

Article

The Influence of Fine-Grained Clay Content on Water Retention in Soil Reconstruction in Shendong Mining Area

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Abstract

The surface soil in the Shendong mining area is dominated by aeolian sand and sandy sediment, while precipitation is limited, and evaporation is intense. Under these conditions, shallow reconstructed soil has difficulty retaining plant-available water, which constrains vegetation restoration. This study evaluated how low-range increases in fine-particle clay content affect both water retention and upward water conduction in sandy reconstructed soil. Sandy material from the Shangwan mining area and exogenous river clay were mixed into four treatments, and soil water characteristic curves (SWCCs) were determined by centrifuge over 10–1000 kPa matric suction. The data were fitted with the Van Genuchten model and combined with capillary-rise tests. The results showed that increasing fine-particle content shifted the SWCC upward and raised both saturated and residual volumetric water contents. SN10 reached 17.18% and 5.55% volumetric water content at 10 and 1000 kPa, respectively, and its effective water capacity in the 33–1500 kPa range was 17.9% higher than that of ST. At the same time, fine-particle enrichment in the bottom layer reduced wetting-front rise during capillary testing, indicating a trade-off between water storage and upward replenishment. Within the tested fine-particle range, moderate clay addition improved the hydraulic performance of sandy reconstructed soil, but soil design should balance precipitation retention, infiltration, and capillary supply. Because each treatment and soil-column configuration was represented by only one independently prepared experimental unit, experimental variability and reproducibility could not be evaluated. This study should therefore be regarded as a preliminary and exploratory laboratory assessment conducted under a specific set of material-preparation procedures, specimen geometries, and boundary conditions. The results describe specimen-level hydraulic contrasts rather than reproducible treatment effects and should not be directly generalized to field-scale soil reconstruction. They support a preliminary hypothesis for future replicated testing: fine-particle enrichment may increase water retention while slowing upward capillary replenishment.

Keywords: sandy reconstructed soil; fine-particle amendment; soil water characteristic curve; matric suction; capillary rise; mining reclamation

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1. Introduction

The Shendong mining area is located in the ecologically fragile arid and semi-arid region in northwest China. The topsoil is mainly wind-sand and sandy sediment, which is characterized by coarse grains, loose structure and weak water retention capacity. Coal mining and land disturbance in the mining area will change the original soil layer structure, putting greater pressure on the reconstituted cover soil in terms of rainfall infiltration, shallow water storage and root water supply. Due to factors such as less concentrated precipitation and intense evaporation, the sandy reconstituted soil after coal mining disturbance often has difficulty stably retaining effective water in the shallow layer, which has become an important factor restricting vegetation restoration and ecological reconstruction [1]. Therefore, clarifying the influence of fine-grained clay content on the water retention performance of sandy reconstituted soil is of great significance for the selection of soil cover materials in mining areas, the optimization of soil structure and ecological restoration.

Existing studies establish two relevant but largely separate lines of evidence. SWCC studies on expansive soil, loess, and other fine-grained soils show that texture, pore-size distribution, compaction, and initial state control saturated and residual water contents, air-entry behavior, and the shape of fitted Van Genuchten curves [2–9]. These studies generally use finer-textured matrices or broad sand–clay substitutions. For reconstructed soils in mining areas, available work has mainly examined broader texture contrasts, water retention, or infiltration through interlayers [10]. At broader scales, compiled SWCC datasets have also been used to characterize soil water parameters [11], but such retention-focused analyses do not directly resolve upward capillary response. However, the coupled response in a sand-dominated Shendong cover material remains unclear when fine-particle content changes over a relatively narrow range. Specifically, the same pore refinement that raises water retention may interrupt coarse-pore continuity and weaken upward capillary replenishment. This retention–conduction trade-off is the specific knowledge gap addressed here.

This study was therefore organized around one central research question: can modest fine-particle enrichment in a sand-dominated reconstructed soil increase water retention without an excessive reduction in upward capillary supply? The SWCC and capillary-rise tests are not treated as independent research objectives; they are complementary measurements of the storage and transport responses of the same amendment sequence. Four engineered mixtures spanning 10.75–21.84% fine particles were examined. The contribution is an exploratory, paired assessment of both sides of the trade-off under Shendong-relevant material conditions. Because only one experimental unit was available for each treatment and column configuration, this study does not estimate treatment variability or identify an optimum amendment ratio. Instead, it reports specimen-level hydraulic contrasts and formulates a testable hypothesis for future replicated experiments [12].

2. Materials and Methods

2.1. Test Soil Sample

The sandy material was collected in the Shangwan area of the Shendong Mining Area at the Shaanxi–Shanxi–Inner Mongolia junction (109°49′–111°06′ E, 38°46′–39°44′ N). The retained field record documents four reconnaissance collection points at approximate depths of 1, 2, 3, and 4 m, selected to span the vertical interval of sandy source material encountered at the site. It does not document a probability-based sampling design, exact point coordinates, or additional formal inclusion/exclusion criteria. Accordingly, the term “representative” is not used here: the collected material should be interpreted as a reconnaissance-based composite rather than as a statistically representative sample of the entire

mining area. Material from the four points was homogenized to create a consistent laboratory sand source. The applicability of the results is therefore limited to engineered materials with particle-size distributions similar to those reported in Table 1.

Table 1. Particle gradation and design dry density of the four test soil samples.

Soil Sample	Clay Particles/%	Silt Particles/%	Sand Particles/%	Dry Density/(g·cm ⁻³)
ST	0.15	10.60	89.25	1.4976
SN50	1.12	12.00	86.88	1.5185
SN20	1.34	13.91	84.75	1.5305
SN10	2.41	19.43	78.16	1.5683

2.2. SWCC Measurement

Figure 1 links the study components in four sequential stages. The experimental-design column identifies the reconnaissance-based composite sand, preparation of the four mixtures, the two complementary tests, and the directly observed variables. The data-processing column shows Van Genuchten fitting, moisture-interval calculation, and comparison of wetting-front development. The interpretation column contrasts storage-related indicators (θ_s , θ_r , and plant-available water) with transport-related indicators (wetting-front rise and vertical moisture profiles). The final column limits the engineering output to a provisional amendment hypothesis and the requirements for replicated validation. Thus, the figure maps the logic connecting the central research question to the measurements and interpretation; it does not provide an independent dataset.

SWCCs were measured using the centrifuge method. Each mixture was packed into a 100 cm³ ring at its designed dry density and saturated slowly for 10–20 h. The specimens were then centrifuged stepwise to target matric suctions of 10–1000 kPa at 11 measurement levels. Before each run, the rotor was balanced to within 0.02 g. Specimen mass was recorded after equilibration at each suction level, and volumetric water content was calculated from the dry-soil mass and the masses of the ring and centrifuge tube. After the sequence, each specimen was oven-dried to constant mass to provide a consistent dry-mass reference. ST served as the control specimen. The 11 suction levels are repeated measurements on one specimen within each treatment; they are not independent experimental replicates. Therefore, the manuscript reports treatment-level hydraulic observations and does not present error bars or inferential hypothesis tests; this limitation is carried into the interpretation of Figure 4 and the engineering implications.

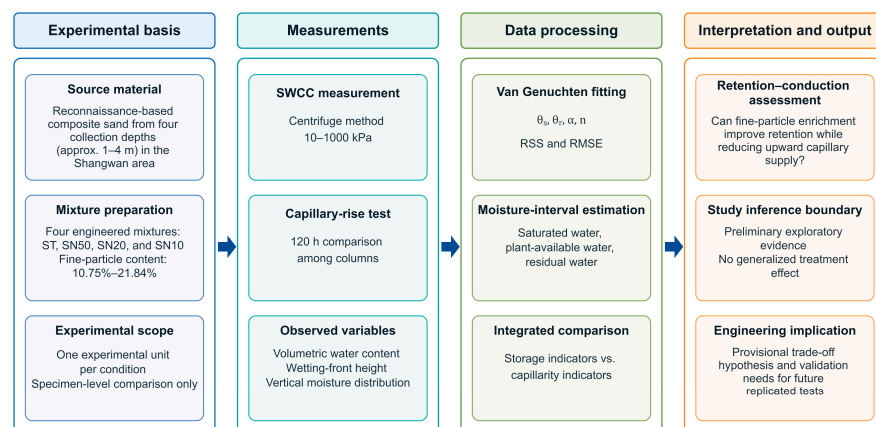


Figure 1. Study workflow linking source-material selection and specimen preparation to SWCC measurement, Van Genuchten fitting, capillary-rise testing, integrated interpretation of storage and transport, and provisional engineering hypotheses.

2.3. VG Model Fitting and Moisture Interval Simulation

The Van Genuchten model [13] was used to describe the relationship between soil volumetric water content and matric suction, as shown in Equation (1):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n]^m}, m = 1 - \frac{1}{n} \quad (1)$$

In Equation (1), θ , θ_r , and θ_s are expressed in $\text{cm}^3 \text{cm}^{-3}$, and h is expressed in cmH_2O . Model parameters were estimated by nonlinear least-squares fitting. Model performance was evaluated using the residual sum of squares (RSS) and the root mean square error (RMSE), which is defined in Equation (2) [14,15]. Before fitting, the volumetric water-content values reported as percentages in Table 2 were divided by 100 and converted to $\text{cm}^3 \text{cm}^{-3}$. RMSE was calculated as follows:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (\theta_{obs,i} - \theta_{VG,i})^2} \quad (2)$$

where $\theta_{obs,i}$ and $\theta_{VG,i}$ are the observed and VG-predicted volumetric water contents at the i -th matric-suction level, respectively, and N is the number of observations. In this study, $N = 11$ for each treatment.

To visualize how fitted parameters changed with fine-particle content, θ_s , α , and n were further plotted against treatment-level fine-particle percentage [16]. Because only four designed mixture levels were available and no replicate-based regression dataset was collected, the resulting trend lines are used here as descriptive response curves ($n = 4$) within the tested range rather than as universal predictive equations.

Based on the fitted VG curve, soil water was divided into saturated water, gravity-drainable water, plant-available water (33–1500 kPa), and residual water. Here, 33 kPa was taken as the approximate field-capacity limit, and 1500 kPa was taken as the approximate permanent-wilting limit. Because measurements were conducted up to 1000 kPa, the 1000–1500 kPa interval was estimated by extrapolating the fitted VG curve and is used only for relative comparison among treatments [17].

Table 2. Volumetric water content of four soil samples at different matric suctions.

Suction/kPa	Negative Pressure/cmH ₂ O	ST/%	SN50/%	SN20/%	SN10/%
10	102	14.49	14.72	14.44	17.18
20	204	10.75	11.13	11.4	13.31
40	408	8.35	8.83	9.33	10.94
60	612	7.21	7.68	8.33	9.61
80	816	6.59	7.0	7.66	8.85
100	1020	6.14	6.54	7.18	8.25
200	2040	5.59	5.94	6.54	7.58
400	4080	4.93	5.27	5.87	6.9
600	6120	4.48	4.84	5.34	6.33
800	8160	4.18	4.51	4.98	5.9
1000	10,200	3.91	4.21	4.7	5.55

2.4. Capillary-Rise Test

To analyze how fine-particle enrichment affected upward water conduction, a capillary-rise soil-column test was conducted. The apparatus consisted of a constant-head water-supply system, a transparent acrylic soil column, and an automatic volumetric water-content acquisition system equipped with MC-TWS sensors. The transparent acrylic column was 1000 mm high, with an inner diameter of 160 mm and an outer diameter of 190 mm. The soil was packed to an effective height of 1000 mm. Wetting-front height was measured vertically upward from the bottom boundary of the packed soil. An ST column

was used as the control, whereas composite columns containing a 3 cm-thick bottom layer of SN50, SN20, or SN10 and an overlying ST layer were used to evaluate wetting-front development and moisture redistribution. Wetting-front height was monitored continuously for 120 h. The monitoring system used MC-TWS soil temperature–moisture sensors supplied by Beijing Mengchuang Weiye Technology Co., Ltd. (Beijing, China). Here, 40#–45# denote fixed installation-position numbers rather than instrument serial numbers. The sensors were inserted horizontally through opposing sidewall ports into the soil column. According to the sensor-position layout, the center heights above the column base were 12.5, 25.0, 37.5, 52.0, 64.5, and 77.0 cm for 40#–45#, respectively; thus, the vertical spacing was 12.5 cm between 40# and 41#, 12.5 cm between 41# and 42#, 14.5 cm between 42# and 43#, 12.5 cm between 43# and 44#, and 12.5 cm between 44# and 45#. Each sensor used a three-prong 55 mm probe (3 mm diameter per prong; sensor-body width 16 mm) to measure the local soil volume surrounding the fully embedded probe segment and to output volumetric water content. The available device description reports a 0–100% measurement range and notes built-in zero-drift and temperature-compensation circuits. During installation, the probes were fully inserted and sealed in place to reduce operational error; however, the source description did not report a separate numerical accuracy coefficient or an additional in-house recalibration procedure.

2.5. Experimental Limitations, Reproducibility, and Scope of Results

This study should be regarded as a preliminary and exploratory laboratory assessment. Each SWCC treatment and each capillary-column configuration were represented by only one independently prepared experimental unit. Consequently, experimental variance, repeatability, confidence intervals, and treatment-level statistical significance cannot be estimated. The 11 suction steps within an SWCC sequence, the multiple sensors installed in one soil column, and the repeated measurements collected over time are observations within the same experimental unit and cannot be treated as independent replicates. The analyses are therefore descriptive and specimen specific. The reported differences do not establish a reproducible treatment effect, an optimum amendment ratio, or a field-scale design prescription.

Exact replication and broader interpretation are also constrained by several features of the methodology. The sandy source material was prepared as a reconnaissance-based composite rather than being obtained through a probability-based sampling design, and complete provenance and mineralogical information for the purchased river clay were unavailable. Fine-particle content and designed dry density increased simultaneously across the four mixtures, preventing their individual effects from being fully separated. In addition, the SWCC and capillary-rise tests used different specimen geometries and boundary conditions, the complete centrifuge-speed schedule and an independent numerical recalibration record for the moisture sensors were not retained, and water contents in the 1000–1500 kPa interval were estimated by extrapolation from the fitted Van Genuchten curves. The conclusions are therefore conditional on the specific materials, preparation procedures, instruments, and test configurations used here. Future confirmation requires independently prepared replicates, a fully standardized and documented protocol, controlled or factorial dry density, complete material and pore-structure characterization, verified instrument calibration, and field-scale validation.

3. Results

3.1. Measured SWCC Results

Centrifuge results showed that the volumetric water content of all four treatments decreased as matric suction increased, reflecting typical desorption behavior of unsaturated soil (Figure 2). At 10 kPa, the volumetric water contents of ST, SN50, SN20, and SN10 were 14.49%, 14.72%, 14.44%, and 17.18%, respectively. At 1000 kPa, they decreased to 3.91%, 4.21%, 4.70%, and 5.55%, respectively. Overall, SN10 maintained the highest water content across the tested suction range, indicating a stronger treatment-level retention response at higher fine-particle content.

From the low-suction zone to the high-suction zone, the ST and SN50 curves remained relatively close, whereas SN20 gradually separated from the first two treatments, and SN10 showed the most obvious overall upward shift. After matric suction increased from 10 to 1000 kPa, substantial dehydration occurred in all soil samples, but SN10 maintained the highest final value, indicating that fine-particle enrichment not only improved absolute water storage but also enhanced retention under high-suction conditions.

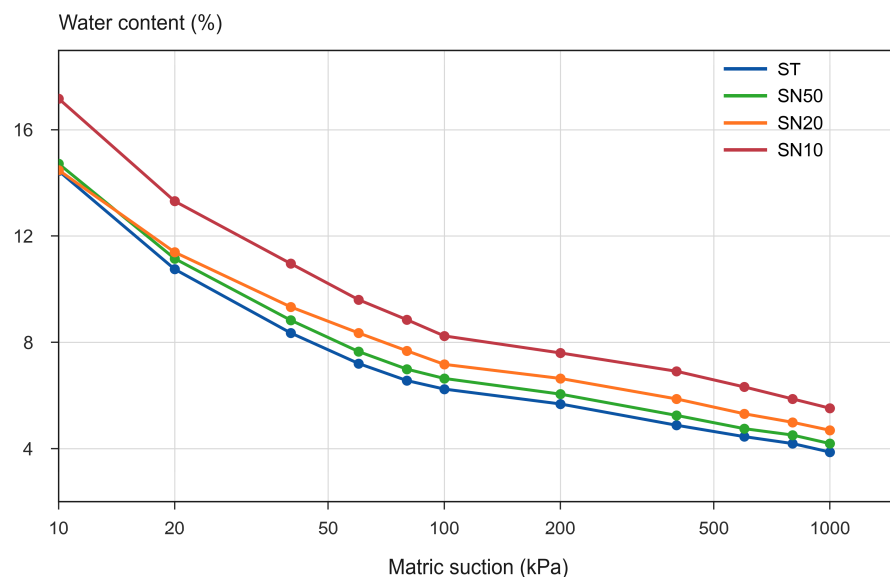


Figure 2. Measured SWCC data points for the four soil samples under different matric suctions.

3.2. VG Model Parameters and Moisture Interval Simulation Results

$2.282 \times 10^{-5} 4.055 \times 10^{-5} \theta_s \theta_r$ The VG model closely reproduced the measured SWCC data for all four treatments (Table 3). The RSS values ranged from 0.00002282 to 0.00004055, and the corresponding RMSE values for ST, SN50, SN20, and SN10 were 0.001520, 0.001481, 0.001440, and 0.001920 $\text{cm}^3 \text{cm}^{-3}$, respectively (Table 4). Among the four treatments, SN20 had the lowest RMSE, whereas SN10 had the highest. These metrics describe within-specimen curve fit and are not measures of between-treatment variability. Nevertheless, the RMSE values were small relative to the measured volumetric water contents, indicating close agreement between the measured data and the fitted VG curves. The fitted saturated volumetric water content, θ_s , increased from 0.3297 in ST to 0.4044 in SN10, whereas the residual volumetric water content, θ_r , increased from 0.0349 to 0.0475.

Table 3. Van Genuchten model parameters for the four soil treatments.

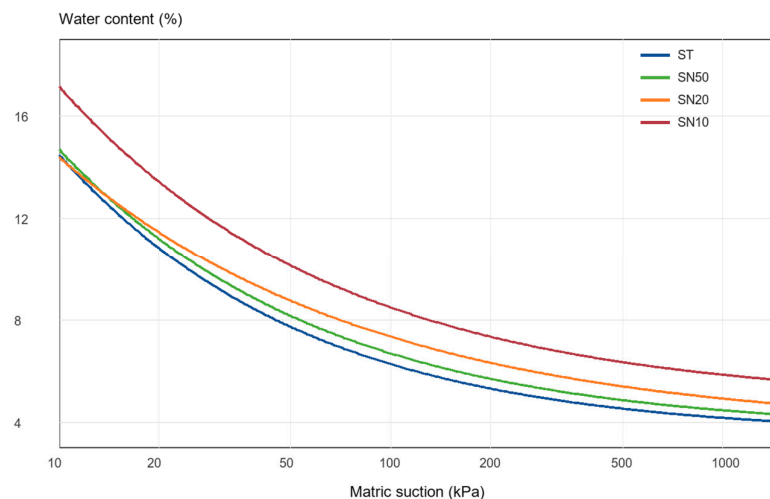
Soil Samples	α (cm ⁻¹)	n (–)	θ_s (cm ³ cm ⁻³)	θ_r (cm ³ cm ⁻³)	Residual Sum of Squares (RSS)
ST	0.0474	1.6083	0.3297	0.0349	0.00002541
SN50	0.0526	1.5715	0.3318	0.0366	0.00002414
SN20	0.0918	1.4736	0.3489	0.0371	0.00002282
SN10	0.0708	1.5271	0.4044	0.0475	0.00004055

Table 4. Root mean square error of Van Genuchten model fitting for the four soil treatments.

Soil Treatment	ST	SN50	SN20	SN10
RMSE (cm ³ cm ⁻³)	0.001520	0.001481	0.001440	0.001920

Note: RMSE values were recalculated from 11 measured matric-suction points ($N = 11$) for each treatment after the percentage water-content values were divided by 100 and converted to cm³ cm⁻³.

Parameters α and n reflect changes in air-entry behavior and pore-size distribution. The higher α of SN20 indicates that this treatment was more sensitive to the onset of drainage under the intermediate mixing ratio, whereas the lower n value of SN10 suggests a more complex pore-size distribution and a more dispersed water-release process. The fitted curves are consistent with the measured points and can therefore be used for subsequent parameter interpretation and moisture-interval calculation (Figure 3).

**Figure 3.** Comparison between measured SWCC data and fitted Van Genuchten curves for the four soil samples.

When the fitted parameters were plotted against fine-particle content, θ_s increased monotonically within the tested range, and the fitted linear relationship $\theta_s = 0.0072F + 0.2445$ yielded $R^2 = 0.960$. Because Figure 4 uses only four treatment levels ($n = 4$), the regression is used here only to summarize the observed trend that higher fine-particle content was associated with higher saturated water content (Figure 4).

The parameter α showed a nonlinear variation with fine-particle content, whereas n decreased only weakly within the tested range. The fitted relationships in Figure 4 are therefore descriptive rather than predictive. Together, the parameter changes suggest that, when fine particles fill the large pores between sand grains, the pore-size distribution becomes more refined and the water-release process shifts from rapid drainage to slower, more dispersed release.

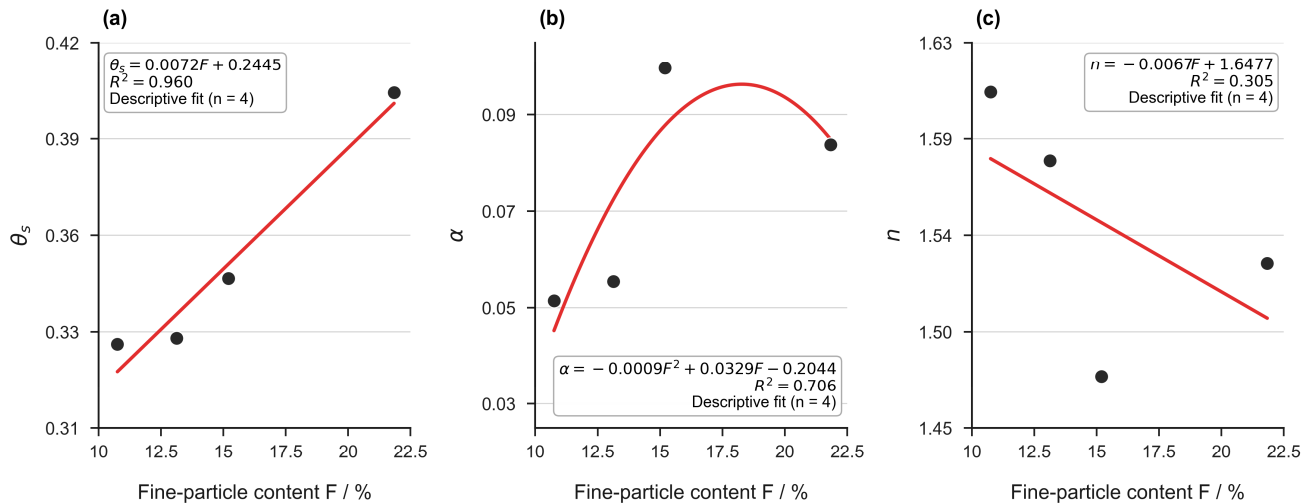


Figure 4. Specimen-level comparison of fitted Van Genuchten parameters across the four prepared mixtures. Points are individual fitted values, not replicate means; no regression model is applied. (a) Residual water content θ_s ; (b) Fitting parameter α ; (c) Pore-size distribution index n .

When the effective water capacity is defined in the range of 33 to 1500 kPa, the effective water capacities of ST, SN50, SN20 and SN10 are 4.91%, 5.05%, 5.12% and 5.79%, respectively. SN10 increased by 17.9% over ST, indicating that a higher content of fine particles can expand the range of available water for plants. Since the upper limit of the measured suction in this study was 1000 kPa and the water content at 1500 kPa was extrapolated from the fitting curve, this result was mainly used for relative comparison between different ratios (Table 5).

Table 5. Moisture interval distribution based on the fitted VG curves.

Soil Sample	θ_s -033/%	033-01500/%	θ_{1500} - θ_r /%	θ_r /%	Effective Water Accounts for θ_s /%
ST	24.04	4.91	0.54	3.49	14.88
SN50	23.83	5.05	0.64	3.66	15.21
SN20	25.05	5.12	1.01	3.71	14.68
SN10	29.00	5.79	0.90	4.75	14.33

In terms of the proportion of available water to saturated water content, the corresponding values for the four soil samples were 14.88%, 15.21%, 14.68%, and 14.33%, respectively, showing limited variation and no monotonic increase with fine-particle content. This indicates that, although increasing fine particles can raise the absolute value of effective water capacity, their proportion in total saturated water content is still controlled by pore-structure redistribution. At the same time, the increase in residual water content suggests that strongly adsorbed water also becomes more important as retention improves (Figure 5).

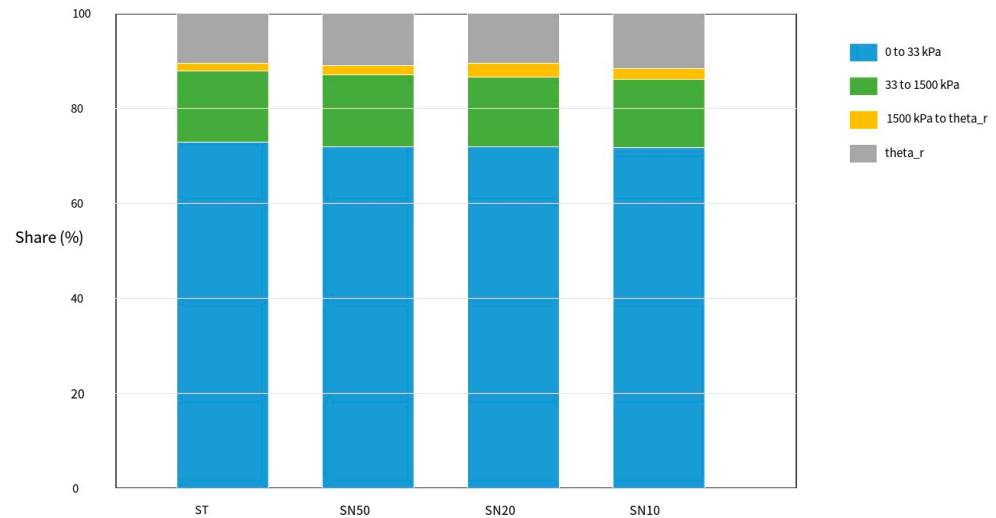


Figure 5. Proportional distribution of moisture intervals in the four soil samples.

3.3. Capillary-Rise Results

The capillary-rise test showed that the higher the fine-particle content in the bottom 3 cm cushion layer, the lower the wetting-front height after 120 h. The wetting-front rise was rapid in the first 10 h and then entered a slower-growth stage. At the common 120 h comparison point, the wetting-front height of the ST soil column was 71.7 cm, whereas that of the SN10+ST soil column decreased to 65.5 cm. The ST control was further monitored to 500 h and finally reached 80.2 cm, confirming that 120 h captures the main rapid-rise stage while remaining directly comparable with the other three configurations. Meanwhile, the stable moisture content of the 40# sensor near the bottom increased from 26.18% to 28.25%, whereas the stable moisture contents of the 41#–43# sensors in the upper part decreased. In this layout, 40#–43# denote fixed installation positions rather than instrument serial numbers and were positioned at 12.5, 25.0, 37.5, and 52.0 cm above the column base, respectively (Table 6).

Table 6. Wetting-front height at 120 h and stable volumetric water contents measured at fixed monitoring positions 40#–43# (12.5, 25.0, 37.5, and 52.0 cm above the column base) for the four soil-column configurations.

Soil Columns	Wetting-Front Height at 120 h (cm)	40#/%	41#/%	42#/%	43#/%
ST	71.7	26.18	21.16	14.35	3.71
SN50+ST	69.6	27.08	19.17	14.14	3.65
SN20+ST	68.1	27.78	18.9	13.95	3.41
SN10+ST	65.5	28.25	18.56	13.05	3.27

The capillary-rise results suggest that fine-particle enrichment in the bottom soil layer increases local water retention, leaving more water in micropores and adsorption sites and thereby slowing the upward supply rate. The added process data also show that the wetting-front turning point appears earlier and the comparable 120 h rise height decreases as bottom-layer fine-particle content increases. For reconstructed topsoil in the mining area, fine-particle replenishment can improve water storage, but its configuration should still account for capillary continuity and root-zone water supply.

4. Discussion

4.1. Mechanism of Action of Fine Particles on Water Retention

The increase in retention after fine-particle addition is consistent with previous studies on expansive soils, loess, and other fine-grained materials, which report that pore refinement and greater specific surface area raise θ_s , θ_r , and water content under high suction [3,4,7,9,12]. In our tests, when fine-particle content increased from 10.75% in ST to 21.84% in SN10, θ_s increased from 0.3297 to 0.4044 (+22.7%), and θ_r increased from 0.0349 to 0.0475 (+36.1%). This direction agrees with the expansive-soil results of Alnmr et al. [7], who showed that increasing sand addition reduced water retention and that α varied with sand percentage whereas n changed less regularly. Field profile data from the Shangwan area provide a useful baseline for the laboratory mixtures. In those field profiles, mean sand/silt/clay contents in the control area were $87.77 \pm 7.29\%$, $12.07 \pm 7.19\%$, and $0.16 \pm 0.10\%$, whereas the corresponding goaf values were $82.34 \pm 9.91\%$, $17.37 \pm 9.61\%$, and $0.29 \pm 0.33\%$. The ST treatment (89.25% sand, 10.60% silt, and 0.15% clay) therefore closely matches the field control baseline, whereas SN10 (78.16% sand, 19.43% silt, and 2.41% clay) represents a more strongly fine-enriched scenario than the mean field goaf profile and exceeds the reported deep-layer mean clay content of $0.69 \pm 0.39\%$. Within this context, three structural processes likely acted together. First, fine particles provide additional adsorption sites. Second, they fill large pores between sand grains and shift the pore-size distribution toward medium and small pores. Third, stronger capillary forces in those finer pores slow the release of water in the medium- and high-suction range. These mechanisms explain why the measured SWCC shifted upward as fine-particle content increased.

A distinctive aspect of this study is that the tested fine-particle interval was relatively low, from 10.75% in ST to 21.84% in SN10. Even within this narrow range, θ_s , θ_r , and high-suction water content responded consistently, indicating that sandy reconstructed soil in the Shendong mining area is sensitive to modest changes in fine-particle enrichment. This sensitivity is notable when compared with Tan et al. [4], who reported a 10.9% decrease in saturated volumetric water content across natural loess layers, whereas the present engineered mixtures showed a 22.7% increase in θ_s over an 11.09 percentage-point rise in fine-particle content. At the same time, the weak change in n compared with some finer-textured soils suggests that the sand-dominated framework remained influential throughout the tested range. Part of the retention increase may also reflect the systematic rise in dry density from 1.4976 to 1.5683 g cm⁻³ across the four treatments, so the observed response should be interpreted as a coupled effect of fine-particle enrichment and denser packing rather than as clay content alone. The parameter relationships shown in Figure 4 are therefore descriptive hydraulic tendencies within the tested range, not general constitutive equations. The two tests therefore address complementary sides of one design question rather than two independent objectives.

4.2. Comparative Analysis of Field and Indoor Results

Field-profile observations from the Shangwan and Buertai areas further support the laboratory interpretation. In Shangwan, finer-particle enrichment was reported at 300–350 cm, where the deep goaf layer contained $69.49 \pm 9.71\%$ sand, $29.83 \pm 9.39\%$ silt, and $0.69 \pm 0.39\%$ clay. In the same profile, mean water content in the deep goaf interval reached $11.62 \pm 2.67\%$ at 350–400 cm in July, whereas the deep control interval averaged $5.13 \pm 2.37\%$ over 350–490 cm. In Buertai, finer-particle lenses at 290, 410, and 450 cm were likewise associated with local moisture accumulation. Plant-water contribution analysis also showed that soil water from 200 to 250 cm contributed 83.0% of *Artemisia ordosica* water use in the Shangwan control profile and 58.9% in the Buertai control profile, confirming

the ecological significance of deeper stored water. Taken together, these field data are consistent with the laboratory finding that higher fine-particle content promotes local storage but slows percolation and upward redistribution.

From an engineering perspective, ST represents a near-pure sand cover scenario, SN50 and SN20 represent moderate fine-particle replenishment, and SN10 represents the upper fine-particle scenario tested here. The gradual increase in water storage across the four treatments agrees with reconstructed-soil design studies that emphasize optimizing particle-size composition rather than maximizing clay content alone [18]. However, the capillary-rise results also show that stronger bottom-layer retention can suppress upward water migration. Therefore, reconstructed cover-soil design in arid mining areas should balance surface storage, subsurface drainage, and root-zone capillary supply rather than pursuing water retention as a single target.

4.3. Engineering Implications

Based on the findings of this study, it is not advisable to use pure sand alone for surface reconstruction in the Shendong mining area. If the aim is to enhance rainfall retention near the surface, the particle-size optimization strategy reported for reconstructed soils [18] can be used as a reference while maintaining a sufficient proportion of coarse particles to preserve infiltration and root aeration. Within the tested range, SN10 provided the strongest retention response, but its clay fraction of 2.41% is substantially higher than the mean deep-layer clay content observed in the Shangwan goaf profile (0.69%). Accordingly, SN10 is better interpreted as an upper-bound design case than as a universal field target, and its reduced capillary rise warns against forming an excessively water-stagnant layer. The present dataset does not support selecting an optimum mixture or recommending SN10 as a field target.

In practical reclamation, a stratified particle-size configuration may be preferable: a moderate increase in fine particles in the surface layer can prolong rainfall retention, whereas the lower layer should preserve sufficient drainage and upward replenishment capacity. Field implementation should also consider rainfall intensity, cover thickness, vegetation rooting depth, salt migration, and the spatial heterogeneity of subsidence areas [19–21]. These interacting controls explain why the laboratory results should be used as guidance for ratio selection rather than as a direct one-to-one field prescription.

4.4. Limitations

The present study should be regarded as a preliminary and exploratory laboratory assessment. Its conclusions are conditional on the specific source materials, mixture-preparation procedures, specimen geometries, monitoring arrangement, instruments, and boundary conditions used in the experiments. The primary limitation is the absence of independent experimental replication. One SWCC specimen per treatment and one column per configuration cannot estimate experimental variability, repeatability, confidence intervals, or generalizable treatment effects. This limitation cannot be corrected retrospectively. Accordingly, the reported differences describe only the tested specimens and should not be interpreted as reproducible treatment effects, an optimum amendment ratio, or a field-scale design prescription.

Several additional methodological factors constrain exact replication and interpretation. The sandy material was obtained through reconnaissance-based composite sampling rather than a probability-based sampling design, and complete provenance and mineralogical information for the purchased river clay was unavailable. Fine-particle content and designed dry density increased simultaneously, preventing their independent effects from being fully separated. The SWCC and capillary-rise tests also used different specimen geometries and boundary conditions; the complete centrifuge-speed schedule and

independent numerical sensor-recalibration records were not retained; and the 1000–1500 kPa water-content interval was estimated by extrapolation. Short-term laboratory conditions further limit field applicability. A confirmatory experiment should therefore use at least three independently prepared specimens and columns per condition, randomize preparation and test order, hold dry density constant or include it as a factorial variable, fully characterize amendment mineralogy and pore structure, retain complete operating and calibration records, and predefine primary storage and transport outcomes. Field-scale validation is required before any amendment ratio is recommended.

5. Conclusions

This exploratory laboratory study provides specimen-level observations from four prepared mixtures and four soil-column configurations. Because no independent replicates were available, the following statements describe the tested units and should not be interpreted as reproducible treatment effects.

- (1) Within the tested mixture range, increasing fine-particle content was accompanied by higher volumetric water content across the measured matric-suction range. As fine-particle content increased from 10.75% in ST to 21.84% in SN10, volumetric water content increased from 14.49% to 17.18% at 10 kPa and from 3.91% to 5.55% at 1000 kPa. Because dry density also increased across the four mixtures, these treatment-level differences should be interpreted as the coupled response to fine-particle enrichment and denser packing.
- (2) Increasing fine particles shifted the overall soil water characteristic curve upward and enhanced the saturated water storage space, high-suction water holding capacity, and plant-available water range of sandy reconstructed soil. VG fitting showed that saturated volumetric water content θ_s increased from 0.3297 in ST to 0.4044 in SN10, whereas residual volumetric water content θ_r increased from 0.0349 to 0.0475. In the range of 33–1500 kPa, effective water capacity increased from 4.91% in ST to 5.79% in SN10, an increase of 17.9%. Within the tested range, moderate fine-particle enrichment therefore improved both water retention and plant-available water reserve.
- (3) In the single-column comparison, 120 h wetting-front height decreased from 71.7 cm in ST to 65.5 cm in SN10+ST, while water content near the base increased. This paired pattern supports a testable storage–conduction hypothesis: fine-particle enrichment may increase local retention while slowing upward capillary supply. Replicated experiments that control dry density and characterize the amendment are required before the hypothesis is generalized or used for field design.

Accordingly, the conclusions of this study are preliminary and specific to the experimental configuration examined here. The observed increase in water retention and accompanying reduction in upward capillary rise should be treated as a specimen-level hypothesis that requires independently replicated laboratory experiments and field-scale validation before it can be generalized or used to guide engineering design.

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