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Article

Optimization of Roots and Copper Slag to Reinforce Soft Soil Using Response Surface Method

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Abstract: In this paper, roots and copper slag were used to overcome the weakness and reinforce the mechanical property of soft soil. The experiments were designed by the Response Surface Method (RSM), the content optimizing of the root permeated copper slag mixed soil for achieving appropriate values of shear strength and the final results evaluating were also conducted by RSM. Four independent variables including moisture content (12–21% by dry weight of the mixture), slag content (10–20% by dry weight of the mixture), roots content (0–1.1% by dry weight of the mixture), and aspect ratio of roots L/d (5–40) were studied and a generalized response model was built to predict the experimental results. The optimum contents of the four independent variables were suggested as 15.41% (moisture), 16.30% (copper slag), and 0.82% (roots) with an aspect ratio of 28.14, respectively. It can be concluded from the verification experiments that the predicted values of the soil mechanical property are almost equal to the experimental values, which validate the response model. Moreover, a typical subgrade model was built for proving the practical advantages of using the above-mentioned mixture as subgrade fill.

Keywords: Response surface; shear strength; roots; copper slag

1 Introduction

Copper slag is a common kind of industrial waste that was collected during the ore smelting and the copper refining process. The annual amount of copper slag produced by the metallurgy enterprises in China is more than 20 million tons [1,2], disposing of the large amount of copper slag in a sustainable method is a challenge in recent years [3,4]. A potential disposal of copper slag in subgrade filling is mixing it with soil materials. However, the strengthening effect of mixing the soil materials with copper slag is only prominent at the beginning, and the mixture is prone to become softer with time, possibly lead to slope failures eventually [5,6]. On the other hand, mixing soft soils with slag is potentially a cost-effective way to reinforce the soft soils [7–13].

Previous studies on the recycling of copper slag have shown that copper slag is harmless after reasonable disposition in factories [14]. They have also demonstrated that in civil engineering projects copper slag can be used in various ways [15–17], such as the raw material substituting sand in cement mortar and concrete [18,19] and aggregates in asphalt [20]. Such as Prasad et al. [21] studied the interaction between geogrids and copper slag through the pull-out experiments, the results showed that copper slag can make an effective fill for reinforcing soil structures. In sum, these previous studies mainly concentrated on the methods of application, replacement ratio of copper slag in a mixed material, and the percentage of strength increase.

On the other hand, soil reinforcement using grass roots is considered as an advisable method which relies on the interaction of the plant roots with the mechanical properties of the soil. This method is effective in the medium–long term, which means that the reinforcing effect of grass roots will not be weakened because of the natural regeneration of grass roots [22,23]. In the studies on roots-based soil reinforcement as an effective bio-geotechnical method, the application of grass roots to enhance the strength of soil has become popular in recent years [24,25]. The tensile strength of grass roots can significantly improve the strength of soil [26–29].

Furthermore, mixing the soil with fiber can reduce the shrinkage strain up to 90% and increase the strength of soil up to 70% [30] but the fiber increase the hydraulic conductivity up to 50 times the hydraulic conductivity of the soil without fiber [31–33]. Therefore, the root is more effective in slag treated soil tan fibers. Nano material is also one of the treatment materials used to reinforce the soil. However, treatment by Nano material bring the soil to a more granular nature and decrease the water absorption potential [34,35].

It can be concluded from the above-mentioned literature that the published works on soil reinforcement by mixing with copper slag and grass roots are very limited. The reinforcement mechanism of the root permeated copper slag mixed soil is an interesting investigation.

Since both reinforcement mechanisms of slag-mixed soil and root-permeated soil can function in the soil reinforcement, this paper attempts to combine slag and plant roots for soil improvement. The influences are examined of the slag content, the roots content, and aspect ratio of roots, and the moisture content on the shear strength of root- permeated soil, to find the optimum values of the four independent variables. The application of the mixture in geotechnical engineering is also worth to be studied. The study results are expected not only to enhance the stability of geotechnical construction, but also help to recycle the industry-generated copper slag.

To investigate the optimum contents and contribution ratio of each additive (i.e., copper slag and grass roots), the shear strength tests and triaxial compression tests are conducted and the results are analyzed with the response surface method. This method can efficiently determine the optimum values of variables for the desirable response and assess the effect of one variable while the others varying at the same time, with no need to be kept constant.

This paper aims to investigate the optimal ratio of each additive for achieving the maximum mechanical properties based on the Response Surface Methodology (RSM) [36–39], and to demonstrate the advantage of using the root-permeated, slag-mixed soil in enhancing a subgrade through the result of a numerical simulation.

2 Materials and Methods

2.1 Materials

In this study, the raw materials are including soft soil, copper slag, and grass roots. The copper slag is collected from the Daye Metal Company in Huangshi city of China, the largest particle size of copper slag is smaller than 5 mm. Tab. 1 shows the chemical composition of the copper slag, the majority components of the copper slag are SiO_2, Al_2O_3, and CaO, whose percentages of weight are 33.18%, 28.46%, and 22.50%, respectively. The leaching tests indicate that the copper slag has limited hazards to the environment [40,41]. The soft soil is collected from the bank of the Yangtze River in Huangshi city of China. Tab. 2 shows the mechanical indexes of the soil. The roots are collected from the Bermuda grass (scientific name is Cynodondactylon), which are widely adopted for the slope protection of expressway. There are high variances in root length (L) and root diameter (d), which approximately vary from 1 to 5 cm and 0.5 to

2.5 mm, respectively. Therefore, to assess the influence of root length and root diameter on soil strength, the aspect ratio of roots (L/d) is studied as an independent variable in the experiment design. These results of the copper slag, roots are shown in Fig. 1.

Table 1: Composition of copper slag

Ingredient	MgO	Al_2O_3	CaO	MnO	P_2O_5	Cr_2O_3	SiO_2	TiO_2
Weight percentage (%)	6.35	28.46	22.50	5.21	0.03	2.35	33.18	1.92

Table 2: Mechanical indexes of soils

Moisture content	Initial void ratio	Plasticity index	Optimum dry density	Optimum moisture content	Specific gravity
27.6%	0.59	15.3	1.49 g/cm³	19.57%	2.65

Figure 1: (a) Photograph of Copper slag after grinding and sieving and (b) The roots of Bermuda grass

2.2 Experiment Design and Response Surface Methodology (RSM)

The Box–Behnken Design (BBD), which is a widely used form of RSM, is one of the best approaches to design the tests and reduce the number of experiments. Therefore, the experiments are designed by the BBD, the content optimizing of the root permeated copper slag mixed soil for achieving appropriate values of shear strength and the final results evaluating are all conducted by the RSM.

By running the experiments of Box–Behnken Design (BBD), four independent variables are considered and designed, including the moisture content by the dry weight of the mixture, the content of slag by the dry weight of the mixture, the content of roots by the dry weight of the mixture, and the aspect ratio of roots (L/d).

There are two test stages, one is the preliminary experiments which are conducted to obtain the value range of each variable, and assess the effect of a single variable on the shear strength of root-permeated, slag- mixed soil. The level of moisture content varies from 12 to 21%, the content of slag varies from 10 to 20%, the content of roots changes from 0 to 1.1%, and the aspect ratio of roots (L/d) changes from 5 to 40. The other is the main experiments, in this stage, the Design-Expert software is adopted to design a four-factor and three-level response surface, and 29 experiment runs are designed in this stage. In the response surface analysis, the experimental data are fitted to a second-order polynomial model as follows [42]:

$$F = \beta_0 + \sum_{i=1}^{4} \beta_i N_i + \sum_{i=1}^{4} \beta_{ii} N_i^2 + \sum \sum_{i\langle j=1}^{4} \beta_{ij} N_i N_j \quad (1)$$

where F is the predicted response; β_0, β_i, β_{ii}, and β_{ij} are the regression coefficients for the intercept, linear, quadratic, and interaction terms, respectively; N_i and N_j are the independent, variable parameters. Besides, the statistical significance and the accuracy of the polynomial model are evaluated by the analysis of variance.

2.3 Test-Sample Preparation

There are 4 steps in test-sample preparation [43]:

Step 1, Dry the raw materials in an oven for about 24 h, then grind them with a pulverizer, and then screen them.

Step 2, Cure the soil and copper slag in an airtight container, mix them after curing, and then pour water until the optimum moisture content is reached, carefully stirring them to ensure the mixtures are uniformly mixed.

Step 3, Put the mixture evenly into the container of compaction test apparatus and compact it for three or four times, then uniformly insert the roots into the mixture (the lengths of roots should be perpendicular to the diameter of the specimen, and the lengths of roots should be parallel to each other), and then compact the mixture again to meet the maximum dry density.

Step 4, Maintain the mixture in a sealed container for 24 h, after that, remeasure the moisture content and compensate the loss in moisture content, then vertically push the cutting ring to the compacted mixture and get the test samples (see Fig. 2), then shear the specimens, and then calculate the shear strength.

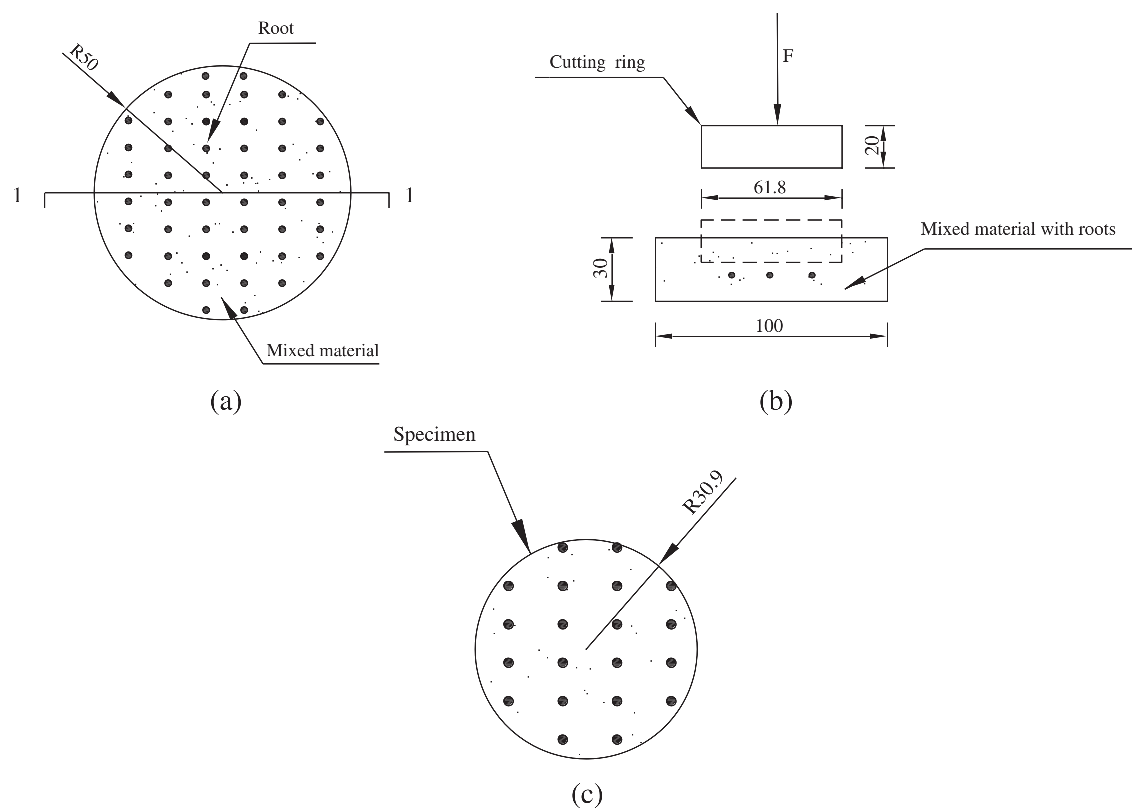

Figure 2: (a) Plane figure of compacted mixed material specimen (unit: mm), (b) 1-1 Profile of the specimen (unit: mm) and (c) Plane figure of the shearing specimen (unit: mm)

The shear test is conducted by the strain-controlled direct shear apparatus [44,45], the vertical stress on the shear surface is set to be 100, 200, 300, and 400 kPa, the area of the soil sample is 30 cm^2 and the shear rate was 0.8 mm/min.

3 Results and Discussions

3.1 Preliminary Experiment Results

Fig. 4 shows the results of the preliminary experiment.

The shear strength of prepared test samples is tested through a strain-controlled direct shear apparatus. Based on the prepared experimental samples, the shear stress displacement curves are plotted for each of the samples. A typical plot showing the stress displacement relationship of the soil sample is shown in Fig. 3 when the parameters of slag content, roots content, moisture content, and aspect ratio are all constants with the actual values of 16%, 0.8%, 14.5%, and 30, respectively. It is easy to see that the shear stress of the sample increases with the increase of the displacement before the failure of the sample, the peak value of the curves can be collected as the shear strength value under different vertical stress.

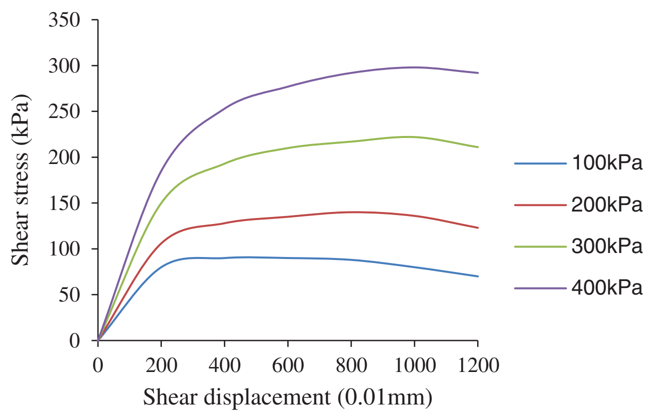

Figure 3: Shear stress-shear displacement curve (1 day curing time)

The influence of moisture content. In this group of experiments, the parameters of slag content, roots content, and aspect ratio are all constants with the actual values of 16%, 0.8%, and 30, respectively. It can be known from Fig. 4a that the shear strength is improved with the increasing of moisture content when it is less than 15% and after then the shear strength begins to decrease. Therefore, the advisable lower, middle, and upper values for the moisture content in the RSM design should be 13%, 15%, and 17%, respectively.

The influence of slag content. The value of moisture content is set to be 15%, the roots content is 0.8%, and the aspect ratio is 30. The variation of the shear strength with the slag content is shown in Fig. 4b, the shear strength increases with the increase of slag content up to 16% and then begins to decrease after that. Therefore, the appropriate middle level for the slag content in the RSM design should be 15%.

The influence of roots content. The value of moisture content is set to be 15%, the slag content is 16%, and the aspect ratio is 30. Fig. 4c shows that when the content of roots ranges from 0.7 to 0.9%, the value of shear strength is near the peak. Therefore, the appropriate middle level for the content of roots in the RSM design should be 0.8%.

The influence of the aspect ratio of roots. In this group of experiments, the parameters of slag content, root content, and moisture content are all constants with the actual values of 16%, 0.8%, and 15%, respectively. It can be known from Fig. 4d that the shear strength is slowly improved with the increase of aspect ratio, and when the value of the aspect ratio varies from 25 to 35, the shear strength is near the peak. The mechanism of strength improvement by roots is that the contact between the soil and roots enhances the friction angle of the root-permeated, copper slag-mixed soil.

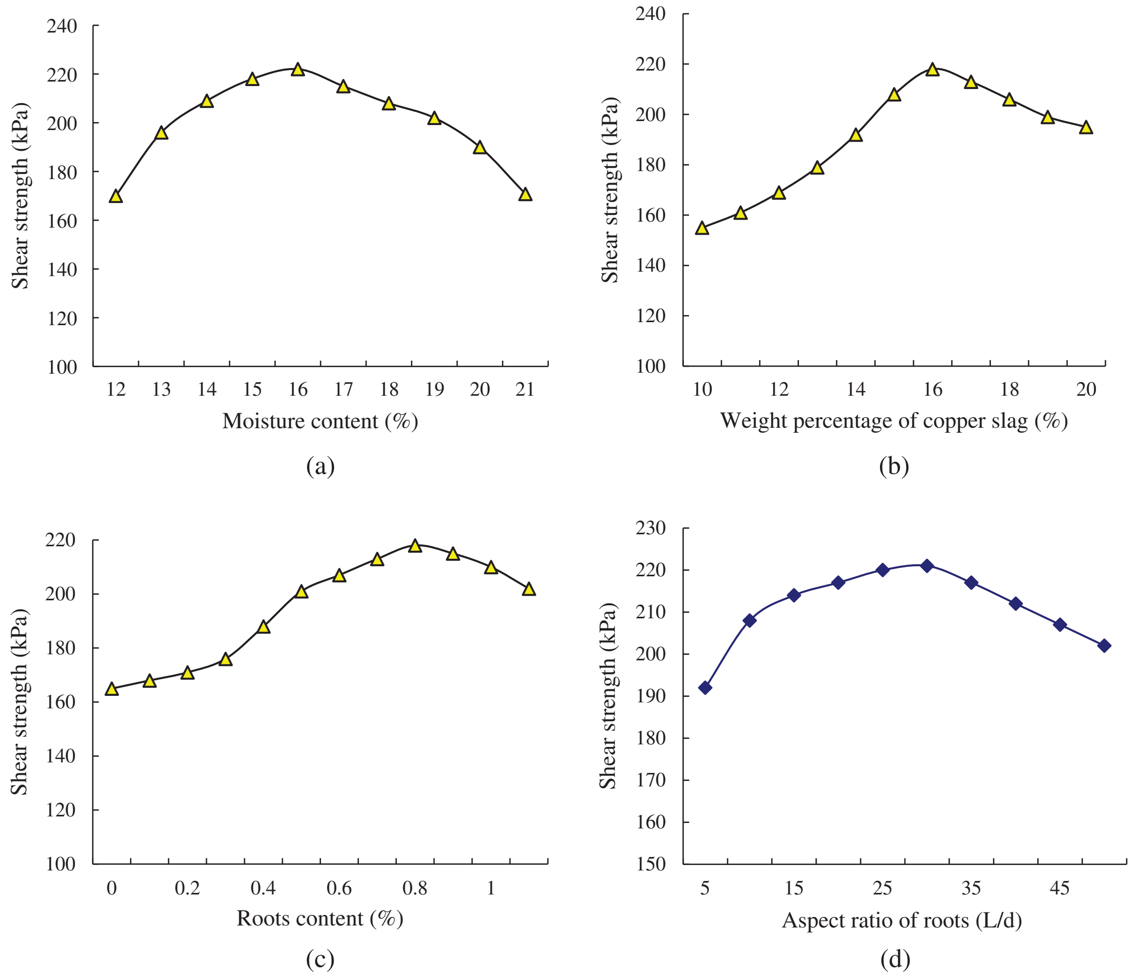

Figure 4: (a) Impacts of moisture content on shear strength of mixture with vertical stress of 300 kPa, (b) Impacts of slag content on shear strength of mixture with vertical stress of 300 kPa, (c) Impacts of roots content on shear strength of mixture with vertical stress of 300 kPa and (d) Impacts of aspect ratio of roots (L/d) on shear strength of mixture with vertical stress of 300 kPa

Moreover, it can be concluded from Fig. 4 that the range of variation of shear strength resulting from the increase of the aspect ratio of roots is smaller than that resulting from the increase of any other parameter. Therefore, among the 4 studied parameters, the aspect ratio of roots shows the least influence on the shear strength.

3.2 Main Experimental Results

3.2.1 Statistical Analyses

Based on the results of the preliminary experiment, the actual values of each variable adopted in the design of the main experiment are chosen and shown in Tab. 3.

Table 3: Independent parameters and their actual values used for optimization

Serial number	Independent variables	Units	Symbol	Level		
				−1	0	1
N_1	Moisture content	%	A	13	15	17
N_2	Slag content	%	B	14	16	18
N_3	Roots content	%	C	0.4	0.8	1.2
N_4	Aspect ratio of roots (L/d)	–	D	5	25	40

The results of all the runs of the main experiment are obtained (see Tab. 4) and analyzed by the RSM. In Tab. 5, the R^2 of 0.9547 indicates the fitness of the model is acceptable and there is a strong conformation between the test data and the predicted data, the "Model *p*-value" of 0.0001 shows the high significance of the model and implies only a chance of 0.01% for the failure of the model.

Table 4: The variables and responses obtained from the bench-scale experiment

Run	Variables				Responses
	Moisture content A (%)	Slag content B (%)	Roots content C (%)	Aspect ratio of roots D (L/d)	Shear strength (kPa)
1	15	16	0.4	40	191.68
2	17	14	0.8	25	200.72
3	17	16	0.8	10	215.04
4	15	16	1.2	40	191.68
5	13	16	0.4	25	162.04
6	17	16	0.4	25	174.35
7	15	18	0.4	25	178.37
8	15	14	0.8	10	180.88
9	13	16	0.8	40	206.33
10	15	16	0.8	25	228.11
11	15	16	0.8	25	225.60
12	15	18	0.8	40	210.77
13	15	16	0.8	25	221.58
14	15	16	0.4	10	178.11
15	15	14	0.8	40	176.86
16	13	16	0.8	10	181.38
17	15	18	0.8	10	192.69
18	15	16	1.2	10	191.68
19	15	16	0.8	25	221.58
20	17	18	0.8	25	195.70
21	15	18	1.2	25	178.11
22	15	14	1.2	25	176.10
23	17	16	1.2	25	190.17
24	13	14	0.8	25	163.04

(Continued)

Table 4 (continued).

Run	Variables				Responses
	Moisture content A (%)	Slag content B (%)	Roots content C (%)	Aspect ratio of roots D (L/d)	Shear strength (kPa)
25	13	16	1.2	25	173.84
26	13	18	0.8	25	190.93
27	15	14	0.4	25	162.04
28	15	16	0.8	25	211.53
29	17	16	0.8	40	207.51

Table 5: The verification index of experimental results of RSM

Source	Sum of Squares	df	Mean Square	*F* Value	*p*-value	
Model	10071.50	14	719.39	21.09	<0.0001	significant
A-Moisture content	935.26	1	935.26	27.42	0.0001	
B-Slag content	629.62	1	629.62	18.46	0.0007	
C-Root content	252.24	1	252.24	7.40	0.0166	
D-L/d	169.08	1	169.08	4.96	0.0429	
AB	270.76	1	270.76	7.94	0.0137	
AC	4.04	1	4.04	0.12	0.7359	
AD	263.78	1	263.78	7.73	0.0147	
BC	51.26	1	51.26	1.50	0.2404	
BD	122.18	1	122.18	3.58	0.0793	
CD	46.01	1	46.01	1.35	0.2649	
A^2	1355.83	1	1355.83	39.75	<0.0001	
B^2	2946.40	1	2946.40	86.39	<0.0001	
C^2	5293.37	1	5293.37	155.20	<0.0001	
D^2	275.14	1	275.14	8.07	0.0131	
Residual	477.51	14	34.11	–	–	
Lack of Fit	317.76	10	31.78	0.80	0.6512	*not significant*
Pure Error	159.75	4	39.94	–	–	

Note: RSM: Response Surface Method.
R^2 = 0.9547.

Fig. 5 shows the actual values and predicted values of shear strength (τ) are all around the diagonal line, indicating the high precision of the proposed model. Therefore, the model can be considered as a well-fitted model. The mathematic relation between the variables and the corresponding responses can be written as Eq. (2).

$$\tau = 221.68 + 8.83A + 7.24B + 4.58C + 3.75D - 8.23AB + 1.00AC - 8.12AD - 3.58BC + 5.53BD - 3.39CD - 14.46A^2 - 21.31B^2 - 28.57C^2 - 6.51D^2 \quad (2)$$

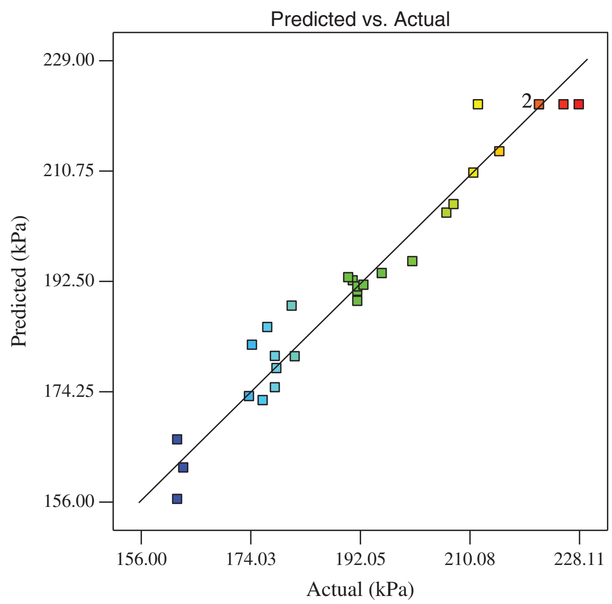

Figure 5: Plot of the predicted values *vs.* actual value for shear strength

Furthermore, the significance of each variable and their combination on the responses can be checked by their "*p*-value" in Tab. 5. The smaller is the "*p*-value", the more significant would be the variable or the combination of variables in the model, and if the "*p*-value" is smaller than 0.05, the corresponding variable is significant. Therefore, the variables can be ordered by their significance as moisture content, slag content, roots content, and aspect ratio of roots. It also can be seen in Tab. 5 that variables of moisture content, slag content, root content, and aspect ratio (L/d) are all significant, indicating that the four parameters can significantly influence the shear strength of root-permeated, copper-slag-mixed soil.

3.2.2 Effect of Variables on Shear Strength

Based on the predicted model and the experimental results, the response surfaces of the interaction between different variables on the strength of root-permeated slag-mixed soil are drawn in Figs. 6–12.

In the response surface of Fig. 6, the actual value of root content is 0.8%, and L/d is 25. Before the moisture content of 15.41% is reached, increasing the moisture content significantly boosts the shear strength, but after that, the shear strength decreases. Similarly, when the moisture content is constant, the shear strength increases at first and then decreases with the slag content. Besides, a value of 0.0137 for the "*p*-value of AB" (Tab. 5) shows that the combination of moisture content and slag content is significant on the shear strength since the metal oxides (i.e., Al_2O_3) of copper slag can react with the water to form hydration products, which will affect the mechanical properties of the soil mixture.

In the response surface of Fig. 7, the actual value of slag content is 16.0%, and L/d is 25. At a constant moisture content, the increase of root content contributes significantly to the increase of the shear strength, but the shear strength will decrease after the root content reaches a higher value of 0.82%. Similarly, increasing the moisture content also results in significant enhancement (when the moisture content is less than 15.41%) and reduction (when the moisture content is more than 15.41%) of shear strength. Furthermore, a value of 0.7359 for the "*p*-value of AC" (Tab. 5) shows that the combination of moisture content and root content is insignificant on the shear strength since the moisture content of soil mixture does not determine the sharing ratio of shear force on the roots.

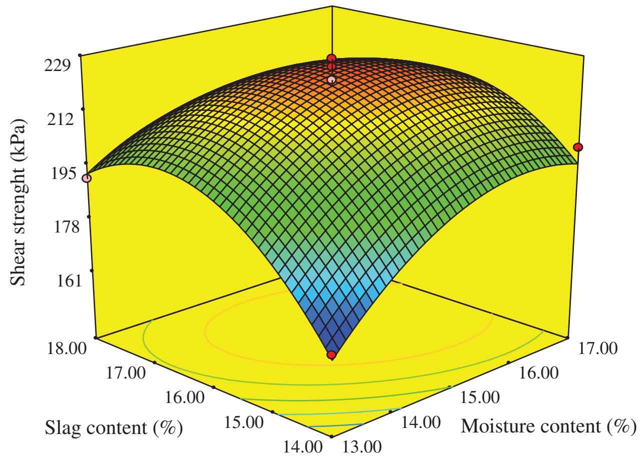

Figure 6: Response surface of moisture content and slag content on shear strength

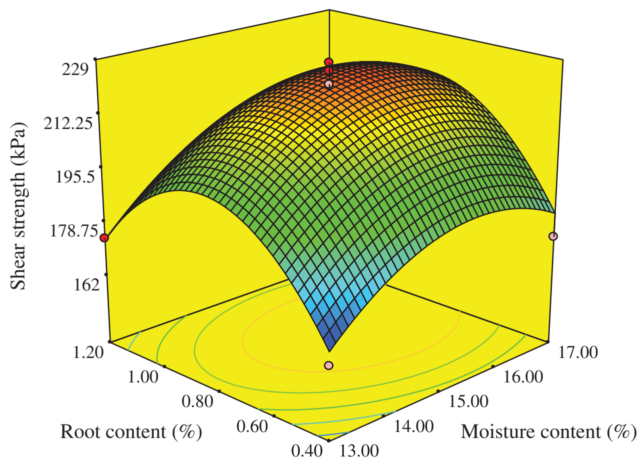

Figure 7: Response surface of moisture content and root content on shear strength

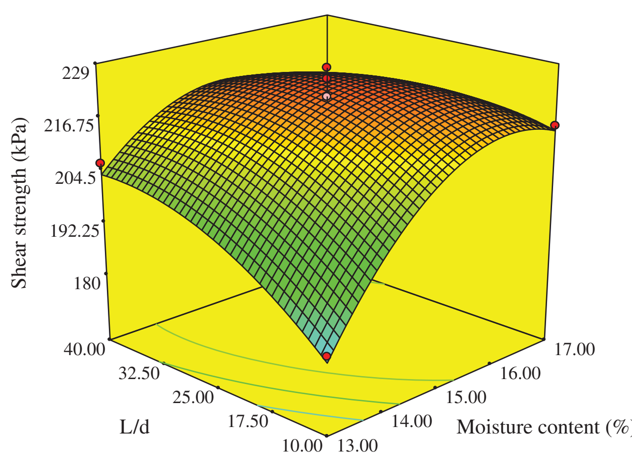

Figure 8: Response surface of moisture content and aspect ratio on shear strength

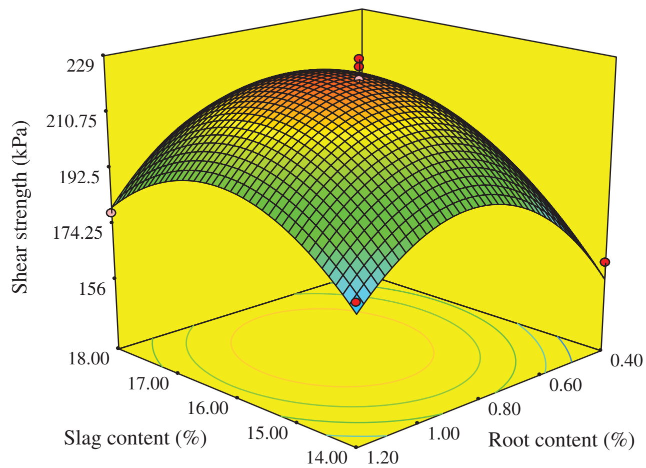

Figure 9: Response surface of slag content and root content on shear strength

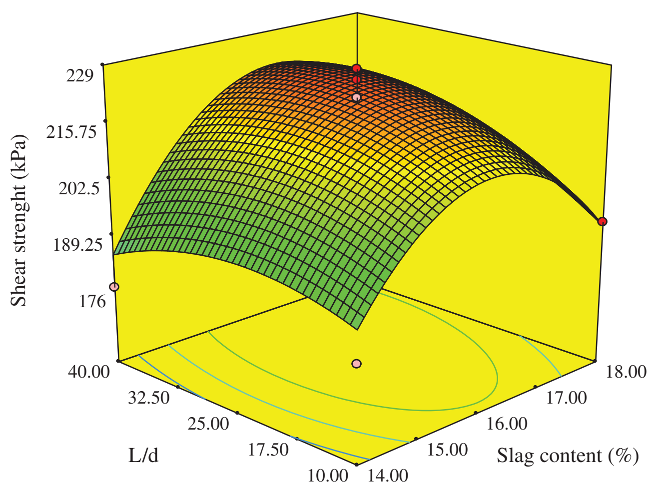

Figure 10: Response surface of slag content and aspect ratio on shear strength

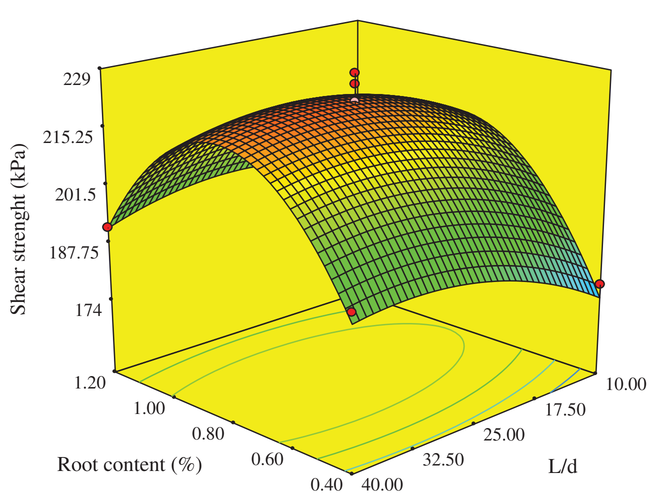

Figure 11: Response surface of root content and aspect ratio on shear strength

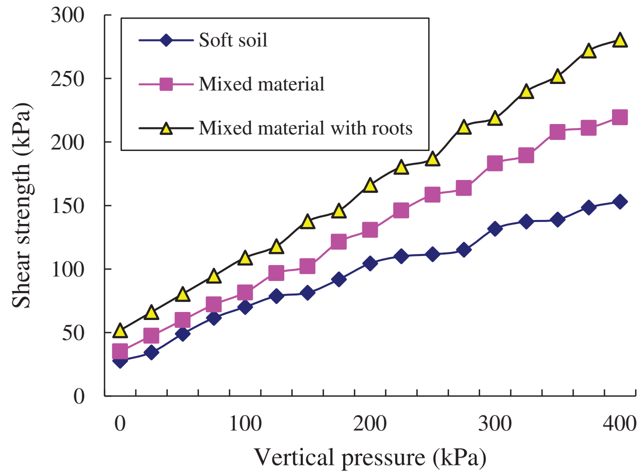

Figure 12: Comparison of the shear strengths of different samples under different vertical pressure

According to the response surface in Fig. 8 where the actual value of root content is 0.8%, and the slag content is 16, it can be seen that before the aspect ratio (L/d) of 28.14 is reached, increasing the L/d results in significant enhancement of shear strength, but the shear strength decreases slowly after that, and the effect of moisture content on the shear strength is similar with that of L/d. Besides, a value of 0.0147 for the "*p*-value of AD" (Tab. 5) shows that the combination of moisture content and L/d is significant on the shear strength since the combination is partly decided on whether the roots adhere to the mixture tightly and the tensile strength of roots is mobilized.

According to the response surface in Fig. 9 when the actual value of moisture content is 15%, and L/d is 25, it can be seen that the increase of root content at a constant slag content contributes significantly to the increase of shear strength; however, the shear strength will decrease after the root content reaches a higher value of 0.82%. The roots and copper slag are both effective additives which could enhance the mechanical properties of soil separately; therefore, a value of 0.2404 for the "*p*-value of BC" (Tab. 5) shows that the combination of the slag content and root content is insignificant.

Fig. 10 shows the effects of slag content and aspect ratio of roots on the shear strength. In Fig. 10, the actual value of root content is 0.8%, and the moisture content is 15%. Before the slag content reaches 16.30%, increasing the slag content results in significant enhancement of shear strength, but after that, the value shear strength value decreases. Similarly, when the slag content is constant, the shear strength increases at first and then decreases with L/d. Besides, a value of 0.0793 for the "*p*-value of BD" (Tab. 5) shows that the combination of slag content and L/d has an insignificant effect on the shear strength.

Fig. 11 shows the effects of root content and aspect ratio (L/d) on the shear strength. In this response surface, the moisture content is 15%, and the slag content is 16%. When the aspect ratio (L/d) is constant, the shear strength increases with the root content up to 0.82%, and after that, the shear strength decreases. Similarly, when the root content is constant, the shear strength increases at first and then decreases with the aspect ratio. Furthermore, a value of 0.2649 for the "*p*-value of CD" (Tab. 5) shows that the combination of root content and aspect ratio has an insignificant effect on the shear strength, the combination indicates that the sharing shearing force on roots doesn't fully depend on the aspect ratio (L/d).

3.2.3 Optimization

In the optimization process, the maximum desirable value of shear strength is considered at the optimum amount of variables. Only one desirable solution is obtained using RSM. The result (Tab. 6) shows that the maximum shear strength of the root-permeated, copper-slag mixed soil could be improved to 223.67 kPa by adding 15.41% of water, 16.3% of copper slag, 0.82% of roots, and 28.14 of aspect ratio when the vertical stress on the shear surface is 300 kPa. The desirability value of this result is 0.907.

Table 6: The verification indexes of the results of RSM

Moisture (%)	Slag (%)	Root (%)	Aspect ratio (L/d)	Shear strength (kPa)	Desirability
15.41	16.30	0.82	28.14	223.668	0.907

3.2.4 Comparison of the Shear Strengths of Different Samples

For better understanding, the effect of roots on the strength of copper slag-mixed soil, some samples of soft soil, and copper slag-mixed soil are well prepared with the optimum water content. Samples of mixed material with roots are also prepared with the optimum amount of variables (Tab. 6). Through the standard direct shear tests, the shear strengths of the soft soil, mixed material, and mixed material with roots are obtained and the results are shown in Fig. 12. When the vertical pressure is low, the differences are small among the shear strengths of all samples under the same vertical pressure, and the differences between the three types of soil samples all become larger with the increasing of the vertical pressure. It also shows that the soft soil is remarkably reinforced by mixing with copper slag. The copper slag mixed soil can be further reinforced by adding grass roots, which could be tightly embedded in the mixed soil, so the tensile strength and adhesion strength of roots can bear parts of the shear force on the shear surface. Before the failure of the specimen, the shear force has to cut off the roots.

Moreover, the curves in Figs. 13 and 14 help to show the contributions of root content on the cohesion and friction angle more clearly. When the cohesion is changed from 34.3 to 51.8 kPa, the friction angle is changed from 25.2 to 29.7°.

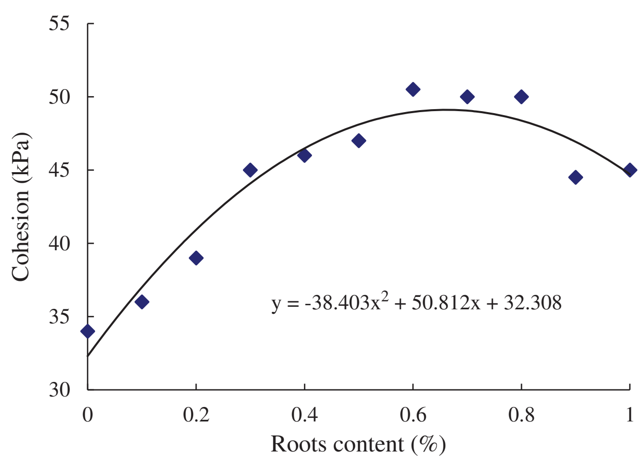

Figure 13: Cohesion of the mixture with different roots content

According to the above analysis, the mechanical properties of the root-permeated, copper slag-mixed soil are well characterized. However, it still needs further study on whether this soil performs well in practical applications. Hence a further investigation is conducted using the FLAC3D in the following section.

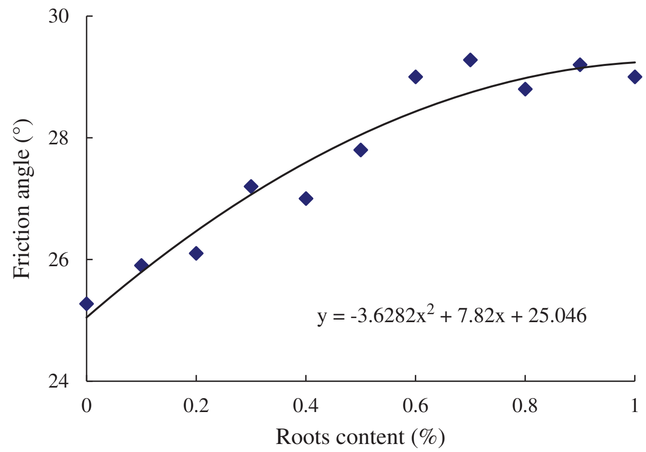

Figure 14: Friction angle of the mixture with different roots content

4 Application in Subgrade Construction

The subgrade of Wuhan to Huangshi expressway in China is taken as the research background, a typical subgrade model is used in this study for demonstrating the practical advantages of the root-permeated copper slag-soil mixture in decreasing the subgrade settlement.

4.1 Basic Model

In this subgrade model, the soil layers are ideal elastoplastic bodies with the Mohr–Coulomb failure envelopes, and the soils are identified as isotropic and homogeneous materials.

This mixture to be used as the subgrade filling for building a subgrade is assumed to be the optimal root-permeated, slag-mixed soil obtained in the above study. The width and height of the subgrade are 34 m and 10 m, respectively (half of the subgrade is studied in the model), and the subgrade foundation in this study has a width of 100 m and a height of 30 m. The slopes of the subgrade have the height-over-width ratios of 1:1.5 and 1:1.75. A uniform load ranging from 0 to 300 kPa is applied by a vehicle at the top of the subgrade. Eight monitor points are set at the surface of the model. The detailed information is plotted in Fig. 15.

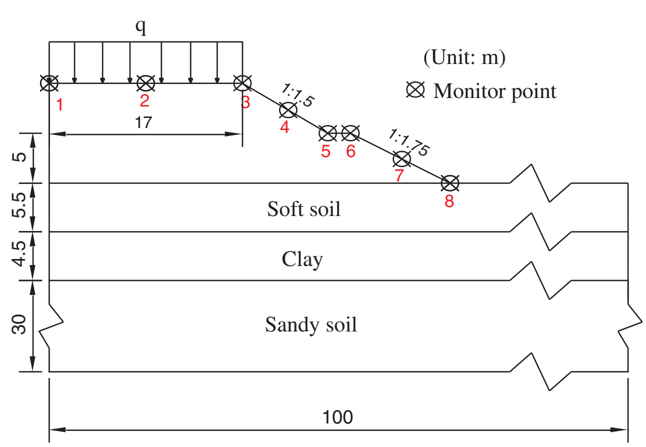

Figure 15: Schematic diagram of the model (unit:m)

The software $FLAC^{3D}$ is used to perform the numerical analysis. Since the subgrade is perfectly symmetric, the analysis will only investigate half of the soil subgrade. In terms of boundary conditions, the horizontal displacements at both sides are constrained and the vertical displacement along the bottom is also constrained. The water could drain out freely at the surface of the ground. The bottom boundary of the numerical model is also assumed impervious because of the low permeability of soil layers. The type of mesh for the numerical model is the eight-node quadrilateral.

The information on the soil conditions in the model is provided. The first layer is the soft soil, which will be replaced by the root-slag-soil mixture. Further deeper soil layers are the clay soil layer and sandy soil layer. The root-slag-soil mixture simulated in the model is in the best and desirable practical condition obtained by the laboratory experiments in Section 3.2.3, and more detailed information can be found in Tab. 7. It is assumed that the consolidation settlement of foundation soils is finished.

Table 7: Information of soil conditions

Layer	Soil texture	Thickness of soil (m)	Moisture content (%)	Poisson's ratio	Deformation modulus (MPa)	Cohesion (kPa)	Friction angle (°)
1st	Before replacement	5.5	27.68	0.37	12.4	35.17	7.05
	After replacement	5.5	15.41	0.34	16.1	51.84	29.76
2nd	Clay	4.5	21.52	0.35	14.7	40.52	18.09
3rd	Sandy soil	30	22.76	0.25	15.33	27.9	25.53

4.2 Results and Discussion

Fig. 16 shows the distribution of vertical settlement for the subgrade foundation when the vertical pressure is 300 kPa. The settlement curves at the monitoring points under different pressures are shown in Fig. 17, demonstrating that the settlement of the model decreases with the increase of horizontal distance and vertical distance from the monitoring point 1. Before the vertical pressure reaches 200 kPa, the settlement of the model is approximately increasing linearly, and the deformation is still within the elastic limit of the model.

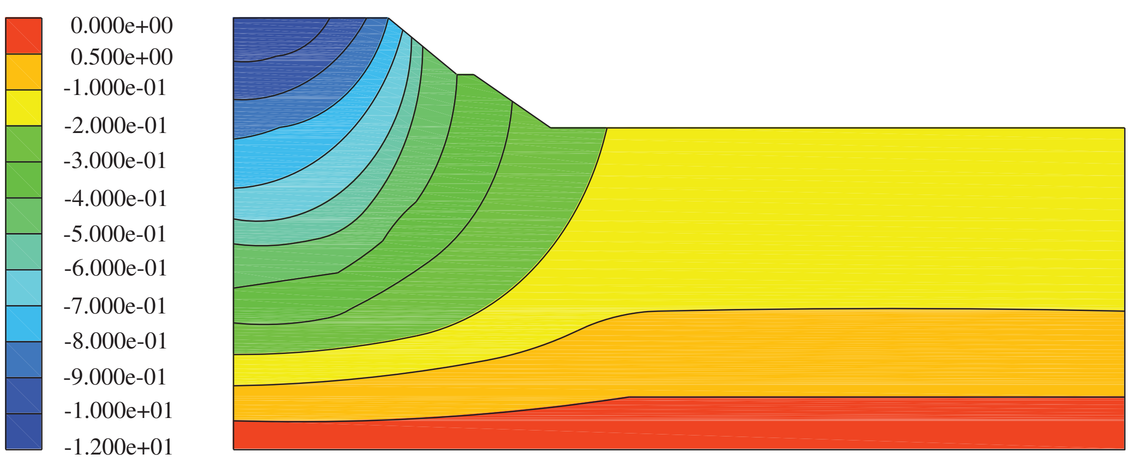

Figure 16: The vertical settlement contours of the model when p = 300 kPa

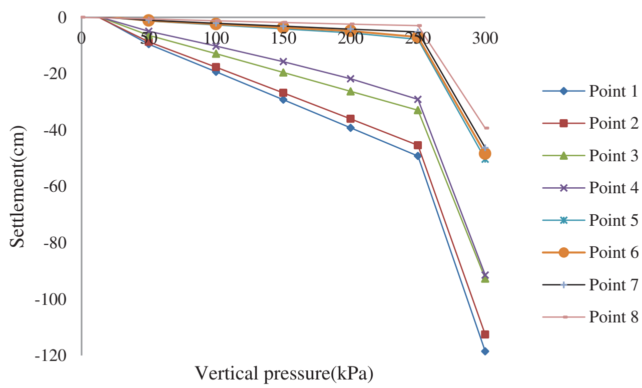

Figure 17: The settlement curves of monitor points

Furthermore, Fig. 18 shows the vertical settlement along the central line of the model when the vertical pressure is 50 kPa. It can be seen that after replacing the soft soil by the root-slag-soil mixture, the settlement is relatively lower. Compared with the model with soft soil at the ground surface, the settlement is decreased by 54.76% in the case with the root-slag-soil mixture. This further proves the applicability of the root-permeated, copper slag-mixed soil in the subgrade.

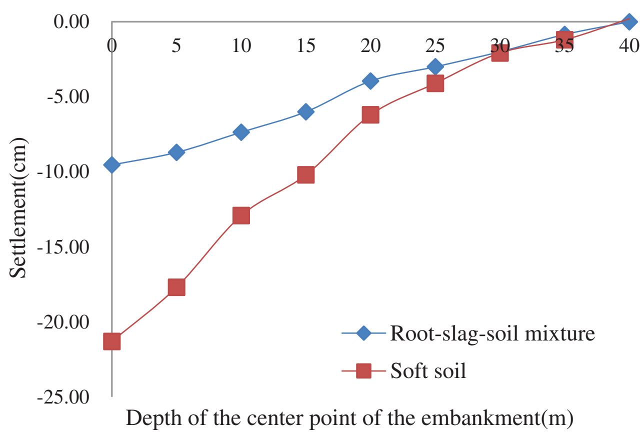

Figure 18: Vertical settlement along the centerline of the model when p = 50 kPa

5 Conclusion

Response surface method (RSM) is adopted to assess the enhancement of the shear strength of a soft soil stabilized by the Bermuda grass roots and copper slag. Based on the finding and results, the following conclusions can be drawn:

Plant roots and copper slag are effective, environmentally friendly, and inexpensive additives to reinforce soft soil.

Statistical analyses indicate that the predicted values from the RSM model are similar to the test values, which validate the response model. Therefore, RSM can be used to seek the optimal conditions of additives for the stabilizing of soils.

According to the analysis of variance and percentage of contribution, the moisture, slag content, root content, and its L/d are all considered as effective parameters on increasing of the soil strength. Also, the combined effect of moisture and slag content has the most effect on increasing the soil strength.

Box–Behnken Design (BBD) of RSM is employed to optimize the practical condition of the soil additives, and the optimization result shows that the best and desirable practical condition for the root-permeated soil mixture is collected by adding 15.41% of water, 16.30% of copper slag, 0.82% of roots, and 28.14 of root aspect ratio, which it caused improvement of 40.62% in shear strength.

Through a numerical study conducted to study the settlement of a typical subgrade which utilizes the root-permeated soil mixture as subgrade filling, it is proved the use of root-permeated soil mixture could help to reduce soil settlement by about 54.76% and the strength is improved sufficiently for engineering applications.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

References

1. Gorai, B., Jana, R. K., Premchand (2003). Characteristics and utilisation of copper slag—a review. *Resources, Conservation and Recycling, 39(4),* 299–313. DOI 10.1016/S0921-3449(02)00171-4.
2. ICSG (2015). *The world copper fact book*. Lisbon, Portugal: International Copper Study Group.
3. Song, J. W. (2013). Study on the effect of copper slag admixtures to properties and structure of concrete. *Information Technology Journal, 12(23),* 7396–7400. DOI 10.3923/itj.2013.7396.7400.
4. Pappu, A., Saxena, M., Asolekar, S. R. (2007). Solid wastes generation in India and their recycling potential in building materials. *Building and Environment, 42(6),* 2311–2320. DOI 10.1016/j.buildenv.2006.04.015.
5. Yao, K., Chen, Q., Ho, J., Xiao, H., Lee, F. H. (2018). Strain-dependent shear stiffness of cement-treated marine clay. *Journal of Materials in Civil Engineering, 30(10),* 04018255. DOI 10.1061/(ASCE)MT.1943-5533.0002460.
6. Wang, J., Gutierrez, M. (2010). Discrete element simulations of direct shear specimen scale effects. *Géotechnique, 60(5),* 395–409.
7. Yao, K., Li, N., Chen, D. H., Wang, W. (2019). Generalized hyperbolic formula capturing curing period effect on strength and stiffness of cemented clay. *Construction and Building Materials, 199,* 63–71. DOI 10.1016/j.conbuildmat.2018.11.288.
8. Yao, K., Xiao, H., Chen, D. H., Liu, Y. (2019). A direct assessment for the stiffness development of artificially cemented clay. *Géotechnique, 69(8),* 741–747.
9. Behnood, A., Gharehveran, M. M., Asl, F. G., Ameri, M. (2015). Effects of copper slag and recycled concrete aggregate on the properties of CIR mixes with bitumen emulsion, rice husk ash, Portland cement and fly ash. *Construction and Building Materials, 96,* 172–180. DOI 10.1016/j.conbuildmat.2015.08.021.
10. Hassan, H. F., Al-Jabri, K. (2011). Laboratory evaluation of hot-mix asphalt concrete containing copper slag aggregate. *Journal of Materials in Civil Engineering, 23(6),* 879–885. DOI 10.1061/(ASCE)MT.1943-5533.0000246.
11. Oluwasola, E. A., Hainin, M. R., Aziz, M. M. A. (2016). Comparative evaluation of dense-graded and gap-graded asphalt mix incorporating electric arc furnace steel slag and copper mine tailings. *Journal of Cleaner Production, 122,* 315–325. DOI 10.1016/j.jclepro.2016.02.051.
12. Bharati, S. K., Chew, S. H. (2016). Geotechnical behavior of recycled copper slag-cement treated Singapore marine clay. *Geotechnical and Geological Engineering, 34(3),* 835–845. DOI 10.1007/s10706-016-0008-8.

13. Shanmuganathan, P., Lakshmipathiraj, P., Srikanth, S., Nachiappan, A. L., Sumathy, A. (2008). Toxicity characterization and long-term stability studies on copper slag from the ISASMELT process. *Resources, Conservation and Recycling, 52(4),* 601–611. DOI 10.1016/j.resconrec.2007.08.001.
14. Dash, M. K., Patro, S. K., Rath, A. K. (2016). Sustainable use of industrial-waste as partial replacement of fine aggregate for preparation of concrete–a review. *International Journal of Sustainable Built Environment, 5(2),* 484–516. DOI 10.1016/j.ijsbe.2016.04.006.
15. Abdelfattah, H. F., Al-Shamsi, K., Al-Jabri, K. (2018). Evaluation of rutting potential for asphalt concrete mixes containing copper slag. *International Journal of Pavement Engineering, 19(7),* 630–640. DOI 10.1080/10298436.2016.1199875.
16. Lori, A. R., Hassani, A., Sedghi, R. (2019). Investigating the mechanical and hydraulic characteristics of pervious concrete containing copper slag as coarse aggregate. *Construction and Building Materials, 197,* 130–142. DOI 10.1016/j.conbuildmat.2018.11.230.
17. Murari, K., Siddique, R., Jain, K. K. (2015). Use of waste copper slag, a sustainable material. *Journal of Material Cycles and Waste Management, 17(1),* 13–26. DOI 10.1007/s10163-014-0254-x.
18. Yao, K., Chen, Q., Xiao, H., Liu, Y., Lee, F. H. (2020). Small-strain shear modulus of cement-treated marine clay. *Journal of Materials in Civil Engineering, 32(6),* 04020114. DOI 10.1061/(ASCE)MT.1943-5533.0003153.
19. Yao, K., Pan, Y., Jia, L., Yi, J. T., Hu, J. et al. (2020). Strength evaluation of marine clay stabilized by cementitious binder. *Marine Georesources & Geotechnology, 38(6),* 730–743. DOI 10.1080/1064119X.2019.1615583.
20. Kubissa, W., Jaskulski, R., Ng, P. L., Chen, J. (2018). Utilization of copper slag waste and heavy-weight aggregates for production of pre-cast shielding concrete elements. *Journal of Sustainable Architecture and Civil Engineering, 22(1),* 39–48. DOI 10.5755/j01.sace.22.1.20006.
21. Prasad, P. S., Ramana, G. V. (2016). Feasibility study of copper slag as a structural fill in reinforced soil structures. *Geotextiles and Geomembranes, 44(4),* 623–640. DOI 10.1016/j.geotexmem.2016.03.007.
22. Fan, C. C., Su, C. F. (2008). Role of roots in the shear strength of root-reinforced soils with high moisture content. *Ecological Engineering, 33(2),* 157–166. DOI 10.1016/j.ecoleng.2008.02.013.
23. Pollen, N., Simon, A. (2005). Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. *Water Resources Research, 41(7),* 226–244. DOI 10.1029/2004WR003801.
24. Pallewattha, M., Indraratna, B., Heitor, A., Rujikiatkamjorn, C. (2019). Shear strength of a vegetated soil incorporating both root reinforcement and suction. *Transportation Geotechnics, 18,* 72–82. DOI 10.1016/j.trgeo.2018.11.005.
25. Mahannopkul, K., Jotisankasa, A. (2019). Influence of root suction on tensile strength of *Chrysopogon zizanioides* roots and its implication on bioslope stabilization. *Journal of Mountain Science, 16(2),* 275–284. DOI 10.1007/s11629-018-5134-8.
26. Norris, J. E. (2005). Root reinforcement by hawthorn and oak roots on a highway cut-slope in southern England. *Plant and Soil, 278(1–2),* 43–53. DOI 10.1007/s11104-005-1301-0.
27. Greenwood, J. R. (2006). SLIP4EX–a program for routine slope stability analysis to include the effects of vegetation, reinforcement and hydrological changes. *Geotechnical and Geological Engineering, 24(3),* 449–465. DOI 10.1007/s10706-005-4156-5.
28. Thomas, R. E., Pollen-Bankhead, N. (2009). Modeling root-reinforcement with a fiber-bundle model and Monte Carlo simulation. *Ecological Engineering, 36(1),* 47–61. DOI 10.1016/j.ecoleng.2009.09.008.
29. Ye, C., Guo, Z., Li, Z., Cai, C. (2017). The effect of Bahiagrass roots on soil erosion resistance of Aquults in subtropical China. *Geomorphology, 285,* 82–93. DOI 10.1016/j.geomorph.2017.02.003.
30. Shahbazi, M., Rowshanzamir, M., Abtahi, S. M., Hejazi, S. M. (2016). Optimization of carpet waste fibers and steel slag particles to reinforce expansive soil using response surface methodology. *Applied Clay Science, 142 (6),* 185–192. DOI 10.1016/j.clay.2016.11.027.
31. Tang, C. S., Shi, B., Zhao, L. Z. (2010). Interfacial shear strength of fiber reinforced soil. *Geotextiles and Geomembranes, 28(1),* 54–62. DOI 10.1016/j.geotexmem.2009.10.001.

32. Wang, Y., Guo, P., Shan, S., Yuan, H., Yuan, B. (2016). Study on strength influence mechanism of fiber-reinforced expansive soil using jute. *Geotechnical and Geological Engineering, 34(4),* 1079–1088. DOI 10.1007/s10706-016-0028-4.
33. Asskar, J. C., Mostafa, A. S., Saman, S. K. (2019). Mechanical properties soil stabilized with nano calcium carbonate and reinforced with carpet waste fibers. *Construction and Building Materials, 211,* 1094–1104. DOI 10.1016/j.conbuildmat.2019.03.306.
34. Gomes, S. I. L., Caputo, G., Pinna, N., Scott-Fordsmand, J. J., Amorim, M. J. B. (2015). Effect of 10 different TiO_2 and ZrO_2 (nano)materials on the soil invertebrate *Enchytraeus crypticus*. *Environmental Toxicology and Chemistry, 34(10),* 2409–2416. DOI 10.1002/etc.3080.
35. Taha, M. R., Taha, O. M. E. (2012). Influence of nano-material on the expansive and shrinkage soil behavior. *Journal of Nanoparticle Research, 14(10),* 1190. DOI 10.1007/s11051-012-1190-0.
36. Khuri, A. I., Mukhopadhyay, S. (2010). Response surface methodology. *Wiley Interdisciplinary Reviews: Computational Statistics, 2(2),* 128–149. DOI 10.1002/wics.73.
37. Mohammed, B. S., Adamu, M. (2018). Evaluating the static and dynamic modulus of elasticity of roller compacted rubbercrete using response surface methodology. *International Journal of Geometer, 14(41),* 186–192.
38. Toft, H. S., Svenningsen, L., Moser, W., Sorensen, J. D., Thogersen, M. L. (2016). Assessment of wind turbine structural integrity using response surface methodology. *Engineering Structures, 106(1),* 471–483. DOI 10.1016/j.engstruct.2015.10.043.
39. Goswami, S., Ghosh, S., Chakraborty, S. (2016). Reliability analysis of structures by iterative improved response surface method. *Structural Safety, 60,* 56–66. DOI 10.1016/j.strusafe.2016.02.002.
40. Chinese Standard (2008). *Chinese environmental quality standard for soils (GB-15618)*. Beijing, China: Chinese Environmental Protection Agency.
41. Cheng, T., Hu, R., Xv, W., Zhang, Y. (2017). Mechanical characterizations of oxidizing steel slag soil and application. *Periodica Polytechnica Civil Engineering, 61(4),* 815–823.
42. Zhang, D. B., Zhang, Y., Shen, Z., Cheng, T., Bai, Y. (2019). Evaluation and optimization of parameters in the measurement for airborne scanner using response surface method. *Measurement and Control, 52(5–6),* 354–368. DOI 10.1177/0020294019837992.
43. Zhang, D. B., Zhang, Y., Cheng, T. (2018). Measurement of grass root reinforcement for copper slag mixed soil using improved shear test apparatus and calculating formulas. *Measurement, 118,* 14–22. DOI 10.1016/j.measurement.2018.01.005.
44. Chinese Standard (2001). *Chinese geotechnical engineering specification (GB50021-2001)*. Beijing, China: China Building Industry Press.
45. Chinese Standard (2007). *Chinese test methods of soils for Highway Engineering (JTGE40-2007)*. Beijing, China: China Communications Press.