

Research Article

Study on the Modification Formula of Earth Material Compound with Cement and Gravel by Single Lattice Theory

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Received 21 June 2019; Revised 13 August 2020; Accepted 3 December 2020; Published 21 December 2020

Academic Editor: Lei Wang

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Gravel and cement can effectively improve the low strength of traditional Earth materials. There have been few studies on test methods for raw soil-based composite admixtures. By introducing the theory of single lattice formula testing, the compressive strength of 10 formulas and 60 modified raw soil cubic specimens were tested. The failure process, failure mode, and compressive strength of specimens were studied. The effects of different formulations of raw soil on strength, peak displacement, and dispersion were analyzed. The results showed that cement content had a significant effect on the compressive strength and dispersion of earth material specimens. The optimal modification formula of cement, gravel, and raw soil was determined to be 0.1/0.08/0.82 (mass ratio). At the same time, the applicability of the test method was verified, which can be used as a reference for the experimental study on modification formulations of earth materials.

1. Introduction

Earth materials are some of the oldest local building materials and are widely used in dwelling construction all over the world. In fact, one-third of the world's population still lives in earthen dwellings [1, 2]. In the last twenty years, this original material has gained new attention from the construction industry because of its low energy consumption and excellent ability to regulate indoor temperature and humidity [3, 4]. As an important part of traditional architecture, it has the advantages of low energy consumption, good thermal performance, sound absorption, radiation, and environmental protection and can serve as a model for "green architecture" [5–7]. However, the weak strength of raw materials for native construction has always been considered a drawback by structural engineers. Therefore, there has been much research on the modification of raw earth materials all over the world. At present, the modification methods of raw soil materials can be divided into

physical modification, mechanical modification, and chemical modification [8, 9].

Physical modification is to select well graded soil material or add reinforced material into soil material [10]. Mechanical modification refers to the modern manufacturing process. Mechanical dynamic compaction is used to increase the compactness of raw soil foundation blocks [11]. Chemical modification is the incorporation of chemical reagents into materials [12]. Among the main curing agents in modifying earth materials are cement, lime, and fly ash. Spence and Cook of the University of Chichester have studied the modification of earth materials with a certain amount of cement and carried out experiments with Alfred et al. Their results showed that when the cement content is 5%, cement solidified. Also, adobe has good durability and water absorption performance [13, 14]. Stephane Hans of the University of Lyon and others have proposed the modification of raw soil materials with cement and lime and calculated the damage of existing native

buildings in earthquakes [15]. Steve Burroughs of Australia has done stability testing to quantify the linear shrinkage of natural soils and the amount of cement and lime mixed into them [7]. Milani and Labaki studied the sustainability of the original soil materials and evaluated the modified soil materials mixed with cement and lime. The results showed that 7.5 wt% lime and 10 wt% cement have been mixed into the soil to obtain promising mixture materials [4]. Ziegler used fiber materials to modify the raw soil-based materials. This method formed a three-dimensional fiber network inside the materials, which significantly improved the compressive strength and shear strength of the raw soil-based materials [16].

In a word, experimental results have been obtained in the earth modification field. However, the traditional orthogonal test cannot completely solve the problem of modifying material formulas. A single admixture and test methods are not unified from different studies and the existing research results scattered. Modified additives of materials often have complex chemical reactions in soil and modified earth materials are not green and environmentally friendly. In this study, based on the theory of single grid test design, the composite test of raw soil materials with multiple admixtures is carried out. Using physical modification methods according to research results from this research group, a modified formula test was carried out with gravel (gravel, 10–20 mm diameter), cement, and raw soil [17]. The modified formula of earth material was studied using the Voth single lattice model [18, 19]. Sixty specimens were produced for compressive strength testing and the strength, peak displacement, discrete reference parameters, parameter analysis, and elimination element regression were used to draw a triangular contour map. From these results, a reasonable modification test method and formula were presented. The research provided suggestions for similar studies in the future.

2. Voth Single Lattice Theory

In the design of the test, the test level is a factor of each factor accounted for in the proportion of the total, with the percentage of all P factors in the experiment being the percentage of the total. The total composition must be equal to 1 (100%). This kind of design is called formula design, also known as mix design [20].

The level values of P factors in formulation design were

$$x_1, x_2, x_3, \dots, x_p \quad (0 \leq x_i \leq 1, 0 \leq i \leq p). \quad (1)$$

Here, $\sum_{i=1}^p x_i = 1$, x_i is called the scaling factor. If using geometric terms, with p called the dimension, x_i is a point on the P -dimensional plane in Hypothesis 3 factor formulation test. According to P component variables x_i ($0 \leq i \leq p$) in the formulation design. Here, y is the response variable and the mathematical model can be established:

$$y = f(x_1, x_2, \dots, x_p) + \varepsilon, \quad (2)$$

where ε is the random error and observation values y_1, y_2, \dots, y_n from reaction variables n times. The regression

coefficient of the function was estimated and the regression equation obtained:

$$\hat{y} = f(x_1, x_2, \dots, x_p). \quad (3)$$

The above is a polynomial of degree d and the formula test determined by the number of factors P and the number d of directional functions. A formula test was represented by $M\{p, d\}$. Thus, it was also called a single lattice design. Here, $p = n$, $d = m$.

A significance test of multivariate linear regression equation by F -test was used with the square sum (SS_T), the regression square sum (SS_R), and the sum of squares of residuals (SS_e), and F and R^2 are calculated finally.

After passing the F -test, the regression equation was solved and the isoline map drawn as a triangular coordinate map to determine the optimal mixing ratio.

In the design of the single lattice formulation, there was no restriction on x_i ($0 \leq x_i \leq 1$ and $0 \leq i \leq p$). For the formulation design of restricted ingredients, restricted ingredients were expressed in terms of z . If there are lower bounds, upper bounds, or both upper and lower bounds for component z_i , L_i represented the lowest proportion of component i and the highest proportion of component U_i , that is, the upper and lower bounds of z_i . The hypothesis was

$$z_1 + z_2 + \dots + z_p = 1 \quad 0 \leq L_i \leq z_i \leq U_i \leq 1 \quad 0 \leq i \leq p. \quad (4)$$

Because the formula test area was simple, the original ingredients could be changed. A new set of components was defined in the executable formulation area and the change range of the new components still between 0 and 1. The appropriate formulation design structure model was obtained in the restricted area. The component was redefined as the L -coding component. The coding component x_i of i was

$$x_i = \frac{z_i - L_i}{1 - L_i}, \quad (5)$$

$$L = \sum_{i=1}^p L_i \leq 1,$$

where z_i was the actual occupancy ratio after conversion.

3. Experimental

3.1. Experimental Design. According to the previous research results in this research group, adding cement materials to raw soil improves soil cohesion and adding gravel filled pores in the raw soil, thus improving the overall mechanical properties of the material. The cement content was not <3 wt% and the gravel content not <5 wt%. As raw soil was the main material, the content cannot be <75 wt%. Here, z_1 was cement, z_2 gravel, and z_3 raw soil:

$$z_1 + z_2 + z_3 = 1 \quad z_1 \geq 0.03 \quad z_2 \geq 0.05, \quad z_3 \geq 0.75. \quad (6)$$

Because there were three kinds of admixtures, the triangle single grid method was adopted, and ten points in the graph were selected as test-coding points. A single lattice

test-coding diagram is shown in Figure 1 and a limit zone diagram of cement, gravel, and raw soil content in Figure 2. The black spot in Figure 1 is the test mix ratio. Photocopy in Figure 2 is the limited area of material composition.

As can be seen from Section 2 and formulas (4) and (5), $z_{1nsi} = 0.03 + 0.17x_{1nsi}$ ($i = 1-10$), $z_{2nsi} = 0.05 + 0.17x_{2nsi}$ ($i = 1-10$), and $z_{3nsi} = 0.75 + 0.17x_{3nsi}$ ($i = 1-10$).

The calculation results of the experimental grouping formula are shown in Table 1.

3.2. Materials. Soil samples used in this test were loess from the Chang'an District of Xi'an City in China. The optimal loess moisture content was 18.2% and maximum dry density at 2.04 g/cm^3 , according to "Standard of Geotechnical Experiment Methods" (Geotechnical test method standard, 1999) (GBT50123-1999), with the plastic limit at 15%, liquid limit at 26%, and plastic index at 11.3 [21]. The results are shown in Table 2. At the same time, the sieving test of loess is carried out, and the results are shown in Table 3 (the particle size distribution). The gravel was gravel 10–20 mm in diameter. The strength of the cement was 32.5 ordinary Portland cement (School of Civil Engineering, Chang'an University, Xi'an 710061, China, Shaanxi Qinling Cement). Referring to previous research of this research group, the optimal moisture content of raw soil materials mixed with cement was determined [22]:

$$\omega = \omega_0 + 0.27\phi, \quad (7)$$

where ω is the optimal moisture content of modified raw soil, ω_0 at 18.2%, and ϕ the cement content. The moisture content of each group of specimens with a cement-modified formula is shown in Table 4.

Before experimentation, the earth was passed through a 5 mm sieve and mixed to optimal moisture content; see Table 4 for water mixing materials. Using a mold developed by this research group, 60 samples of $100 \times 100 \times 100 \text{ mm}$ cubes were prepared from each earth using a method of jack compression. The preparation device and sample are shown in Figure 2 [23].

3.3. The Loading Device. Molded specimens were cured in a standard curing room and then tested for compressive strength. Here, the specimens were placed in a room at $25-30^\circ\text{C}$ and 55–60% humidity to cure for 28 d. Using an MTS-500 universal uniaxial load tester (Manta Testing Systems Inc., Mississauga, Canada), test data regarding the relationship between displacement and load was automatically collected. A sample was centered and placed horizontally on the ball support, with the sample in close contact with the machine before test initiation. The loading rate was set to 1 mm/min and 30% of the peak load taken as the final condition of a test after peak loading, which ensured normal machine operation. The test procedure is shown in Figure 3.

At the initial stage of loading, cracks did not immediately appear on soil cube surfaces and no other visible cracks appeared. With increased load, specimen corners cracked, cracks developed along the specimen's stress direction, and

the specimen did not immediately break. As the load continued to increase to peak load, many vertical cracks appeared on the test piece surface, along with swelling cracks on the piece's middle surfaces, and portions of the skin soil fell off. With further increased load, cracks continued to develop until the specimen was completely destroyed, accompanied by rapidly decreased load, bearing capacity loss, and failure mode appearing as a typical "hourglass."

4. Results and Discussion

4.1. Compressive Strength Analysis. The average value of protest strength of each group of specimens is taken as the compressive strength of the test samples. The experimental results are shown in Table 5.

Referring to Table 5, the compressive strength of the modified raw soil with gravel and cement is significantly higher than that of the raw soil. The compressive strength of the modified specimen is 1.16–3.55 times that of the raw soil specimen.

Compared with NS3, NS5, and NS2 group, when the cement content is 3% and the gravel content is 5%, 13.5%, and 22%, the compressive strength of the specimen is 5.77 MPa, 4.39 MPa, and 3.75 MPa. The results show that when the cement content is fixed, the strength of the specimen decreases with the increase of the gravel content.

Compared with NS3, NS6, and NS1 group, when the gravel content is 5% and the cement content is 3%, 11.5%, and 20%, the compressive strength of the specimen is 5.77 MPa, 8.87 MPa, and 11.51 MPa. The results show that when the gravel content is fixed, the strength of the specimen increases with the increase of the cement content.

According to a large number of research results, the compressive strength of raw soil-based materials with gravel and cement is higher than that with gravel or cement alone [参考文献]. The strength of gravel is obviously higher than that of soil. However, when the gravel is mixed with the raw soil alone, the bond performance between the gravel and the soil is poor, which leads to the reduction of the time compression performance. As a cementitious material, cement can react with water molecules in the soil to consolidate soil particles and fill the pores in the soil, which improves the particle size distribution and increases the material density. The gravel is wrapped by cement soil and closely bonded, acting as coarse aggregate, playing a skeleton role, and resisting deformation when the material is under pressure, and the material strength is significantly improved.

4.2. Formula Discussion. The raw soil-modified cubic specimens consisted of sand (z_1), gravel (z_2), and raw soil (z_3 , Table 1). There was more than one reaction variable y in the formulation of specimens considering the test results. There were three parameters that reflected the advantages and disadvantages of the modified specimens. The first response variable was the cubic compressive strength (y_1), the second response variable was the cubic peak displacement (y_2), and the third response variable was the cubic Standard deviation (y_3). Integrating Tables 1 and 3 yielded Table 6.

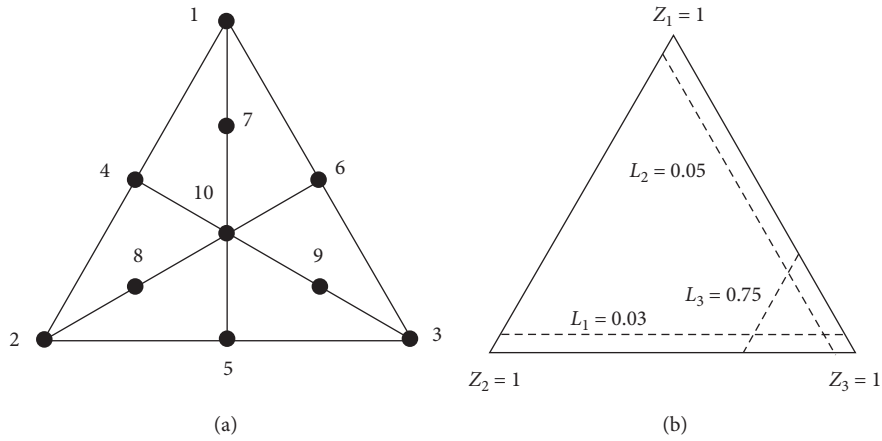


FIGURE 1: (a) Triangular simplex design test points. (b) Limited areas of cement, gravel, and raw soil content.

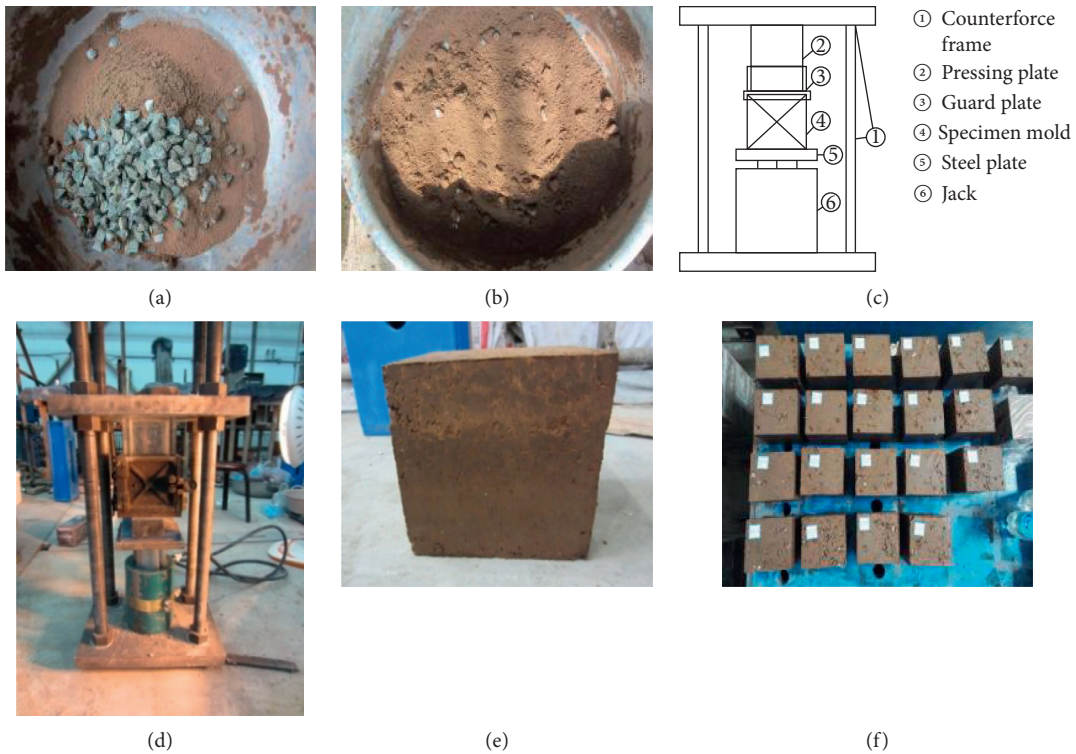


FIGURE 2: Manufacturing equipment and test specimens. Raw material (a), mixture mixing, (b) schematic diagram of the device (c), specimen making (d), specimen (e), and specimen maintenance (f).

(1) Regression analysis of response variable y_1 was carried out with reference to Table 4. The calculation was simplified by examining the first-order polynomial for the regression model $\hat{y} = f(x) = ax_1 + bx_2 + cx_3$ (Table 7), which showed that the coefficient of determination was $R^2 = 0.9249$ by linear regression. According to the F -test, the linear regression equation was significant and the primary regression model concluded to be scientific and reasonable. The polynomial coefficients calculated by MATLAB are shown in Table 8. The corresponding regression equation was $y_1 = 12.23x_1 + 4.13x_2 + 5.92x_3$.

According to the coordinates of the equation solution in Table 9, a contour map corresponding to the equation was drawn in triangular coordinates using Origin 9.0 drawing software (Figure 4).

Parameters x_1 , x_2 , and x_3 represented the admixtures of cement, gravel, and raw soil, respectively (Figure 4). The gradient of the isoline decreased from x_1 point to the x_2x_3 coordinate axis step by step. The isoline basically deviated to the x_1x_2 coordinate axis. The average strength line fell on the x_1x_2 and x_1x_3 axes, which showed that the cement content of these three admixtures played a major role in compressive

TABLE 1: Axis point extended simplex lattice design scheme for cement and gravel mixed with the modified raw soil test.

Test formation	Test coding			Mix ratio of test materials (by wt)		
	x_1	x_2	x_3	z_1	z_2	z_3
NS1	1	0	0	0.20	0.05	0.75
NS2	0	1	0	0.03	0.22	0.75
NS3	0	0	1	0.03	0.05	0.92
NS4	1/2	1/2	0	0.12	0.14	0.75
NS5	0	1/2	1/2	0.03	0.14	0.84
NS6	1/2	0	1/2	0.12	0.05	0.84
NS7	2/3	1/6	1/6	0.14	0.08	0.78
NS8	1/6	2/3	1/6	0.06	0.16	0.78
NS9	1/6	1/6	2/3	0.06	0.08	0.86
NS10	1/3	1/3	1/3	0.09	0.11	0.81

TABLE 2: The index of soil-based materials.

Name	Maximum dry density P_d , (g/cm ³)	Optimum moisture content w_0 , (%)	Plastic limit w_p , (%)	Liquid limit w_L , (%)	Plastic index
Loess	2.04	18.2	15	26	11

TABLE 3: Size distribution of loess screening result.

Particle size (mm)	≥ 4.75	4.75 ~ 2.36	2.36 ~ 1.18	1.18 ~ 0.60	0.60 ~ 0.30	0.30 ~ 0.15	≤ 0.15
Particle content (%)	0.00	14.07	20.63	17.00	14.00	8.40	26.00

TABLE 4: The moisture content of each group of specimens containing cement.

Test formation	NS1	NS2	NS3	NS4	NS5	NS6	NS7	NS8	NS9	NS10
Moisture content	0.23	0.19	0.19	0.21	0.19	0.21	0.22	0.20	0.20	0.20

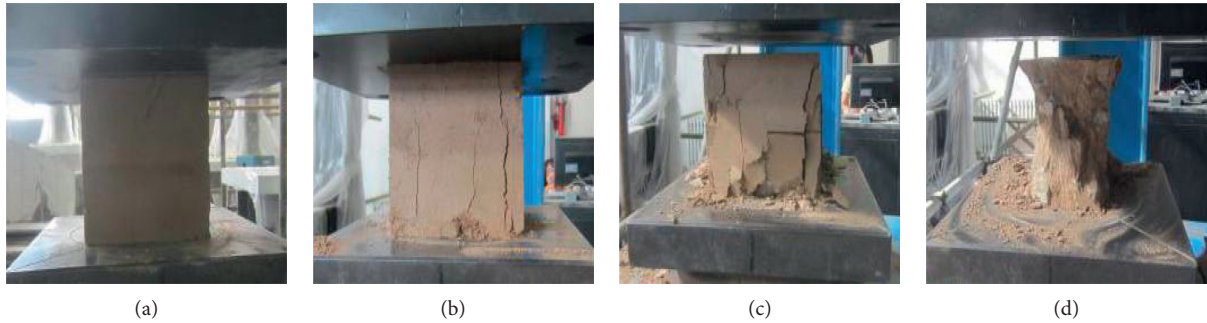


FIGURE 3: Compressive strength tests of raw soil material cubes. Loading (a), cracking (b), damage (c), and completely destroyed (d).

TABLE 5: Test results of compressive strength of specimens mixed with cement, gravel, and raw soil.

Test formation	Peak load (kN)	Peak displacement (mm)	Compressive strength		
			Average of strength (MPa)	Standard deviation	Coefficient of variation
NS1	115.12	3.57	11.51	1.290	0.112
NS2	37.52	2.97	3.75	0.447	0.119
NS3	57.75	4.11	5.77	0.492	0.085
NS4	79.73	3.33	7.97	2.202	0.276
NS5	43.92	3.43	4.39	1.108	0.252
NS6	88.74	3.81	8.87	0.971	0.109
NS7	111.02	3.55	11.10	1.067	0.096
NS8	68.12	3.58	6.81	1.178	0.173
NS9	72.06	3.70	7.21	1.005	0.139
NS10	69.15	3.70	6.91	0.734	0.106
Raw soil	32.42	2.7	3.24	0.393	0.121

TABLE 6: Axis point extended simplex lattice design and the result of lower limit component boundary in mixed cement and gravel modified with raw soil.

Test formation	Test coding			Mix ratio of test materials			Response variables		
	x_1	x_2	x_3	z_1	z_2	z_3	y_1	y_2	y_3
NS1	1	0	0	0.20	0.05	0.75	11.51	3.57	1.290
NS2	0	1	0	0.03	0.22	0.75	3.75	2.97	0.447
NS3	0	0	1	0.03	0.05	0.92	5.77	4.11	0.492
NS4	1/2	1/2	0	0.12	0.14	0.75	7.97	3.33	2.202
NS5	0	1/2	1/2	0.03	0.14	0.84	4.39	3.43	1.108
NS6	1/2	0	1/2	0.12	0.05	0.84	8.87	3.81	0.971
NS7	2/3	1/6	1/6	0.14	0.08	0.78	11.10	3.55	1.067
NS8	1/6	2/3	1/6	0.06	0.16	0.78	6.81	3.58	1.178
NS9	1/6	1/6	2/3	0.06	0.08	0.86	7.21	3.70	1.005
NS10	1/3	1/3	1/3	0.09	0.11	0.81	6.91	3.70	0.734

TABLE 7: Regression analysis of compressive strength of raw soil mixed with cement and gravel.

Source parameter	d_f	SS	MS	F	$p > F$		
Regression	3	SS_R	54.31	MS_R	18.104	28.73	Remarkable
Deviation	7	SS_e	4.41	MS_e	0.031		
Uncorrected summation	10	SS_T	58.72				
	R^2	0.9249					

TABLE 8: Estimation of the partial regression coefficient of y_1 regression equation for compressive strength of mixed cement and gravel modified with raw soil.

Regression term	Partial regression estimation	t-test	$p > \{t\}$	Regression error of partial regression estimation
x_1	12.23	21.34	0.0001	0.573
x_2	4.13	7.22	0.0001	0.571
x_3	5.92	10.32	0.0001	0.571

Combining regression equation y_1 , solving the equation $y_{max} = 11.51$, $y_{min} = 3.75$, range $\Delta = 7.76$, $\bar{y}_1 = 7.43$, gradient $\nabla = 1$, using Mathcad software, the results of equation y_1 are shown in Table 9.

TABLE 9: Compressive strength y_1 regression equation calculations.

y_1	11	10	9	8	7	6	5							
x_1	0.85	0.8	0.73	0.65	0.6	0.49	0.48	0.33	0.35	0.17	0.23	0.02	0.1	0
x_2	0.15	0	0.27	0	0.4	0	0.52	0	0.65	0	0.77	0	0.9	0.51
x_3	0	0.2	0	0.35	0	0.51	0	0.67	0	0.83	0	0.98	0	0.49

The solution of the intersection point between the equation and the triangular coordinate axis is shown.

strength. The strength of gravel was higher than that of raw soil. Gravel particles here were mainly composed of quartz and the surfaces well encapsulated, adsorbed, and bonded with raw soil. However, when the gravel content increased, the gravel occupied a large amount of internal space, such that the soil particles did not bond well. With increased cement content, the hydration cementation of the cement was enhanced, which enhanced the cohesive force between soil particles and the material strength clearly increased. If only the compressive strength index was considered, the area of the enclosure area with $y_1 = 11$ and x_1 vertices was the optimal ratio area. From Figure 4, $0.8 \leq x_1 \leq 1$, $0 \leq x_2 \leq 0.15$, and $0 \leq x_3 \leq 0.2$ were calculated from Section 3.1, with $0.17 \leq z_1 \leq 0.2$, $0.05 \leq z_2 \leq 0.08$, and $0.75 \leq z_3 \leq 0.78$, and thus the optimal formula of cement, gravel, and raw soil was 0.18/0.06/0.76 (mass ratio, resp.).

(2) The regression analysis of response variable y_2 was carried out with reference to Table 6. The calculation was simplified by examining the first-order polynomial for the regression model $\hat{y} = f(x) = ax_1 + bx_2 + cx_3$. The regression results showed the coefficient of determination at $R^2 = 0.9441$ by linear regression (Table 10). According to the F-test, the linear regression equation was significant and the primary regression model concluded to be scientific and reasonable. The polynomial coefficients calculated using MATLAB are shown in Table 11. The corresponding regression equation was $y_2 = 3.6x_1 + 3.08x_2 + 4.04x_3$.

According to the coordinates of the equation y_2 solution, a contour map corresponding to the equation was drawn in triangular coordinates using Origin 9.0 drawing software (Table 10, Figure 5).

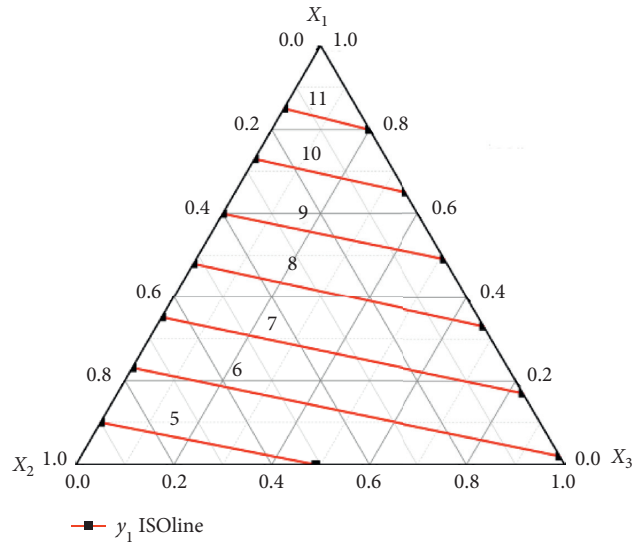


FIGURE 4: Isogram of compressive strength y_1 regression equation.

TABLE 10: Regression analysis of peak displacement of raw soil mixed with cement and gravel.

Source parameter	d_f	SS	MS	F	$p > F$
Regression	3	SS_R 0.94	MS_R 0.3133	28.73	Remarkable
Deviation	7	SS_e 0.12	MS_e 0.0170		
Uncorrected summation	10	SS_T 1.06			
	R^2	0.9441			

TABLE 11: Estimation of the partial regression coefficient of y_2 regression equation for peak displacement of mixed cement and gravel modified with raw soil.

Regression term	Partial regression estimation	t-test	$p > \{t\}$	Regression error of partial regression estimation
x_1	3.6	36.85	0.0001	0.098
x_2	3.08	31.57	0.0001	0.097
x_3	4.04	41.38	0.0001	0.097

Combining regression equation y_2 , solving the equation $y_{max} = 4.11$, $y_{min} = 2.97$, range $\Delta = 1.14$, $\bar{y}_2 = 3.57$, gradient $\nabla = 0.1$, using Mathcad software, the results of equation y_2 are shown in Table 12.

TABLE 12: Peak displacement y_2 regression equation calculations.

y_2	4	3.9	3.8	3.7	3.6	3.5	3.4
x_1	0.1	0	0.32	0	0.55	0	0.77
x_2	0	0.05	0	0.15	0	0.25	0
x_3	0.9	0.95	0.68	0.85	0.45	0.75	0.23
y_2	3.3	3.2	3.1				
x_1	0.42	0	0.23	0	0.04	0	
x_2	0.58	0.77	0.77	0.87	0.96	0.97	
x_3	0	0.23	0	0.14	0	0.03	

The solution of the intersection point between the equation and the triangular coordinate axis is shown.

Parameters x_1 , x_2 , and x_3 represented the admixtures of cement, gravel, and raw soil, respectively (Figure 5). The gradient of the isoline decreased from x_3 point to the x_1x_2 coordinate axis step by step. The average line of peak displacement was located on the middle line of the coordinate triangle, which showed that the raw soil content of these three admixtures played a major role in peak displacement.

With increased cement content, the hydration cementation of the cement was enhanced, which enhanced cohesive forces between soil particles and the peak displacement of the material decreased. The mean line was on the middle line of the coordinate triangle, which showed that the influences of gravel and cement on the peak displacement of specimens were basically the same. If only the peak displacement index

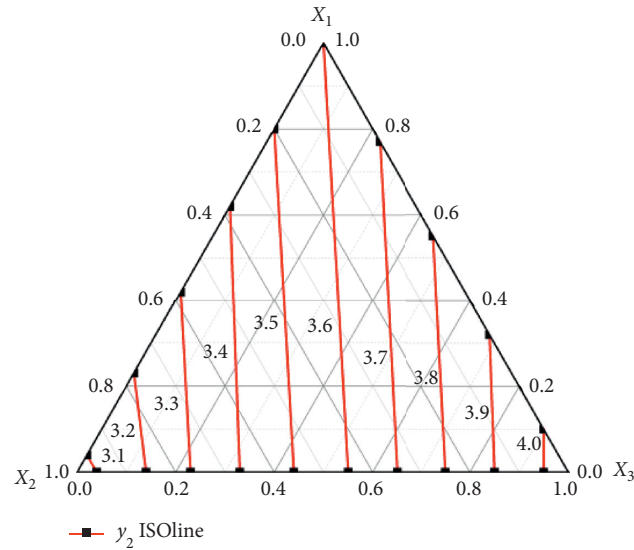


FIGURE 5: Isogram of peak displacement y_2 regression equation.

TABLE 13: Regression analysis of the standard deviation of raw soil mixed with cement and gravel.

Source parameter	d_f	SS	MS	F	$p > F$
Regression	3	SS_R	3.28	MS_R	12.14
Deviation	7	SS_e	0.63	MS_e	0.09
Uncorrected summation	10	SS_T	3.91		
	R^2	0.8387			

TABLE 14: Estimation of the partial regression coefficient of y_3 regression equation for the standard deviation of mixed cement and gravel modified with raw soil.

Regression term	Partial regression estimation	t-test	$p > \{t\}$	Regression error of partial regression estimation
x_1	1.51	4.36	0.0003	0.347
x_2	1.04	2.98	0.002	0.346
x_3	0.6	1.72	0.0129	0.346

Combining regression equation y_3 , solving the equation $y_{max} = 2.20$, $y_{min} = 0.447$, range $\Delta = 1.755$, $\bar{y}_3 = 1.04$, gradient $\nabla = 0.1$, using Mathcad software, the results of equation y_3 are shown in Table 15.

TABLE 15: Standard deviation y_3 regression equation calculations.

y_2	1.5	1.3	1.1	0.9	0.7
x_1	0.98	0.97	0.77	0.55	0.55
x_2	0	0.03	0	0.45	0
x_3	0.02	0	0.23	0	0.45

The solution of the intersection point between the equation and the triangular coordinate axis is shown.

was considered, the area of the sieve with $y_2 = 4$ and x_3 vertices was the optimal ratio area. From Figure 5, $0 \leq x_1 \leq 0.1$, $0 \leq x_2 \leq 0.05$, and $0.9 \leq x_3 \leq 1$ were calculated from Section 3.1, with $0.03 \leq z_1 \leq 0.05$, $0.05 \leq z_2 \leq 0.06$, and $0.9 \leq z_3 \leq 0.92$, and thus the optimal formula for cement, gravel, and raw soil was 0.04/0.06/0.9 (mass ratio, resp.).

(3) The regression analysis of response variable y_3 was carried out with reference to Table 6. The calculation was simplified by examining the first-order polynomial for the

regression model $\hat{y} = f(x) = ax_1 + bx_2 + cx_3$. The regression results showed the coefficient of determination $R^2 = 0.8387$ by linear regression (Table 13). According to the F-test, the linear regression equation was significant and the primary regression model concluded to be scientific and reasonable. The polynomial coefficients calculated using MATLAB are shown in Table 14. The corresponding regression equation was $y_3 = 1.51x_1 + 1.04x_2 + 0.6x_3$.

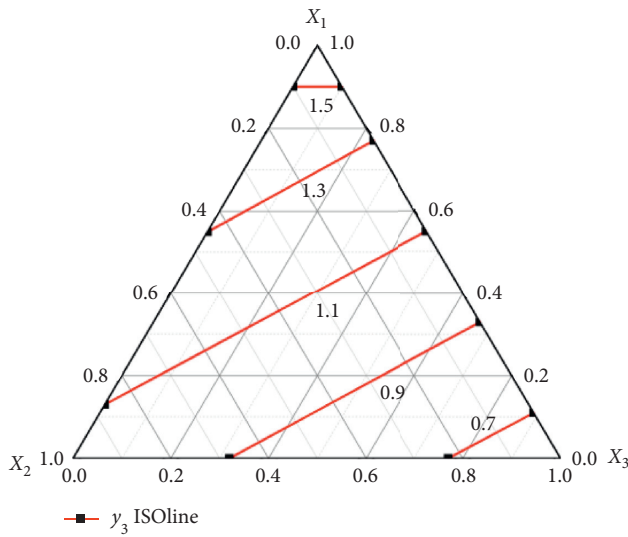


FIGURE 6: Isogram of standard deviation y_3 regression equation.

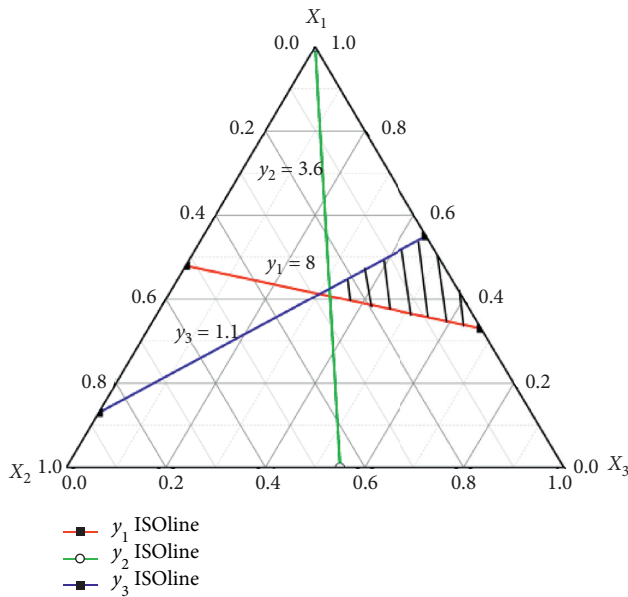


FIGURE 7: Optimal formulation region for synthesizing the three reaction variables y_1 , y_2 , and y_3 .

According to the coordinates of the equation solution in Table 15, a contour map corresponding to the equation was drawn in triangular coordinates using Origin 9.0 drawing software (Figure 6).

Parameters x_1 , x_2 , and x_3 represented the admixtures of cement, gravel, and raw soil, respectively (Figure 6). The gradient of the isoline decreased from x_1 point to the x_2x_3 coordinate axis step by step, which showed that the cement content of these three admixtures played a major role in the standard deviation. If only the standard deviation index was considered, the area of the siege with $y_3 = 7$ and x_3 vertices was the optimal ratio area. From Figure 6, $0 \leq x_1 \leq 0.11$, $0 \leq x_2 \leq 0.23$, and $0.77 \leq x_3 \leq 1$ were calculated from Section 3.1, with $0.03 \leq z_1 \leq 0.05$, $0.05 \leq z_2 \leq 0.09$, and $0.88 \leq z_3 \leq 0.92$, and

thus the optimal formula of cement, gravel, and raw soil was 0.04/0.07/0.89 (mass ratio, resp.).

(4) The optimal formulation should satisfy the three reaction variables at the same time. The strength of specimens also showed the material load resistance. The peak displacement of the specimen reflected the material deformation performance. The standard deviation of a test reflected the stability and discreteness of the material internal structure. Thus, a superposition of Figures 4, 5, and 6 was studied. The optimal formulation area is shown in Figure 7. Here, $y_3 = 1.1$, $y_2 = 3.6$, and $y_1 = 8$ in the shadow of the siege; solution of the equations $0.33 \leq x_1 \leq 0.55$, $0 \leq x_2 \leq 0.28$, and $0.3 \leq x_3 \leq 0.67$ were calculated from Section 3.1, with $0.08 \leq z_1 \leq 0.12$ and $0.8 \leq z_3 \leq 0.86$. Thus, the optimal formula for the cement, gravel, and raw soil was 0.1/0.08/0.82 (mass ratio, resp.).

5. Conclusion

The compressive strength of raw soil modified by cement and gravel is significantly higher than that of plain soil. The compressive strength is 1.16–3.55 times that of raw soil. If the cement content is fixed, the compressive strength of the specimen decreases with the increase of the stone content. If the stone content is fixed, the compressive strength increases with the increase of cement content.

In this study, the single lattice model formulation design method was introduced to effectively improve and control raw soil modification formulation tests affected by many factors. Through regression analysis, the isoline equation image solution was best for verifying this method, which showed that this method was feasible for the test study of raw soil modification. Using the combination of MATLAB modeling software, Mathcad calculation software, and Origin drawing software, programming calculations were performed to improve the efficiency of mathematical calculation.

According to the equation solutions, a contour map of the triangular coordinate system was drawn, which effectively reflected the influence of the admixture on the results. The content of cement and gravel had a significant influence on the compressive strength and standard deviation of specimens. The raw soil content only affected peak displacement.

Considering the compressive strength, peak displacement, and standard deviation, the optimal mass ratio of gravel, cement, and raw soil was 0.1/0.08/0.82 (mass ratio, resp.).

The formulation model provided the method and basis for the standard method of raw soil mixed modification testing.

Data Availability

All data generated or analyzed during this study are included in this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The research for this project was supported by the National Natural Science Foundation of China, for the “Study on the Standard Test Method of Materials and Masonry Based on Raw-Soil” (51478043), the Shaanxi Natural Science Basic Research Program (2019JQ-554), and Natural Fund of Shaanxi Provincial Department of Education (20JK0816). Their financial support is highly appreciated.

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