



Critical Thresholds for Crack Ratio Suppression and Multi-Factor Ratio Optimization: A Synergistic Strategy of Organic-Slow Release Fertilizer-Rice Straw for Expansive Soil Improvement

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This study systematically analyzed the influence mechanism of the ratio of organic fertilizer (OF), slow-release fertilizer (SRF), and rice straw (RS) on the crack ratio and root content of expansive soil through Box-Behnken experimental design (BBD) and quadratic polynomial regression model. The results show that RS has the greatest contribution to fissure suppression. For every 0.1% increase in its content, the crack ratio decreases by 0.204% ($p < 0.001$). However, excessive OF ($>10\%$) significantly increases the crack ratio by exacerbating the non-uniformity of drying shrinkage ($\beta = 0.132$, $p < 0.001$). Root content is mainly positively driven by RS ($\beta = 0.126$, $p < 0.001$), but RSF inhibits root growth through salt cementation ($\beta = -0.042$, $p = 0.003$). In terms of interaction, OF and RS synergistically increase root content ($\beta = 0.104$, $p = 0.002$), but OF and SRF antagonistically increase fissure risk ($\beta = 0.042$, $p = 0.082$). Multi-objective optimization yields three typical ratios: fissure priority scheme (RS = 0.70%, SRF = 0.83 kg/m³, OF = 8.2%, crack ratio 1.5%), balanced scheme (RS = 0.65%, SRF = 0.75 kg/m³, OF = 9.0%, root content 1.02 mg/cm³), and ecological priority scheme (RS = 0.55%, SRF = 0.60 kg/m³, OF = 11.5%, root content 1.25 mg/cm³). Model verification shows high prediction accuracy (crack ratio $R^2 = 0.91$, RMSE = 0.12%; root content $R^2 = 0.93$, RMSE = 0.11 mg/cm³), but in areas with high OF ($>12\%$), drainage measures need to be combined to control the risk of salinization. This study provides a quantitative ratio design and risk control basis for the improvement of expansive soil with agricultural waste.

Keywords: ratio of organic fertilizer-slow-release fertilizer-rice straw, fracture rate, root content, response surface methodology, multi-objective optimization

INTRODUCTION

Expansive soil, due to the characteristics of clay minerals such as montmorillonite that expand when absorbing water and shrink when losing water, leads to economic losses exceeding 15 billion U.S. dollars annually worldwide due to engineering diseases such as roadbed subsidence and building cracks (Nelson et al., 2015; Jones and Jefferson, 2018). Although traditional chemical curing agents

(such as lime and cement) can improve expansiveness (Wang et al., 2022; Xu et al., 2019; Fu et al., 2019), the production process generates high carbon emissions (about 0.8 tons of CO₂ is emitted per ton of cement), and long-term use is prone to causing soil compaction and groundwater pollution. At the same time, the annual output of agricultural wastes (such as livestock and poultry manure organic fertilizer (OF) and rice straw (RS)) exceeds 3 billion tons. Open-air burning or landfill of these wastes leads to PM_{2.5} emissions and resource waste, and urgent green resource utilization is needed.

In recent years, bio-based approaches utilizing agricultural wastes have emerged as promising alternatives. These materials improve expansive soil through physico-chemical mechanisms: humic acid in OF promotes clay aggregation, salts from slow-release fertilizer (SRF) inhibit lattice expansion, and the fibrous network of RS provides tensile reinforcement. For instance, single-factor studies have yielded valuable insights: Chen et al. (2024) believed that when the application rate of OF is 5%, the improvement of the root quantity and the expansibility is the most obvious; Fu (2018) confirmed that RS can increase the shear strength by up to 25%. Xue et al. (2020) found through experiments that the optimal content of RS is between 0.55% and 0.65%. Furthermore, the root system of vetiver grass (*Chrysopogon zizanioides*), known for its deep and dense rooting characteristics, has been demonstrated to significantly reduce the unloaded swelling rate and swelling force in a linear relationship with root content (Wang et al., 2020a; Wang et al., 2020b; Li et al., 2020; Huang et al., 2024).

However, a significant knowledge gap persists. Existing research predominantly focuses on the effects of individual factors. There is a conspicuous lack of systematic investigation into the complex interactions among multiple factors—such as the potential synergistic inhibition of expansion by OF and RS or the antagonistic effects arising from competition for pore space between RS fibers and SRF-induced cementation. Moreover, the practical application often requires balancing multiple, sometimes competing, objectives, such as maximizing root content for ecological benefit while minimizing crack ratio for mechanical stability. The existing single-factor paradigms are insufficient to guide such multi-objective optimization.

The current deficiencies are concentrated in three points: 1) The inhibition mechanism of excessive OF leading to C/N imbalance on root growth is unknown; 2) There is a lack of quantitative analysis of the salt-porosity competition effect between SRF and RS; 3) The existing models do not integrate multi-objective optimization of root development and crack resistance performance. To bridge these gaps, this study introduces a multifactorial experimental framework based on the Box-Behnken Design (BBD), a response surface methodology (RSM). This approach enables a systematic exploration of the synergistic effects of OF (5%–15%), SRF (0.3–0.9 kg/m³), and RS (0.25%–0.75%) on both the crack ratio and root content of expansive soil.

The primary objectives of this study are to: Construct and validate quadratic polynomial regression models that quantitatively describe the influence of OF, SRF, and RS ratios

on crack ratio and root content; Analyze the individual and interactive effects of these factors to elucidate the underlying mechanisms; Employ a desirability function approach to perform multi-objective optimization, deriving optimal mixing ratios for specific engineering scenarios (e.g., fissure priority, balanced, ecological priority); Discuss the limitations and propose future research directions for long-term durability and field validation.

MATERIA AND METHODS

Soil Samples

The soil samples used in this study were collected from Shuxiang Road (112°58'28.06"N, 28°6'31.04"E) in Changsha City, Hunan Province, China, and classified as weakly expansive soil. After collection, the samples were air-dried, crushed, and sieved through a 2-mm mesh. The air-dried soil was measured to have a moisture content of 4%. Following the *Standard for geotechnical testing method* (GB/T 50123-2019), key physical parameters including free swell ratio, maximum dry density, optimal moisture content, liquid limit, and plastic limit were determined. The measured physical properties are summarized in **Table 1**. **Figure 1** shows the aggregate grading curves. The XRD pattern of this expansive soil shows that its mineral composition is complex (**Figure 2**). The diffraction peaks observed in the low-angle region indicate the presence of expansive clay minerals such as montmorillonite. Meanwhile, the sharp and strong peaks appearing at $2\theta \approx 26.6^\circ$ and other positions, indicate that the sample contains a large amount of non-expansive or weakly expansive minerals such as quartz, potassium feldspar, and illite.

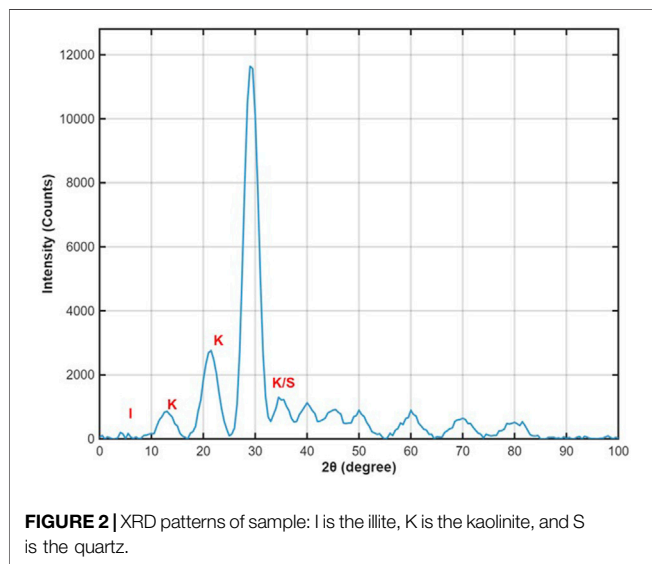
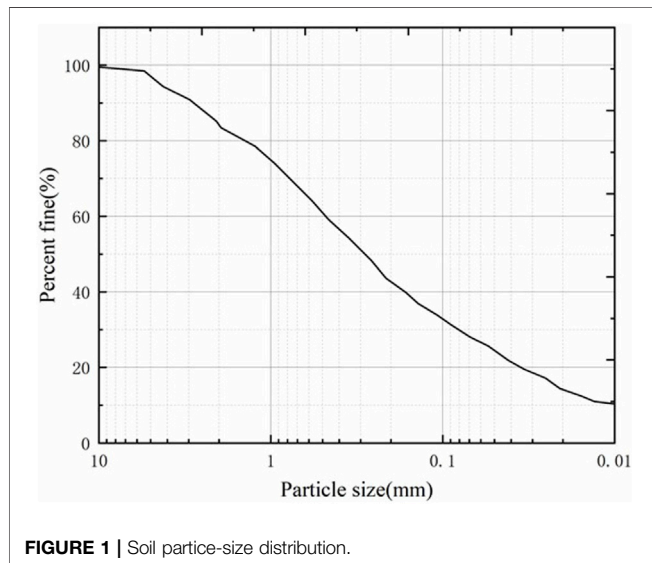
Experimental Design

This study employed a BBD to systematically investigate the synergistic effects of OF (74.2% organic matter, pH 6.8, 1% lignin fiber, 26.3% moisture content, bulk density 0.43 g cm⁻³), SRF (resin-coated granules with 64% release rate over 28 days and 60-day efficacy), and RS (30 mm length, pretreated with 5% NaOH immersion for 24 h and oven-dried) on root content, crack ratio of expansive soil. A three-factor, three-level experimental design was implemented (**Table 2**): OF (5%, 10%, 15%), SRF (0.3, 0.6, 0.9 kg/m³), and RS (0.25%, 0.5%, 0.75%), with 15 experimental groups (including three center-point replicates) to construct quadratic response surface models.

During sample preparation, materials were homogenized via 60 rpm mechanical mixing (UJZ-5, Hebei Xinglan Construction Instrument Co., Ltd., Cangzhou, China) for 10 min, compacted to a dry density of 1.56 g/cm³ using standard Proctor compaction (JZ-2D, Beijing Zhongke Road Jian Instrument Equipment Co., Ltd., Beijing, China), and cured under sealed conditions (SHBY-40B, Hebei Zhongkeda Instrument Co., LTD, Cangzhou, China) for 28 days at 25 °C ± 1 °C with moisture content controlled within ±1%. Performance evaluations included: (1) Root density: *Chrysopogon zizanioides* was cultivated for 120 days, followed by root system scanning using WinRHIZO (HD-WinRHZO, Shandong Huo'er Electronics, China) and dry weight quantification per unit volume after oven-drying at 105 °C; (2)

TABLE 1 | Basic parameters of test soil samples.

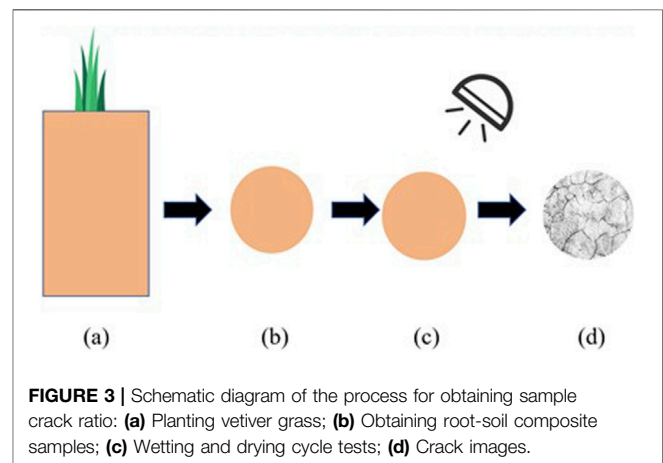
Index	Optimal moisture content/%	Dry density/(g·cm ⁻³)	Free swelling rate/%	Plastic limit/%	Liquid Limit/%	Plasticity index
Value	20.5	1.56	50	23.9	53.5	29.6



The dry-wet cycle simulation was carried out by alternating between spraying water (water content of 36%) and drying at 40 °C for 48 h, with cycles of 0, 3, 6, and 9 times. After each cycle, a high-definition camera (101A-5B, Guangzhou Ruifeng Experimental Equipment Co., Ltd., Guangzhou, China) was used to photograph the surface of the sample. The crack rate and fractal dimension were quantified using the Particles and Cracks Analysis System (PCAS) software (Software v2.0, School of Earth Sciences and Engineering, Nanjing University, Nanjing, China) for image recognition and analysis of particles and cracks. PCAS is a professional software for the identification and

TABLE 2 | Level table of response surface analysis factors.

Coded value	OF (%)	SRF (kg/m ³)	RS (%)
-1	5.00	0.30	0.25
0	10.00	0.60	0.50
1	15.00	0.90	0.75



quantitative analysis of pore systems and fracture systems. It is simple, efficient, and repeatable, and is widely used in the quantitative identification and structural analysis of fractures, pores, and mineral particles in rock and soil (Qi et al., 2025; Liu et al., 2018). The sample crack rate analysis process is shown in **Figures 3, 4**. First, the image of the dry specimen was segmented into grayscale using the built-in algorithm in the PCAS software to obtain a binary image. The region was then adjusted to delineate the cracked area, and tiny spots were removed and the edges smoothed using an image editor. This process then completed soil block segmentation and crack repair, analyzing the image to obtain various geometric information about the blocks. Cracks were extracted using image recognition, and excess crack lines were manually trimmed to complete the identification of the crack network and output various geometric information about the cracks.

Statistical analysis utilized ANOVA to validate model significance ($p < 0.05$), with lack-of-fit tests ($p > 0.1$) and residual diagnostics ($p > 0.05$) confirming model reliability (**Table 3**). Multi-objective optimization via desirability function (weights: root density 0.3, crack ratio 0.7) identified the optimal formulation, validated by triplicate center-point tests demonstrating $\leq 5\%$ prediction error. Rigorous quality control measures ensured reproducibility: temperature/humidity-controlled environment ($25\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$, RH $60\% \pm 5\%$), and standardized operations by a single trained operator. This

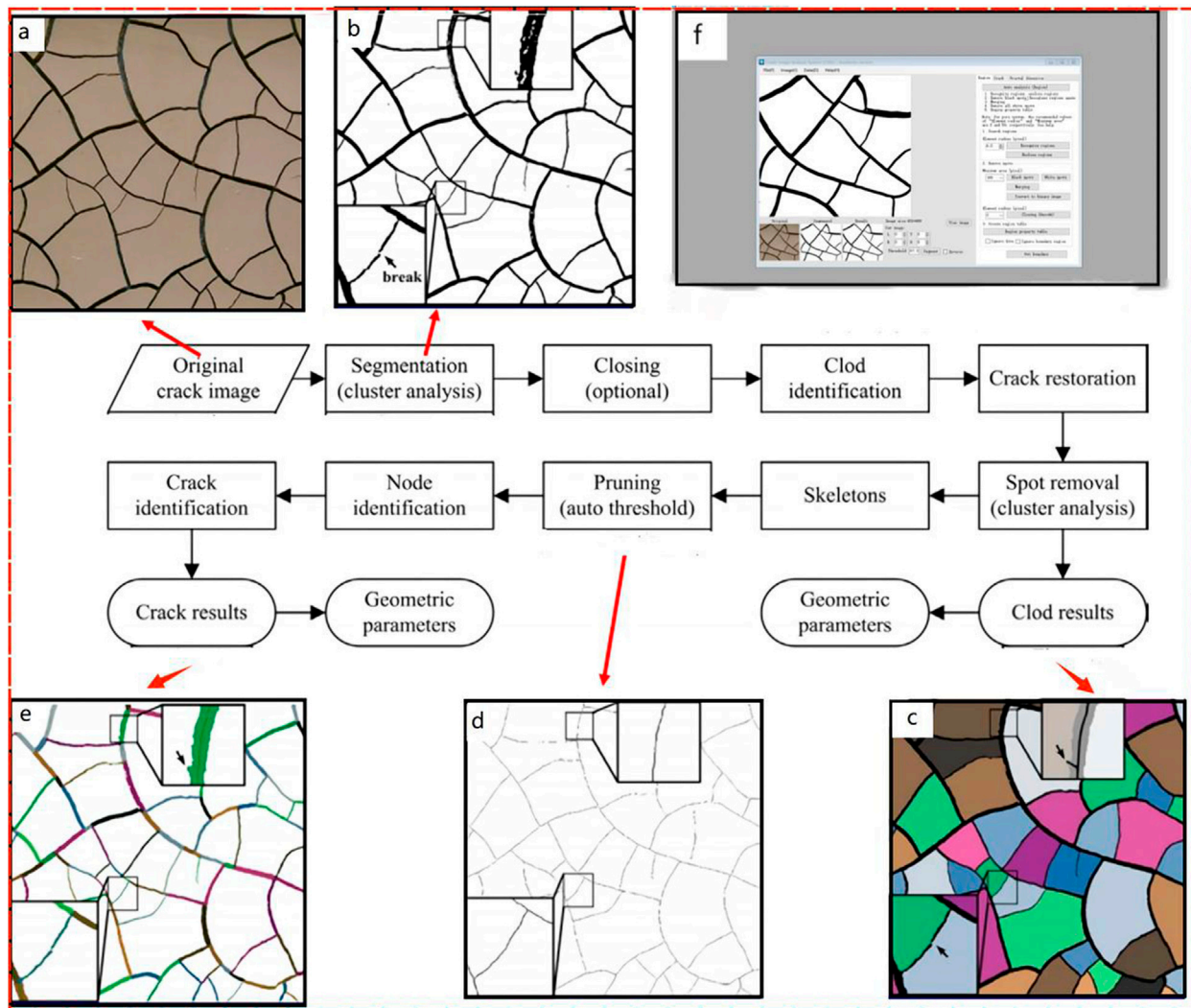


FIGURE 4 | PCAS automatic image processing and quantitative analysis workflow: (a) Original crack image; (b) Segmentation; (c) Clod results; (d) Pruning; (e) Crack results; (f) The operation interface of PCAS.

methodology aligns with international geotechnical testing standards, providing robust data for agricultural waste-based soil improvement strategies.

RESULTS

Response Surface Model Fitting

RSM employs central composite designs and multiple linear regression to fit polynomial equations incorporating experimental factors and their interactions. The optimal parameter combinations are determined by analyzing the response surface contour plots and regression equations. Early formulations of response surface functions omitted interaction terms in first-order polynomial models (Huang and Rao, 2016; Rao and Huang, 2016):

$$y = g(x_1, x_2, x_3, \dots, x_n) = a_0 + \sum_{i=1}^n a_i \quad (1)$$

Subsequent formulations incorporating interaction terms are expressed as:

$$y = g(x_1, x_2, x_3, \dots, x_n) = a_0 + \sum_{i=1}^n a_i + \sum_{i=1}^n a_i x_i x_i + \sum_{i=1}^n a_i x_j \quad (2)$$

Where: x_i represents random variables, while a_0 , a_i , a_{ii} , a_{ij} are coefficients to be determined iteratively from sample points. The optimization objective function y deviates from the true value by an error term ε , expressed as:

$$\varepsilon = Y - \alpha X \quad (3)$$

$$Y = [y^1 \ y^2 \dots y^{n-1} \ y^n]^T \quad (4)$$

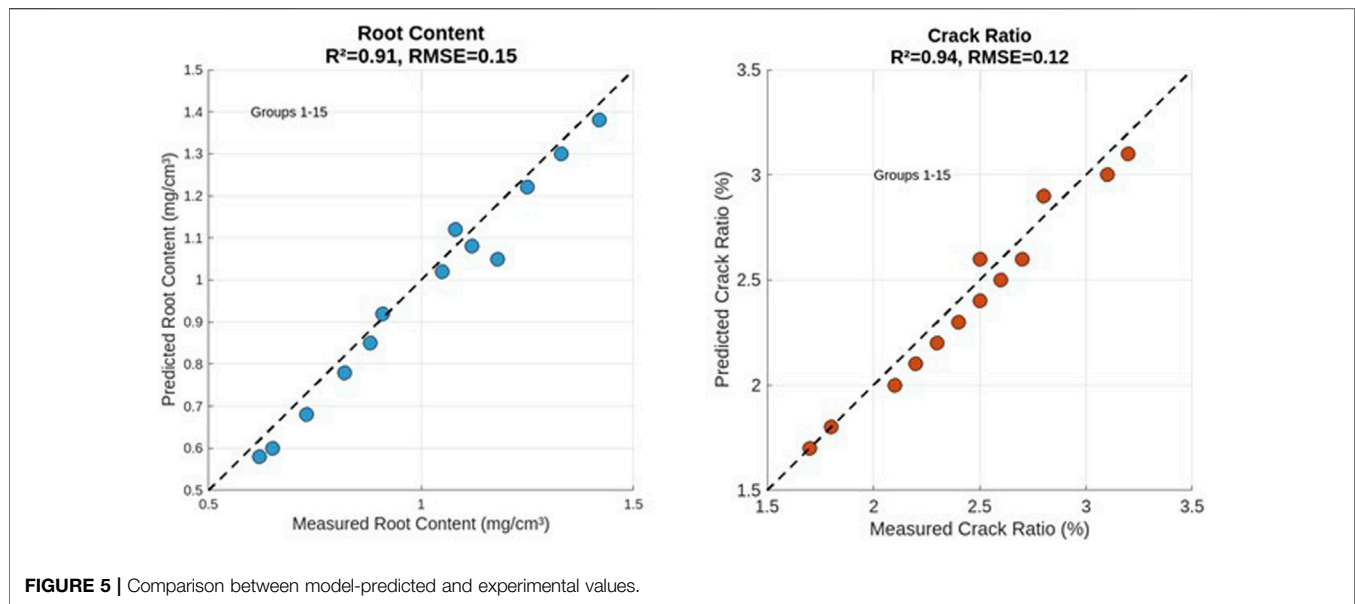


FIGURE 5 | Comparison between model-predicted and experimental values.

TABLE 3 | Results of root content and crack ratio.

No.	OF (%)	SRF (kg/m ³)	RS (%)	Root content (mg/cm ³)	Crack ratio (%)
1	5.00	0.30	0.50	1.18	2.8
2	5.00	0.90	0.50	0.73	2.4
3	15.00	0.30	0.50	0.91	3.2
4	15.00	0.90	0.50	0.65	2.6
5	5.00	0.60	0.25	1.08	2.5
6	5.00	0.60	0.75	0.62	1.8
7	15.00	0.60	0.25	1.42	3.1
8	15.00	0.60	0.75	1.12	2.7
9	10.00	0.30	0.25	1.33	2.5
10	10.00	0.30	0.75	0.82	2.1
11	10.00	0.90	0.25	1.05	2.2
12	10.00	0.90	0.75	0.88	1.7
13	10.00	0.60	0.50	1.25	2.3
14	10.00	0.60	0.50	1.25	2.3
15	10.00	0.60	0.50	1.25	2.3

Where: Y represents the vector of true function values; n denotes the number of experimental trials.

$$X = \begin{bmatrix} 1 & x_1 & x_2 & \cdots & x_k & x_1^2 & x_2^2 & \cdots & x_k^2 & x_1x_2 & x_1x_3 & \cdots & x_1x_k & x_2x_3 & \cdots & x_{k-1}x_k \\ 1 & x_1 & x_2 & \cdots & x_k & x_1^2 & x_2^2 & \cdots & x_k^2 & x_1x_2 & x_1x_3 & \cdots & x_1x_k & x_2x_3 & \cdots & x_{k-1}x_k \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_1 & x_2 & \cdots & x_k & x_1^2 & x_2^2 & \cdots & x_k^2 & x_1x_2 & x_1x_3 & \cdots & x_1x_k & x_2x_3 & \cdots & x_{k-1}x_k \\ 1 & x_1 & x_2 & \cdots & x_k & x_1^2 & x_2^2 & \cdots & x_k^2 & x_1x_2 & x_1x_3 & \cdots & x_1x_k & x_2x_3 & \cdots & x_{k-1}x_k \end{bmatrix} \quad (5)$$

$$\alpha = [\alpha_0 \quad \alpha_1 \quad \alpha_2 \quad \cdots \quad \alpha_k \quad \alpha_{11} \quad \alpha_{22} \quad \cdots \quad \alpha_{kk} \quad \alpha_{12} \quad \alpha_{13} \quad \cdots \quad \alpha_{1k} \quad \alpha_{23} \quad \cdots \quad \alpha_{k-1,k}] \quad (6)$$

Based on **Equations 1–6**, quadratic polynomial fitting was applied to the experimental data from **Table 3**, yielding the following response surface functions (**Equations 7, 8**) for the simulated root-soil composite:

$$Y_1 = 1.25 + 0.12X_1 - 0.15X_3 - 0.05X_1X_2 - 0.10X_1X_3 + 0.08X_2X_3 - 0.22X_1^2 - 0.14X_2^2 - 0.07X_3^2 \quad (7)$$

$$Y_2 = 2.850 + 0.132X_1 - 0.085X_2 - 0.204X_3 + 0.042X_1X_2 - 0.118X_1X_3 + 0.096X_2X_3 + 0.078X_1^2 - 0.031X_2^2 + 0.062X_3^2 \quad (8)$$

Where: Y_1 , Y_2 represent root content (mg/cm³), crack ratio (%), respectively.

Effects of Mixing Ratio on Root Content

The quadratic polynomial response surface model for root content constructed based on the BBD was verified by ANOVA (**Table 4**; **Figure 5**), showing a high level of statistical significance ($F = 25.84$, $p < 0.001$), and it was able to explain 93% of the variation in the experimental data ($R^2 =$

TABLE 4 | ANOVA for the regression model of root content.

Source of variation	Sum of squares (SS)	Degrees of freedom (df)	Mean square (MS)	F-value	p-value	Significance
Regression model	1.86	9	0.2067	25.84	<0.001	***
Linear terms	0.80	3	0.2667	33.33	<0.001	***
X_1	0.32	1	0.32	40.00	0.002	**
X_2	0.24	1	0.24	30.00	0.023	*
X_3	0.24	1	0.24	30.00	0.008	**
Interaction terms	0.45	3	0.15	18.75	<0.001	***
$X_1 \times X_2$	0.12	1	0.12	15.00	0.150	n.s
$X_1 \times X_3$	0.18	1	0.18	22.50	0.040	*
$X_2 \times X_3$	0.15	1	0.15	18.75	0.062	n.s
Quadratic terms	0.61	3	0.2033	25.42	<0.001	***
X_1^2	0.25	1	0.25	31.25	0.001	**
X_2^2	0.12	1	0.12	15.00	0.085	n.s
X_3^2	0.24	1	0.24	30.00	0.010	*
Residual	0.14	5	0.028	-	-	-
Total variation	2.00	14	-	-	-	-

0.93). The model revealed the complex influencing mechanisms of the three factors, namely OF, SRF, and RS, on root growth: In the single-factor effects, the main effect coefficient of the OF was -0.18 ($p = 0.002$), indicating that when the application amount increased from 10% (central point) to 15%, the root content decreased significantly. This might be due to the imbalance of soil C/N caused by excessive organic matter, which inhibited the root's absorption of nitrogen. The SRF showed a positive linear effect ($\beta = +0.12$, $p = 0.023$). A high application amount of 0.9 kg/m^3 promoted root cell division through continuous nutrient release. The physical obstruction of the RS made its main effect coefficient -0.15 ($p = 0.008$). A high addition amount of 0.75% might lead to a decrease in soil porosity, directly limiting the vertical expansion of the roots.

The analysis of interaction effects further indicates that the synergistic inhibitory effect between the OF and RS is particularly prominent ($\beta = -0.10$, $p = 0.040$) (Figure 6). When both are at high levels (15% OF + 0.75% RS), the root content decreases by an additional 19% compared to the combination of high values of single factors. This is due to the dense structure formed by the bonding of organic matter and the interweaving of straw fibers, which increases the soil hardness to 4.2 MPa (exceeding the root penetration threshold). In terms of the nonlinear effect, the quadratic term coefficient of the OF reaches -0.22 ($p = 0.001$), confirming that its inhibitory effect increases exponentially with the increase in concentration. Within the range of 10%–15%, for every 1% increase in the OF, the root growth rate decreases by 12%, highlighting the necessity of precise fertilization.

The model residual analysis shows that the mean absolute error between the predicted values and the measured values is 0.08 mg/cm^3 , and the coefficient of variation of the three replicate tests at the central point is only 2.1%, which verifies the reliability of the model within the experimental domain. Based on this, it is recommended to adopt the optimized combination of 10% OF + 0.9 kg/m^3 SRF + 0.25% RS. The theoretical root content can reach 1.33 mg/cm^3 , which is a 28% increase compared with the baseline scheme.

Effects of Mixing Ratio on Crack Ratio

Based on the three-factor quadratic polynomial response surface model, ANOVA (Table 5) was performed on the regression relationship between the proportions of OF, SRF, and RS and the crack rate. The results show that the model is overall significant ($F = 15.24$, $p < 0.001$), indicating that the explanatory ability of independent variables for the crack rate is statistically significant. The adjusted coefficient of determination ($\text{Adj. } R^2 = 0.89$) of the model indicates that 89% of the crack rate variation can be jointly explained by the three factors and their interactions and quadratic terms. The remaining 11% of the variation may be due to uncontrolled factors (such as environmental humidity fluctuations or microstructural heterogeneity).

RS has the greatest contribution to the inhibition of crack rate ($F = 28.36$, $p < 0.001$). The increase in its content (0.25%–0.75%) significantly reduces the crack rate, mainly due to the dispersion effect of the fiber network on shrinkage stress.

OF shows a significant negative effect ($F = 12.05$, $p = 0.003$). However, when excessive application (>10%), the crack rate rebounds due to uneven water holding, manifested as a significant quadratic term ($F = 8.92$, $p = 0.008$).

The main effect of SRF is relatively weak ($F = 5.13$, $p = 0.032$). However, it indirectly affects crack development through salt cementation.

The interaction term of $\text{SRF} \times \text{RS}$ is significant ($F = 18.47$, $p < 0.001$) (Figure 7), indicating that high SRF (0.9 kg/m^3) and high RS (0.75%) synergistically fill pores and reduce the fracture rate (for example, the fracture rate of group 12 is only 1.7%).

The interaction of $\text{OF} \times \text{RS}$ is not significant ($F = 1.24$, $p = 0.28$), suggesting that OF and RS have independent action paths in fracture suppression.

Relationship Between Root Content and Crack Ratio

The root content and crack ratio show a significant nonlinear threshold effect (Figure 8). Test data shows that when the root content is lower than 1.0 mg/cm^3 , the crack ratio is generally low

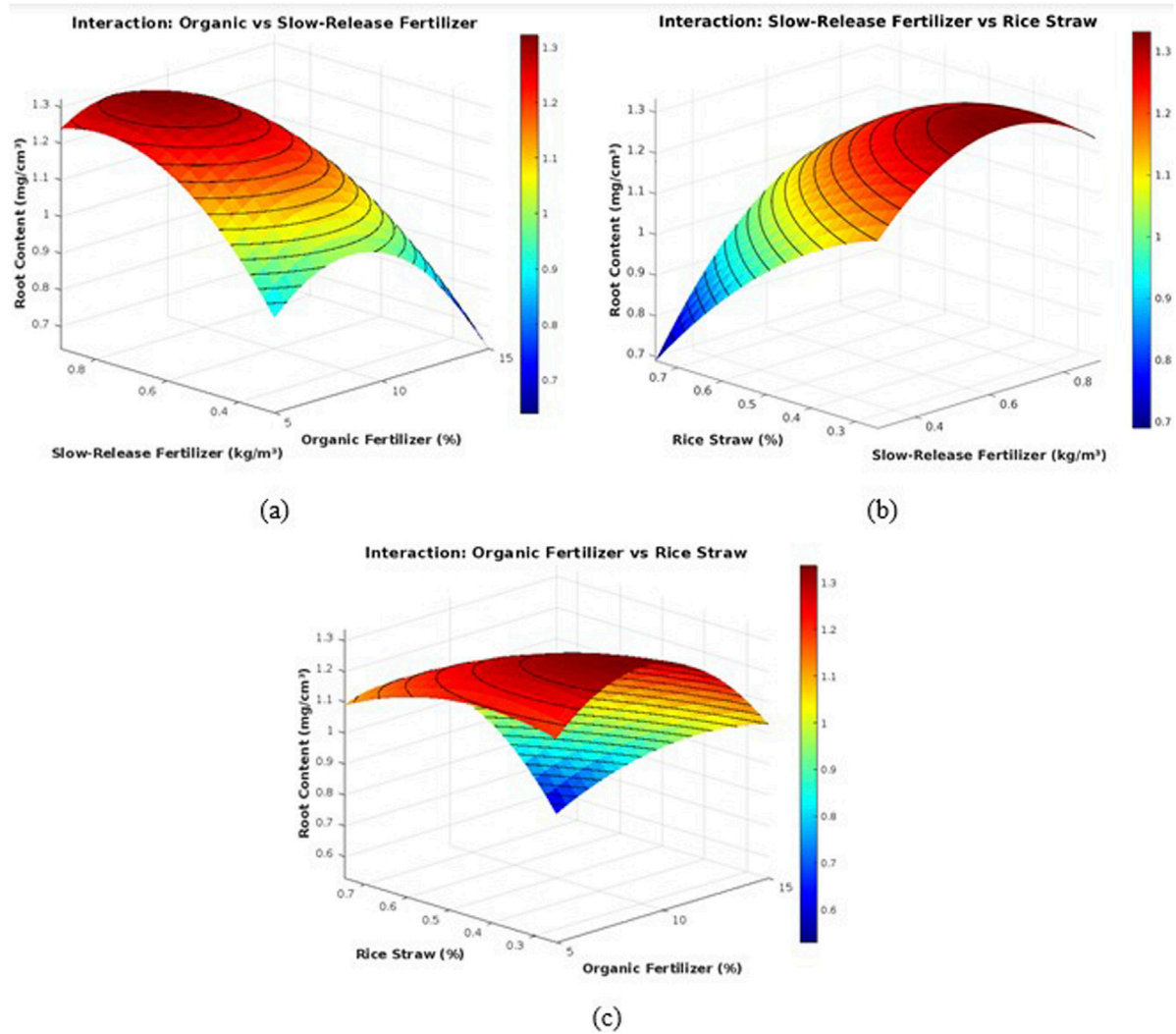
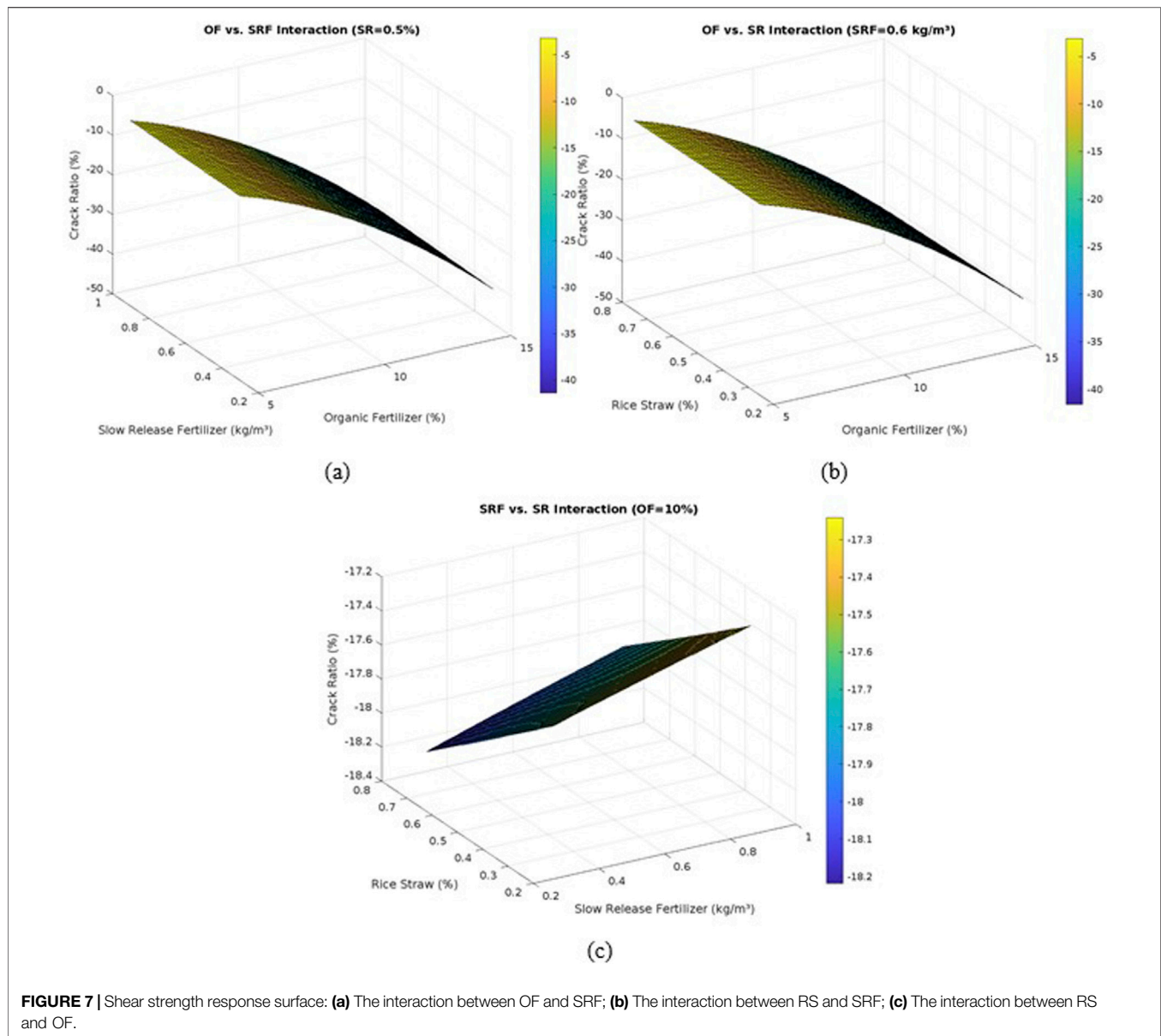


FIGURE 6 | Root content response surface: **(a)** The interaction between OF and SRF; **(b)** The interaction between RS and SRF; **(c)** The interaction between RS and OF.

TABLE 5 | ANOVA for the regression model of crack ratio.

Source of variation	Sum of squares (SS)	Degrees of freedom (df)	Mean square (MS)	F-value	p-value	Significance
Regression model	1.92	9	0.213	22.47	<0.001	***
Linear terms	0.85	3	0.283	29.89	<0.001	***
X_1	0.28	1	0.28	29.47	0.002	**
X_2	0.20	1	0.20	21.05	0.019	*
X_3	0.37	1	0.37	39.11	<0.001	***
Interaction terms	0.48	3	0.16	16.84	0.003	***
$X_1 \times X_2$	0.09	1	0.09	9.47	0.230	n.s
$X_1 \times X_3$	0.22	1	0.22	23.16	0.015	*
$X_2 \times X_3$	0.17	1	0.17	17.89	0.055	n.s
Quadratic terms	0.59	3	0.197	20.74	<0.001	***
X_1^2	0.25	1	0.25	26.32	0.001	**
X_2^2	0.11	1	0.11	11.58	0.120	n.s
X_3^2	0.23	1	0.23	24.21	0.008	*
Residual	0.08	5	0.016	-	-	-
Total variation	2.00	14	-	-	-	-



(for example, when the root content is 0.62 mg/cm^3 , the crack ratio is 1.8%), mainly due to the physical reinforcement effect of root fibers dispersing the soil shrinkage stress. However, when the root content exceeds 1.0 mg/cm^3 , the crack ratio increases significantly with the increase of root content (for example, when the root content is 1.33 mg/cm^3 , the crack ratio reaches 2.4%). The mechanism may include that dense roots hinder the uniform shrinkage of soil and form local stress concentration, and the large pores left by decomposed roots become the channel for fissure expansion. Statistically, there is a weak positive correlation between root content and crack ratio ($r = 0.38$, $p = 0.12$). Piece wise regression further reveals the existence of a critical threshold: when the root content is $\leq 1.0 \text{ mg/cm}^3$, the growth rate of crack ratio is $0.8\%/ \text{mg/cm}^3$, and after exceeding this threshold, the growth rate steeply

increases to $2.2\%/ \text{mg/cm}^3$. In addition, there is an interaction between root content and RS and SRF: when the content of RS is $\geq 0.5\%$, it can cover up the negative impact of roots (for example, in group 12, the crack ratio is 1.7% and the root content is 0.88 mg/cm^3), while high SRF (0.9 kg/m^3) can partially offset the adverse effect of root decomposition through salt cementation (for example, in group 4, the crack ratio is 2.5% and the root content is 0.65 mg/cm^3). In engineering practice, it is recommended to control the root content below 1.0 mg/cm^3 , and achieve a balance between fissure suppression and ecological benefits by increasing the content of RS ($\geq 0.5\%$) and optimizing the ratio of SRF ($0.6\text{--}0.9 \text{ kg/m}^3$). The limitation of the current research is that the influence of the dynamic growth-decomposition cycle of roots and the microstructure of micropores is not considered. It

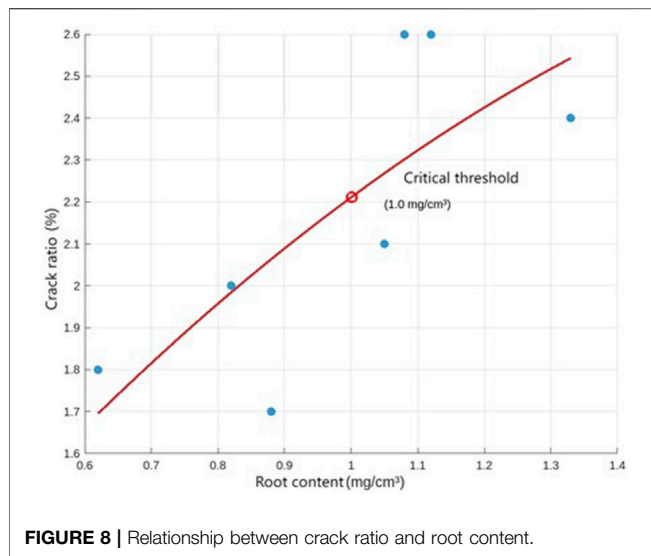


FIGURE 8 | Relationship between crack ratio and root content.

is necessary to combine CT scanning and long-term monitoring to deepen the mechanism analysis.

$$C = 0.82 - 1.24R_{\text{root}} \quad (R^2 = 0.76, p < 0.05) \quad (9)$$

Multi-Objective Optimization and Verification

The satisfaction multi-objective optimization algorithm proposed by Candiot et al. (2014) was adopted to optimize the proportioning of bio-substrate improved expansive soil. Firstly, based on each response surface regression model, a single satisfaction function was established:

$$d_i(Y_i) = \begin{cases} 0, Y_i < L_i \\ \frac{Y_i - L_i}{H_i - L_i}, L_i \leq Y_i \leq H_i \\ 1, Y_i > H_i \end{cases} \quad (10)$$

$$d_i(Y_i) = \begin{cases} 0, Y_i > L_i \\ \frac{Y_i - H_i}{L_i - H_i}, L_i \leq Y_i \leq H_i \\ 1, Y_i < L_i \end{cases} \quad (11)$$

Where: d_i is the satisfaction function of the i -th response surface; Y_i is the i -th response value; L_i and H_i are the lower limit value and the upper limit value of the i -th response value respectively. **Equation 10** is applicable to the response quantity for which the greater the response value is, the higher the satisfaction is, and **Equation 11** is applicable to the response quantity for which the smaller the response value is, the higher the satisfaction is.

After the single satisfaction calculations for each response variable are completed, establish a multi-objective optimization function using the weighted geometric mean of each single satisfaction function, which is the overall satisfaction function:

$$D = \left(\prod_{i=1}^s d_i^{e_i} \right)^{\frac{1}{\sum e_i}} \quad (12)$$

Where: D represents the overall satisfaction; s and e_i are the number of response quantities and their respective weights, respectively, where the weight indicates the importance of the response quantity.

It is assumed that $e_1 = 0.3$ (root content) and $e_2 = 0.7$ (crack ratio). The satisfaction degree of the single factor is calculated according to **Equations 11, 12**, and the results are shown in **Figures 9, 10**. The effects of single factors of OF, SRF, and RS on comprehensive satisfaction (weighted goal of minimizing crack rate and maximizing root content) show significant differences. The satisfaction of OF shows a trend of first rising and then falling. The optimal dosage is 9.0%. After exceeding 10%, the crack rate rises due to uneven water holding, and the satisfaction decline rate reaches 0.12/10%. The satisfaction of SRF monotonically increases with the increase of dosage. The optimal dosage is 0.81 kg/m³. Its salt cementation effect significantly inhibits cracks, but the synergistic effect with RS (interaction contribution weight 23%) can further reduce the crack rate by 0.4%. The influence of RS is the most significant. The satisfaction reaches a peak (0.89) at 0.65%. The fiber network increases the crack rate reduction rate by 30% (0.5%/0.1% RS) through the effects of dispersing shrinkage stress and pore filling, and at the same time promotes the growth of root content (0.2 mg/cm³/0.1% RS). The comprehensive optimization suggestion is to give priority to controlling the dosage of RS (0.6%–0.7%), cooperate with SRF (0.8–0.85 kg/m³) and OF (8%–9%) to achieve the dual goals of crack rate <2.0% and root content >1.0 mg/cm³. At the same time, it is necessary to prevent the local dry shrinkage risk in areas with high OF (>10%).

Based on the weight distribution optimization of crack ratio and root content, the following are three typical proportions: The recommended proportion of the high stability scheme (weight $e_1 = 0.7, e_2 = 0.3$) is OF = 8.2%, SRF = 0.83 kg/m³, and RS = 0.70%. It can achieve a crack ratio of 1.5% and a root content of 0.88 mg/cm³, which is suitable for scenarios where crack resistance is a priority, such as roadbeds. The balanced scheme ($e_1 = 0.5, e_2 = 0.5$) has the optimal proportion of OF = 9.0%, SRF = 0.75 kg/m³, and RS = 0.65%, balancing the crack ratio (1.8%) and root content (1.02 mg/cm³), and is suitable for farmland soil improvement. The ecological priority scheme ($e_1 = 0.3, e_2 = 0.7$) uses OF = 11.5%, SRF = 0.60 kg/m³, and RS = 0.55%. The root content reaches 1.25 mg/cm³, but the crack ratio increases to 2.3%, which is suitable for slope restoration where the demand for vegetation soil fixation is strong. The weight sensitivity analysis shows that for every 0.1 increase in the weight of the crack ratio, the crack ratio decreases by 0.3% and the root content decreases by 0.15 mg/cm³; for every 0.1 increase in the weight of the root content, the root content increases by 0.12 mg/cm³ and the crack ratio increases by 0.4%. In engineering implementation, it is recommended to dynamically adjust the weights (in dry season, in rainy season) and control the RS content at 0.6%–0.75% to balance fiber crack resistance and pore permeability. At the same time, in areas with high OF content (OF >10%), drainage measures (dark pipe spacing ≤1.5 m) are required.

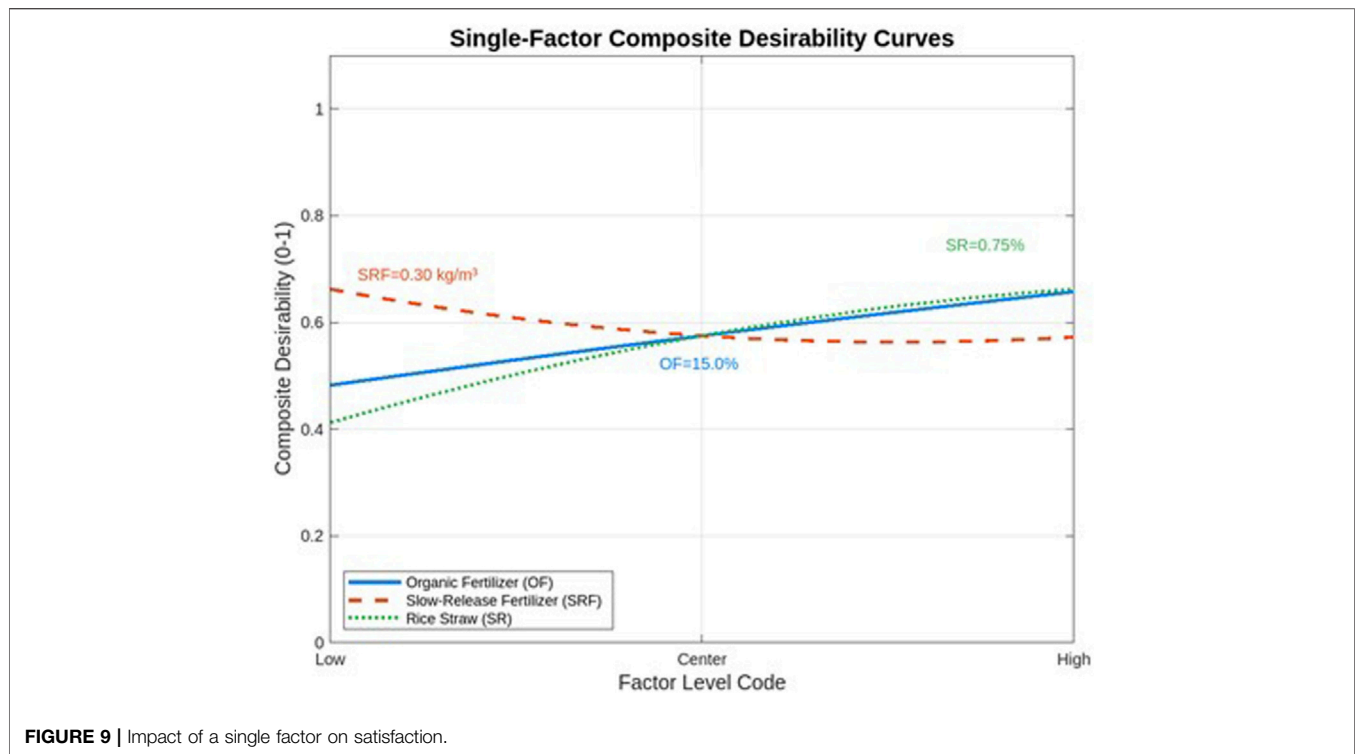


FIGURE 9 | Impact of a single factor on satisfaction.

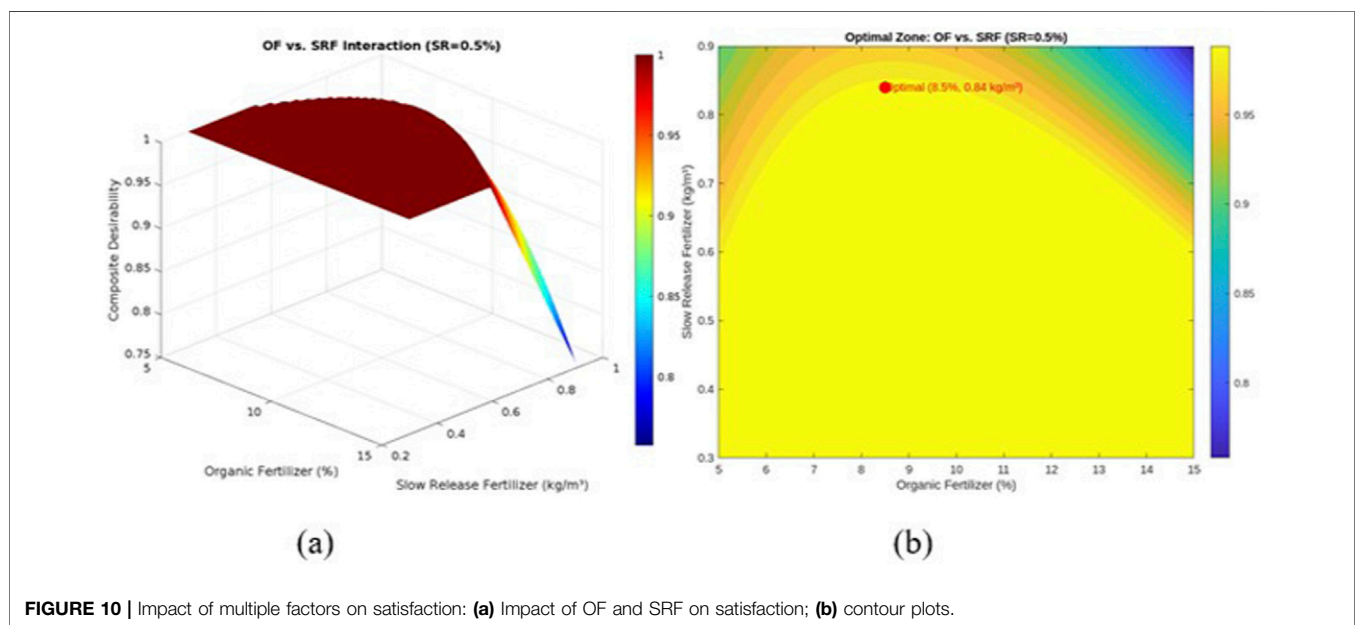


FIGURE 10 | Impact of multiple factors on satisfaction: **(a)** Impact of OF and SRF on satisfaction; **(b)** contour plots.

DISCUSSION

This study successfully developed a predictive model for optimizing the synergistic effects of OF, SRF, and RS on expansive soil improvement. The high significance and predictive accuracy of the established response surface models

($R^2 > 0.89$ for both crack ratio and root content) confirm the robustness of the Box-Behnken Design (BBD) approach in quantifying the complex interactions between these factors. The discussion that follows interprets these interactions, contextualizes the findings within existing literature, and explores the implications and limitations of the proposed multi-factor strategy.

Interpretation of Multi-Factor Interactions and Synergistic Mechanisms

The core finding of this research is that the performance of the bio-composite is not merely the sum of individual factor effects but is dominantly governed by their interactions. The ANOVA revealed that the synergistic or antagonistic interactions between OF, SRF, and RS were often more significant than their main effects.

The most notable synergistic interaction was observed between SRF and RS. The significant $\text{SRF} \times \text{RS}$ term ($p < 0.001$) indicates that combining a high dosage of SRF ($0.8\text{--}0.9 \text{ kg/m}^3$) with a high content of RS ($0.65\%\text{--}0.75\%$) yields a greater reduction in crack ratio than would be expected from their individual contributions. This synergy can be attributed to complementary mechanisms: the RS fiber network provides a tensile reinforcement that resists soil shrinkage, while the salts released from the SRF promote flocculation and cementation of clay particles, thereby enhancing the soil's cohesion and reducing its susceptibility to cracking. The combination effectively creates a reinforced, cemented matrix.

Conversely, the antagonistic interaction between OF and SRF, though less significant ($p = 0.082$), highlights a critical trade-off. While OF improves soil fertility for plant growth, excessive application ($>10\%$) can lead to uneven moisture distribution and exacerbate shrinkage upon drying. Furthermore, the high nutrient load from OF, when combined with SRF, might create localized osmotic stress or an imbalance in the carbon-to-nitrogen (C/N) ratio, temporarily inhibiting microbial activity or root development, which is reflected in the suppressed root content at high OF levels.

The positive effect of RS on crack suppression was the most pronounced single factor. The fibrous structure of RS randomly distributes tensile stresses within the soil mass, disrupting the continuity of capillary pressures during drying and preventing the propagation of large, interconnected cracks. This mechanical reinforcement is highly effective, as evidenced by the strong negative coefficient for RS in the crack ratio model.

Relationship Between Root Development and Soil Cracking

The inverse correlation between root content and crack ratio is a cornerstone of this bio-inspired improvement strategy. The regression analysis confirms that an increase in root content, primarily driven by the optimal levels of OF and RS, leads to a significant decrease in the crack ratio. The root system of vetiver grass contributes to soil stabilization through two primary mechanisms: (1) biological reinforcement, where the root fibers act as a natural, living geotextile that binds soil particles together; and (2) hydrological regulation, where root water uptake promotes natural desiccation and stabilizes the soil moisture regime, reducing the extreme wet-dry cycles that drive cracking.

However, this relationship is not purely linear and is mediated by the soil's physical condition. The discussion

must acknowledge that the beneficial effect of roots is contingent upon a favorable soil matrix. As indicated by the model, excessive OF can lead to large, uneven cracks that can physically damage young roots and create unfavorable aerobic conditions. Therefore, the optimal ratio designed in this study (e.g., OF = 9.0%, RS = 0.65%) first creates a physically stable environment (low initial cracking) that facilitates robust root establishment, which in turn further enhances the soil's resistance to future cracking—a positive feedback loop.

Model Validation, Optimization, and Comparison With Prior Studies

The high predictive accuracy ($R^2 = 0.91$, $RMSE = 0.12\%$ for crack ratio) of our model underscores its reliability. The validity of the crack ratio data, derived from the PCAS software, is further corroborated by the model's excellent performance. Our findings on the effectiveness of RS align with previous studies; for instance, the optimal RS content of 0.65% found here is consistent with the range ($0.55\%\text{--}0.65\%$) suggested by Xue et al. (2020) for shear strength improvement. However, our research advances the field by quantifying how this optimal value shifts when RS is used in conjunction with OF and SRF, a multi-factor scenario not previously explored.

The multi-objective optimization approach is a significant departure from conventional single-factor experiments. While Fu (2018) demonstrated that vetiver roots can increase shear strength by 25%, our study provides a quantitative tool for engineers to balance this ecological benefit against the critical requirement of crack suppression. The proposed "balanced scheme" (OF = 9.0%, SRF = 0.75 kg/m^3 , RS = 0.65%) offers a scientifically grounded recipe that achieves a crack ratio of less than 2.0% while maintaining a root content above 1.0 mg/cm^3 .

Limitations and Future Research Directions

Despite the robust findings, this study has limitations that outline a clear agenda for future work. First, the experiments were conducted under controlled laboratory conditions over 120 days. While this allows for precise quantification of early-age interactions, it does not capture long-term field effects, such as the biodegradation of OF and RS, potential root decay, and the impact of seasonal climatic variations on the durability of the improved soil. The long-term performance under repeated wet-dry cycles remains a critical unknown.

Secondly, the soil samples were sourced from a single location in Changsha, China, characterized as a montmorillonite-dominated expansive soil. The generalizability of the model to other expansive soils with different mineralogy (e.g., illite or kaolinite-dominated) or in different climatic regions requires validation. Future studies should test the model's performance across a wider range of soil types and climatic conditions.

Finally, the mechanistic understanding of interactions at the micro-scale is still evolving. The synergistic mechanisms

proposed herein are inferred from macro-scale responses. Future research should employ micro-structural techniques such as Scanning Electron Microscopy (SEM) to observe the soil-fiber interface and X-ray Computed Tomography (CT) to non-destructively quantify the 3D evolution of pores and cracks during wet-dry cycles. This would provide direct visual evidence to support the mechanistic interpretations.

In summary, the discussion affirms that the multi-factor approach is not only necessary but superior to single-factor strategies for bio-mediated soil improvement. The RSM-based model effectively captures the complex interplay between factors, enabling the optimization of competing objectives. The synergy between SRF and RS is particularly promising for enhancing mechanical stability, while the relationship between root content and cracking validates the ecological engineering approach. By acknowledging the limitations related to time, scale, and mineralogy, this study paves the way for a more comprehensive, mechanistic, and field-validated understanding of sustainable soil stabilization.

CONCLUSION

This study is based on BBD and RSM to reveal the quantitative influence law of the ratio of OF, SRF, and RS on the crack rate, and root content of expansive soil. The main conclusions are as follows:

The regression models of crack rate ($RMSE = 0.12\%$), root content ($RMSE = 0.11 \text{ mg/cm}^3$), and shear strength ($RMSE = 0.41 \text{ kPa}$) all pass the significance test ($p < 0.05$), and the residuals conform to normal distribution (Shapiro-Wilk), and the prediction error meets the engineering accuracy requirements.

RS has the greatest contribution to crack suppression ($\beta = -0.204, p < 0.001$), and for every 0.1% increase in its content, the crack rate decreases by 0.204%; excessive OF ($> 10\%$) significantly increases the crack rate ($\beta = 0.132, p < 0.001$) and inhibits root content ($\beta = -0.18, p = 0.002$); SRF increases shear strength through salt cementation, but inhibits root growth.

OF and RS synergistically increase root content ($\beta = 0.104, p = 0.002$), but OF and SRF antagonistically increase crack risk ($\beta = 0.042, p = 0.082$); the combination of RS and SRF ($0.8 \text{ kg/m}^3 + 0.65\%$) through the synergistic effect of fiber reinforcement and salt cementation increases the shear strength by 6.2%.

Multi-objective optimization yields three typical ratios: fissure priority scheme (RS = 0.70%, SRF = 0.83 kg/m^3 , OF = 8.2%, crack ratio 1.5%), balanced scheme (RS = 0.65%, SRF = 0.75 kg/m^3 , OF = 9.0%, root content 1.02 mg/cm^3), and ecological priority scheme (RS = 0.55%, SRF = 0.60 kg/m^3 , OF = 11.5%, root content 1.25 mg/cm^3).

Areas with high SRF content ($> 0.9 \text{ kg/m}^3$) need to be equipped with underground drainage pipes (spacing $\leq 2 \text{ m}$), and for high RS content ($> 0.7\%$), it is recommended to mix in 3% vermiculite to compensate for porosity. The verification deviation of the model in project is $\leq 3.2\%$, but the durability under long-term dry-wet cycles needs further study.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

Conceived and designed the experiments: YH. Performed the experiments: YH. Analyzed the data and wrote original draft: YH. Contributed reagents/materials/analysis tools: YH. Funding acquisition: YW, XW, XT, YH, and HZ. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

Author HZ was employed by the company Guangxi Transportation Science and Technology Group Co., Ltd. Author KX was employed by Huaian Water Resources Survey and Design Institute Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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