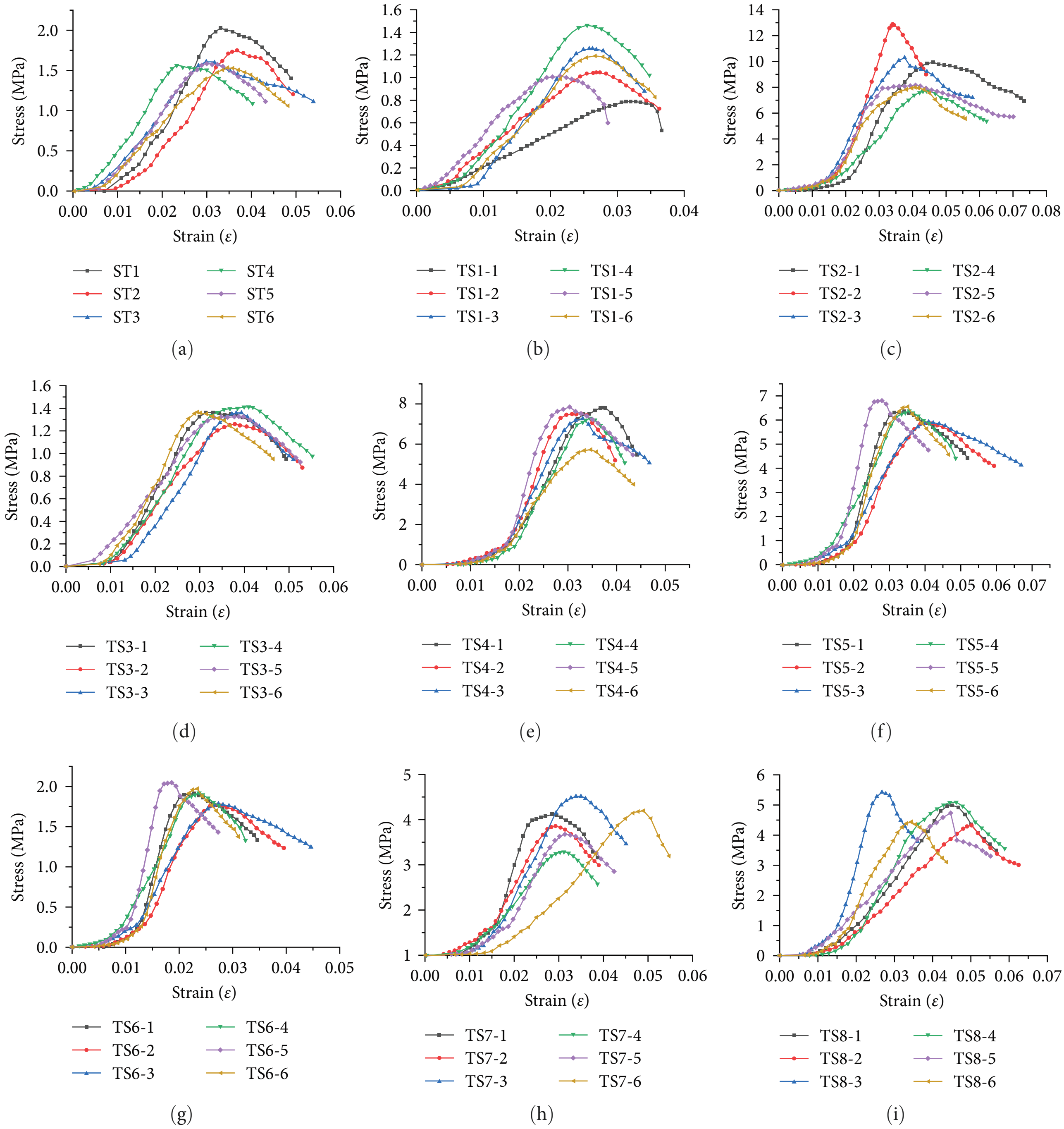


Figure 10: Continued.

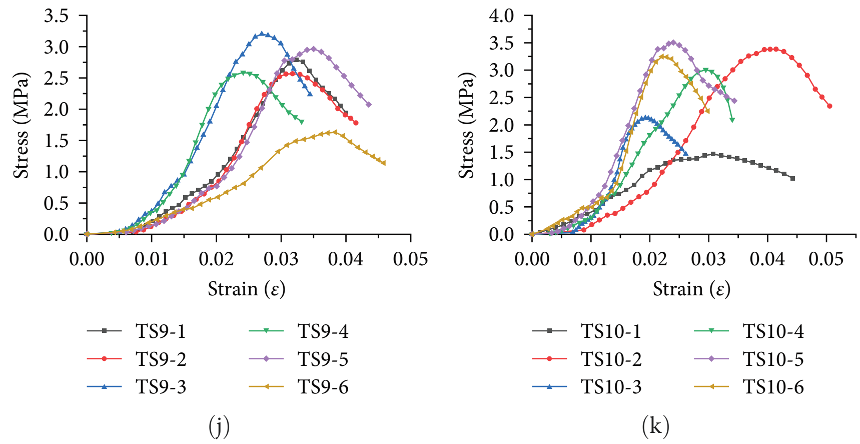


Figure 10: Stress–strain curves for the soil and modified soil. (a) Soil stress–strain curve. (b) TS1 stress–strain curve. (c) TS2 stress–strain curve. (d) TS3 stress–strain curve. (e) TS4 stress–strain curve. (f) TS5 stress–strain curve. (g) TS6 stress–strain curve. (h) TS7 stress–strain curve. (i) TS8 stress–strain curve. (j) TS9 stress–strain curve. (k) TS10 stress–strain curve.

was sparser than that of TS3 and the sparseness of TS6, TS5, and TS3 in order from small to large. Therefore, increased cement content aggravated the dispersion of modified materials. When the tailing content was constant, the cement content was seen to have a greater impact on the strength and dispersion of modified materials but had less effect on the deformation. The strength and dispersion of the modified materials increased with increased cement content.

4.5. Mechanism Analysis. The mechanical properties of materials were closely related to material composition. The modified materials were a mixture composed of soil, cement, and iron tailings, and its mechanical properties the results from interactions of the three.

The main chemical composition of loess and iron tailings was SiO_2 and the chemical properties were very stable. In the process of making a test piece, loess and tailings were fully mixed and the tailings entered gaps in the modified material, thus reducing the gaps in the test piece and increasing its density. Cement is mainly composed of clinker tricalcium silicate (C_3S) and dicalcium silicate (C_2S), with active chemical properties. Cement clinker chemically reacts with water to form colloids, such as calcium silicate hydrate ($3CaO{\cdot}2SiO_2{\cdot}3H_2O$) and $Ca(OH)_2$. A large amount of $Ca(OH)_2$ and SiO_2 will further react slowly at room temperature and form calcium silicate (Ca_2SiO_4). A large amount of hydrated Ca_2SiO_4 and $Ca(OH)_2$ and other gels wrapped on the surface of soil particles. Iron tailings gradually formed a cohesive structure and further filled voids inside the modified material. As curing progressed, the gel material gradually hardened and cemented the soil particles and tailings into a solid whole, thus stabilizing the loose state of the soil and tailings. At the same time, compactness of the specimen was improved and specimen resistance to external force increased. Therefore, the mechanical properties of modified earth specimens were generally higher than those of pure earth specimens [19].

Some of modified earth specimen compressive strengths were always higher than those of pure earth specimens. The compressive strengths of TS3 and TS1 were lower than those of pure earth specimens, the reason for which was that both the cement contents of TS3 and TS1 were 5%, which was low (Table 3). The tailing content in TS3 was 10% and the content too low to completely fill gaps between the soil of the specimens or to give full play to the role of aggregate. However, the tailing content in TS1 was 30% and the content too large, which increased the specific surface area of the tailings and the contact area between soil particles and tailings in the specimen accordingly increased. This resulted in more weak surfaces in contact surfaces of the two heterogeneous materials and, under the action of pressure, weak surfaces were easily damaged. This resulted in the compressive strengths of TS1 and TS3 being lower than those of plain soil specimens.

The discreteness of compressive strength showed that the stability of compressive strength of the modified earth materials depended on the compositions and important for stable building materials in construction projects. The effects of the addition of iron tailings and cement in modified earth material examined in this study involved samples composed of three different materials, varying from the original system composed of a single earth component and resulting in a changes in sample composition. These complex specimens showed different mechanical properties under the action of force. When the cement content was constant, with increased tailing content, the distribution dispersion of tailings in specimens also increased, which reduced the uniformity of the distribution of each component of modified specimens. Meanwhile, the difference in mechanical properties among the components increased, which led to an increased degree of dispersion of compressive strength in modified specimens.

From Section 2.3, when the iron tailing content was constant, the compressive strength dispersion of modified earth specimens was seen to increase or decrease with increased cement content. For example, the compressive strength dispersion of TS3, TS5, and TS2 increased, while the compressive strength dispersion of TS9, TS8 and TS6, TS4 decreased. The main reason for this was that the tailing content of TS3, TS5, and TS2 was low at 10%, which had little effect on overall specimen performance. With increased cement

Table 4: Analysis of formula test frequency of iron tailings and cement-modified earth materials.

Level	X_1		X_2		X_3	
	Number	Frequency	Number	Frequency	Number	Frequency
0	4	0.363	0	0	6	0.545
0.1	2	0.182	0	0	1	0.091
0.2	0	0	1	0.091	1	0.091
0.3	0	0	1	0.091	1	0.091
0.4	1	0.091	1	0.091	1	0.091
0.5	1	0.091	2	0.182	1	0.091
0.6	1	0.091	2	0.182	0	0
0.7	1	0.091	1	0.091	0	0
0.8	1	0.091	2	0.182	0	0
0.9	0	0	1	0.091	0	0
1	0	0	0	0	0	0
Weighted mean	0.291		0.573		0.136	
Standard error	0.095		0.066		0.056	
95% confidence interval	0.105–0.477		0.444–0.703		0.027–0.246	
Actual proportion of each component	0.121–0.195		0.139–0.191		0.655–0.699	

content, cement hydration increased and hydration products increased. These hydration products play a leading role in the discreteness of compressive strength, which resulted in the uneven distribution of components and increased differences in mechanical properties of modified specimens. This, thus, affected the discreteness of compressive strengths in modified specimens. For TS9 and TS8, and TS6 and TS4, the tailing contents were, respectively, 13% and 20% and the proportion of iron tailings large, which had a great impact on the overall performance of specimens. With increased cement content and increased hydration products, a large amount of hydration product gel combined with excessive iron tailings and soil particles, such that the tailings and soil particles had a better bonding effect, which ensured specimen integrity. In the process of applied stress, the mechanical properties of the three could have played a relatively uniform role and, hence, the coefficient of variation deceased. However, the coefficient of variation still increased as cement content continued to increase.

4.6. Regression Analysis and Frequency Optimization. To demonstrate the relationship between the compressive strength and the coding of each component more accurately, the {3,3} cubic polynomial was used to establish the relationship between the compressive strength (Y) of modified earth specimens, with iron tailings (X_1), cement (X_2), and earth (X_3) regression equations between the codes.

The Design Expert software was used to carry out the regression analysis and a statistical model established (Tables 2 and 3), expressed as follows:

$$\begin{aligned} Y = {} & 1.13X_1 + 9.5X_2 + 1.35X_3 + 7.72X_1X_2 \\ & + 2.1X_1X_3 + 3.64X_2X_3 - 73.8X_1X_2X_3 \\ & + 33.16X_1X_2(X_1 - X_2) - 8.84X_1X_3(X_1 - X_3). \end{aligned} \tag{5}$$

The significance test of Equation (5) also was performed and the correlation coefficient was found to be $R = 0.9997$, which indicated that this model well fit the proportional relationship between the strength of the modified earth material and tailings, cement, and earth formulations.

According to Sections 2.2 and 2.3, the differences in iron tailings and cement contents directly affected the compressive strength and discreteness of the modified earth specimens. Therefore, it was necessary to find a reasonable proportion of iron tailing and cement to produce a positive impact on the project practical guidance.

In this study, frequency analysis and optimization of statistical models were carried out [17, 20]. The step size of the three factors X_1, X_2, and X_3 was set to 0.1, each factor having 11 levels: 0–1 and each factor code X_i satisfying the conditions: $0 \le X_i \le 1, \sum_{X_i=1}^{3} X_i = 1$. For different treatment combinations of compressive strength and iron tailing, cement, and earth dosages, 66 combination schemes were optimized by frequency analysis. According to test data analysis, the compressive strength range was set between 6 and 9 MPa, that is, $6 < Y < 9$ MPa. There were 11 of the 66 schemes that meet these requirements, accounting for 16.7% of all schemes. The relevant frequency analysis is shown in Table 4.

According to the value of X_i in the 95% confidence interval and the conversion relationship between X_i and Z_i 1–3, the actual value of each mixture component Z_i was obtained (Table 4). Studies have shown that, when the iron tailing content was 12.1%–19.5%, cement content was 13.9%–19.1%, and earth content was 65.5%–69.9%, the resistance of tailing and cement-modified earth specimens was improved. The compressive strength had a 95% guarantee rate between 6 and 9 MPa.

5. Conclusions

This reported study used the single lattice theory to examine the mechanical properties of modified earth specimens mixed with iron tailings, sand, and cement. Data obtained from compressive strength tests of the experimental materials were used as the basis for comparison. Using the data for the material strength, stress–strain curves, and dispersion analyses, it was shown that iron tailings, sand, and cement could be used as modifying materials for building earth structures. Frequency domain analysis was introduced to establish the optimal mix ratio of earth, iron tailings, sand, and cement, which provided a reference for the application of earth modification engineering in Northwest China.

(1) The data showed that the addition of iron tailings and cement can improve the compressive strength of earth materials, with iron tailings proving to be exceptional when used in modified earth admixtures. From the test results, it was observed that the forms of failure of the iron tailing and cement-modified specimens were basically similar to those of the unmodified earth specimens.

(2) The addition of iron tailings and cement provided a significant improvement in the dispersion of the modified earth's compressive strength, increasing its compressive strength. When the cement content was constant, the discreteness of the compressive strength in the modified specimens increased with increased tailings content. When the tailings content was constant, the discreteness of compressive strength in the modified specimens increased with increased cement content. At the same time, the stress–strain curves of tailings and cement-modified earth materials were similar.

(3) The compressive properties of iron tailing and cement-modified earth materials were significantly improved. On one hand, due to cement hydration, a large amount of gel was generated and this gel bonded together the soil particles and tailings, which increased the stability of the soil and the antislip ability between the contact surfaces. On the other hand, iron tailings themselves are relatively hard and acted as aggregates in the soil. Therefore, the compressive strength and deformation of earth materials modified with iron tailings and cement were improved.

(4) Iron tailings and cement played a significant role in improving the compressive strength of earth materials. When the cement content was constant, a reasonable content of iron tailings should be between 15% and 20% and, when the content of iron tailings was <20%, the compressive strength of the specimens generally increased with increased tailings content. According to the statistical and frequency analyses, the optimal material ratio range was a tailings content of 12.1%–19.5%, a cement content of 13.9%–19.1%, and an earth content of 65.5%–69.9%.

Data Availability

All data generated or analyzed during this study were included here.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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