Evaluation of nonwoven geotextile drainage performance and experimental simulation of key processes in Yellow River sediment-backfilled reclaimed coal-mined subsided lands

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Abstract: The innovative utilization of Yellow River sediment to reclaim coal-mined subsided lands addresses dual environmental challenges by offering a sustainable remediation technique. However, efficient water drainage constitutes a significant hurdle in this context. The strategic placement of nonwoven geotextile at the tail end of the fill sections has ameliorated fine sediment loss and drainage efficacy issues. This study assesses various nonwoven geotextile grades for their effectiveness in moisture expulsion, integrating comprehensive evaluations and simulation tests of pivotal processes. The findings reveal that selected nonwoven geotextiles (N1, N2, T1, T2, T3, T4) demonstrate appropriate apparent opening size (AOS) and permeability, coupled with clogging resistance, aligning with theoretical criteria for soil conservation, water permeation, and blockage prevention. Crucial to the nonwoven geotextile's clogging are factors such as apparent opening size (AOS), thickness, permeability, load capacity, gradient ratio (GR), and sediment retention - all requiring meticulous selection for real-world application. The choice of nonwoven geotextile in the drainage of Yellow River sediment reclaimed lands must hinge on a holistic assessment framework, encompassing retention, permeability, anti-clogging attributes, and additional performance metrics, to ensure that the materials fulfill the specific technical standards while remaining cost-effective. This study provides valuable insights into the selection and application of geotextiles in Yellow River sediment-backfilled reclamation drainage projects, contributing to the advancement of mine ecological restoration practices, particularly in the context of Yellow River sediment-backfilled reclamation projects.

Keywords: nonwoven geotextile, drainage performance, Yellow River sediment, coal-mined subsided land, filling reclamation, engineering construction
DOI: 10.25165/j.ijabe.20241706.8897

Citation: Sun H, Hu Z Q, Song D Y, Wang S, Yu Y. Evaluation of nonwoven geotextile drainage performance and experimental simulation of key processes in Yellow River sediment-backfilled reclaimed coal-mined subsided lands. Int J Agric & Biol Eng, 2024; 17(6): 193–201.

1 Introduction

Due to coal's predominant role in China's energy consumption, accounting for over half of the total, coal mining subsidence has inflicted irreversible damage on cultivated land, exacerbating the scarcity of per capita cultivated resources[1,2]. The imperative to address the reclamation of coal-mined subsided lands is evident. However, the shortage of filling materials and environmental risks have constrained reclamation efforts[3-5]. The accumulation of Yellow River sediment poses a significant hazard, frequently leading to river blockages[6], while the external dredging and sediment deposition also occupy substantial land resources[7]. Therefore, the application of Yellow River sediment as a pollution-free filling material for the reclamation of depleted coal-mined subsided lands not only resolves the issues of dredging sediment and coal-mined subsided lands management but is also regarded as a win-win green and clean technology[8]. This technology has been experimentally implemented in multiple coal-mined subsided lands, successfully restoring cultivated land[9,10].

Yellow River sediment transportation through pipelines is crucial for efficient land reclamation of coal-mined subsided areas, but it presents significant drainage challenges[9-11]. Current drainage methods (Figure 1), involving direct excavation of outlets on embankments, lead to the loss of nutrient-rich fine sediments and result in poor water and nutrient retention in the reclamation soil layer[12]. Additionally, impeded lateral drainage due to embankments at strip ends reduces overall drainage efficiency and prolongs reclamation periods[5]. This study aims to address these issues by exploring the application of geotextile fabric in sediment drainage and retention, with a focus on improving reclamation soil quality and drainage efficiency.

Geotextile fabric, known for its high strength, flexibility, and versatile performance, serves multiple functions in various engineering fields, including filtration, drainage, and sediment retention[13,14]. Nonwoven geotextiles, in particular, are widely used in drainage systems due to their excellent filtration properties and cost-effectiveness[15,16]. According to technical specifications[17],

Received date: 2024-03-04 **Accepted date:** 2024-10-20

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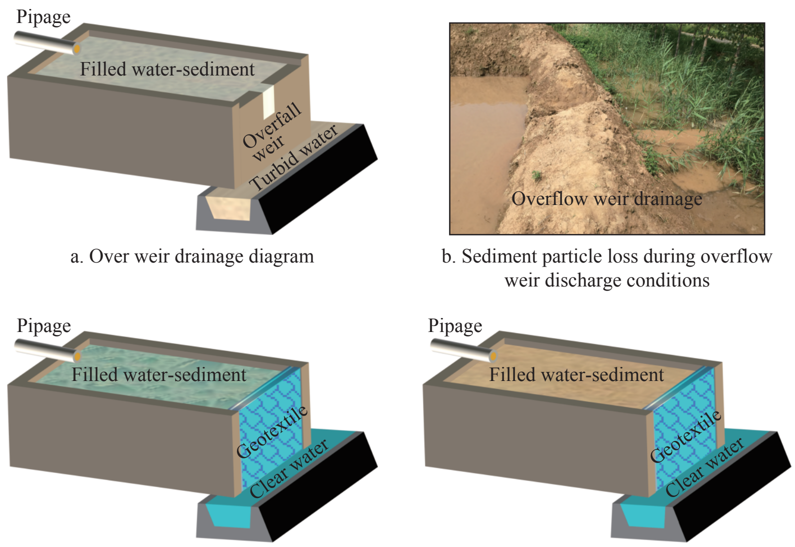


a. Over weir drainage diagram

b. Sediment particle loss during overflow weir discharge conditions

c. Discharge of supersaturated water in geotextile drainage

d. Discharge of supersaturated water in geotextile drainage

Figure 1 Overflow weir drainage and geotextile drainage

geotextiles must meet three key requirements: soil retention, permeability, and anti-clogging properties. These properties are determined by factors such as equivalent opening size (O_{95}), permeability coefficient (k_n), and gradient ratio (GR)[18,19].

Refs.[5]highlighted that in the reclamation of coal-mined subsided lands using Yellow River sediment, needle-punched nonwoven geotextiles with specifications of 250 g/m^2 and 300 g/m^2 were capable of partially intercepting fine sediment particles and exhibited certain effectiveness in lateral drainage. However, in practical engineering applications, the selected needle-punched nonwoven geotextile exhibited clogging, leading to the failure of sediment interception and drainage. Considering the current engineering practice, the selection of geotextiles is based on a comparison of their soil retention, permeability, and anti-clogging properties. Specifically, the equivalent opening size of the geotextile is required to be 90% of the diameter of the intercepted soil particles, i.e., the O_{90}/d_{90} (O_{90} is the equivalent opening size, mm) value should be greater than 1[10]. The permeability coefficient should be more than ten times that of the intercepted soil permeability[18], and the gradient ratio should be less than 3[19]. In actuality, the permeability coefficient of the geotextile sharply decreases under the influence of soil and water pressure[20], and it tends to clog after bonding with clay particles[21]. This leads to the critical importance of the anti-clogging performance of the geotextile, which reduces the effective open size[13]. While existing research and applications primarily focus on basic properties, in practical applications, not only pressure but also factors such as thickness and material characteristics may play crucial roles in drainage performance and anti-clogging capabilities of geotextiles.

To address the issues mentioned above, the present study will undertake the following measures: 1) Evaluate the effectiveness of nonwoven geotextiles in conventional soil conservation, water permeability, and blockage prevention based on indicators such as apparent opening size (AOS), permeability coefficient (k_n), and gradient ratio (GR). 2) Conduct in-depth simulations of key processes such as sediment interception and permeation of nonwoven geotextiles under the load of Yellow River sediment drainage and investigate the causes of nonwoven geotextile clogging. 3) Propose new engineering strategies based on understanding the causes of clogging.

2 Materials and methods

2.1 Experimental materials

2.1.1 Geotextiles

In this experiment, two types of geotextiles with consistent outer fiber but differing manufacturing processes were selected (Table 1). The first type is needle-punched nonwoven geotextile, made of polyester fibers, with specifications including 200 g/m^2 and 300 g/m^2 short fiber needle-punched nonwoven geotextile (Jinan Mingfeng Engineering Materials Co., Ltd., China). The second type is thermal-bonded nonwoven geotextile, composed of polyester fibers-wrapped nylon, with specifications ranging from 100 g/m^2 to 300 g/m^2 of Colback thermal-bonded nonwoven geotextile (Freudenberg Performance Materials (Changzhou) Co., Ltd., China). The basic parameters, such as weight and thickness, are detailed in the table below.

Table 1 Geotextile type, size, gross weight, and thickness of the fundamental state

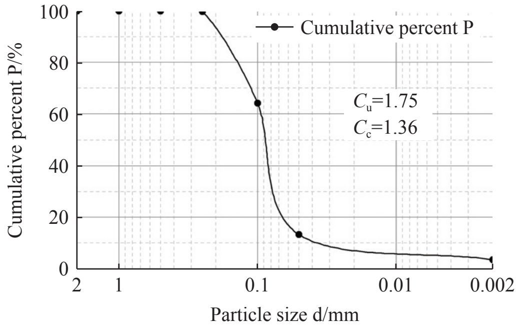
Experiment	Type	Gross weight/ g·m^{-2}	Thickness/ mm	Coefficient of variation
N1	Needle-punched	300	2.75±0.09	2.10%
N2	Needle-punched	200	1.65±0.13	5.40%
T1	Thermal-bonded	300	1.24±0.01	0.60%
T2	Thermal-bonded	250	1.07±0.01	0.75%
T3	Thermal-bonded	200	0.91±0.01	0.62%
T4	Thermal-bonded	160	0.73±0.03	3.35%
T5	Thermal-bonded	120	0.50±0.04	5.28%
T6	Thermal-bonded	100	0.42±0.01	2.09%

Notes: Thickness under 2kPa normal stress (ASTM D5199).

2.1.2 Yellow River sediment

The Yellow River sediment dredged by the sediment dredging ship from the Yellow River main canal in Qiuji Town, Dezhou City, Jining County, Shandong Province, was transported through a pipeline and filled over 200 hm^2 of coal-mined subsided lands at a concentration of 200-300 kg/m^3[10,11]. The sediment utilized (Figure 2a) in this study was extracted from the Yellow River Jijin Main Canal by a sediment dredging ship and underwent purification to remove impurities before being utilized as experimental material. To replicate the actual filling conditions as closely as possible, experimental water with pH 7.64 and conductivity of 696 μS/cm was employed to closely mimic field conditions. The particle size distribution, uniformity coefficient (C_u), and curvature coefficient (C_c) of the sediment extracted by the sediment dredging ship from the Yellow River Jijin Main Canal were as follows (Figure 2b).

a. Dredging ships clearing accumulated sediment



b. The particle size distribution curve of Yellow River sediment

Figure 2 Dredging ships clearing accumulated sediment and the particle size distribution curve of Yellow River sediment

2.2 Foundational experiment

The apparent opening size (AOS) of geotextiles was determined using a specialized geotextile AOS tester (Cangzhou Zhisheng Test Instrument Factory, China) through a dry sieving method[22]. The test followed the standard operating procedure and required drawing the opening size distribution curve upon completion. To ensure accurate results, obtaining data on the sieving rate for 3-4 particle size levels was necessary, ensuring that these data were evenly distributed on the curve. Such a curve reflects the pore structure of the geotextile, calculates the AOS, and ensures the reliability of the measurement results, providing a scientific basis for the selection of geotextiles. Using the cubic spline interpolation method to fit the distribution curve of the remaining rate and opening size in the experiment, the AOS was the particle size value corresponding to the 95% residual rate on the distribution curve. According to research, the AOS of the geotextile should be less than the product of the characteristic particle size (d_{85}) of the protected soil and the coefficient (B_s) of the particle size distribution[17]. For Yellow River sediment, with a C_u value of 1.75, d_{85} of 0.158 mm, and B_s value of 1, the geotextile's AOS should be less than 0.158 mm to achieve effective soil protection. The residual rate (S_j) can be calculated using the Equation (1):

$$S_j = \left(1 - \frac{M_j}{M_0}\right) \times 100\% \tag{1}$$

where S_j is the residual rate, %; M_0 is the initial mass of particles placed on the sieve, g; and M_j is the mass of particles remaining on the sieve after sieving, g.

The permeability coefficient (k_n) of geotextiles was determined in strict accordance with the ASTM D 5493 standard[23]. To ensure accuracy, five parallel tests were conducted for each type of geotextile, with three repeated measurements in each group. Every step was meticulously recorded to guarantee the accuracy of the data. Upon completion, the average of the repeated tests in each group was taken as the permeability coefficient for that group. Then the averages of all groups were combined to obtain the final permeability coefficient. The permeability coefficient (k_n) of the geotextile needed to be determined, and then the geotextile selection was performed based on the criterion that the permeability coefficient of the geotextile (k_n) should be greater than ten times that of the protected soil (k_s)[18]. The calculation of the permeability coefficient (k_n) was carried out according to Equation (2):

$$k_n = \frac{V \cdot \delta}{A \cdot \Delta h \cdot t}\eta \tag{2}$$

where k_n is the permeability coefficient of the sample at n °C, cm/s; V is the permeated water volume, cm^3; δ is the thickness of the geotextile sample, cm; A is the area of water passage through the geotextile sample, cm^2; Δh is the difference in water level between upstream and downstream, cm; t is the duration of the permeated water volume V, s; and η is the water temperature correction factor.

The clogging test for geotextiles should be conducted in accordance with the ASTM D 5101-01 standard[24]. The clogging performance was assessed through the gradient ratio (GR) filtration test, which calculates the hydraulic gradient between different locations of the geotextile, thus obtaining the hydraulic gradient. The GR value represents the ratio of the unit head loss of the soil-geotextile system (25 mm-thick soil layer plus geotextile) to that of the soil layer alone (50 mm-thick). Typically, to ensure good clogging resistance of the geotextile, the GR should be less than 3[19]. The GR is calculated using Equation (3).

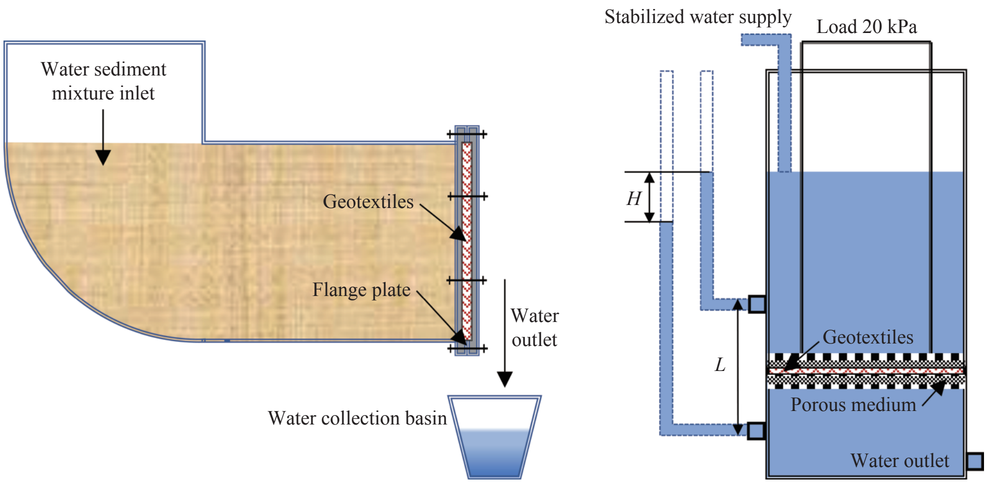
$$\mathrm{GR} = \frac{i_{s-g}}{i_s} \tag{3}$$

where GR is the gradient ratio; i_{s-g} is the hydraulic gradient across 25 mm-thick sediment layer plus geotextile; and i_s is the gradient in 50 mm-thick sediment layer above the geotextile.

2.3 Sand interception and drainage experiments

Indoor simulation tests were conducted to assess the sediment interception and drainage performance of the geotextile. Initially, the geotextile was evenly laid out on the sediment interception and drainage device (Figure 3a), with a water collection basin placed at the drainage outlet to collect effluent. Subsequently, a water-sand mixture with a concentration of 300 kg/m^3 was prepared and uniformly poured into the device to simulate the process of sediment drainage. The experiment commenced with the immediate activation of a timer, and the drainage volume in the collection basin was recorded at 10-minute intervals over a duration of 30 min. One hour after the conclusion of the test, the remaining sediment in the basin was collected and dried to a constant mass. Simultaneously, the geotextile was cleaned and dried, and its post-test mass recorded. These procedures were employed to analyze the sediment interception effectiveness and drainage performance of the geotextile, providing a basis for assessing its actual performance in engineering applications.

The calculation for the unit area sediment loss (SL_u) is as follows in Equation (4):



a. Diagram of sand drainage test set

b. Diagram of infiltration test setup for geotextile under load

Figure 3 Diagram of sand drainage test setup and infiltration test setup for geotextile under load

$$\mathrm{SL}_u = \frac{(m_2 - m_1)}{a} \tag{4}$$

where SL_u is the unit area sediment loss, g/m²; m_1 is the weight of the basin before the drainage test, g; m_2 is the weight of the basin after the drainage test, g; and a is the area of the drainage test geotextile, m².

The geotextile's sediment retention rate (T_g) is defined as the proportion of the volume of sediment particles (V_s) retained per unit volume of geotextile pore space (V_g)[25], expressed as Equation (5):

$$T_g = \frac{V_s}{V_g} = \frac{M_g}{\delta\rho_f - u_g} \times \frac{\rho_f}{\rho_s} \times 100\% \tag{5}$$

where V_g is the geotextile pore space; V_s is the volume of sediment particles retained per unit volume of geotextile; ρ_s is the density of sediment particles (2.69×10^3 kg/m³); ρ_f is the fiber density (1.37×10^3 kg/m³); δ is the geotextile thickness, m; M_g is the weight of sediment particles retained per unit area of geotextile, g/m²; and μ_g is the weight of clean geotextile per unit area, g/m².

2.4 Permeability coefficient of geotextiles under load

In Yellow River sediment reclamation projects, geotextiles are subjected to various directional loads, including the vertical pressure from overlying soil and lateral earth pressure[11]. These loads can alter the geotextile's pore structure, consequently impacting its permeability[20,26]. This study utilized a constant head permeameter and porous acrylic plates to simulate this process to mimic the homogenous soil condition[27]. Different horizontal pressures were applied in the vertical direction to test the changes in the permeability of the geotextile under various pressures (Figure 3b). Initially, the geotextile samples were cut to appropriate sizes and laid flat on the acrylic plates. The samples were then placed in the permeameter, and different horizontal and vertical pressures were applied according to the predetermined scheme to simulate the multi-directional pressure states that the geotextile may experience in practical use. The permeability test was then initiated, and accurate water flow and time data were recorded to calculate the permeability under each pressure condition.

The permeability coefficient (k_n^p) was calculated using the following Equation (6):

$$k_n^p = \frac{Q \cdot L}{A \cdot H \cdot T}\eta \tag{6}$$

where k_n^p is the permeability coefficient (cm/s) at p kPa water temperature n °C; Q is the amount of water permeating during time T s, cm³; L is the height of the geotextile sample between the two pressure measuring holes; H is the average water level difference, cm; and η is the water temperature correction coefficient.

2.5 Analysis method

The study used a one-way analysis of variance (ANOVA) to examine the impact of different levels of geotextile test indicators and experimental results on the dependent variable. When analyzing variance, it was essential to ensure that the data met the basic requirements of normal distribution and homogeneity of variance. Subsequently, significance differences were determined by calculating the F-statistic and subsequent post hoc comparisons, employing Fisher's least significant difference test.

Furthermore, a nuanced application of partial correlation analysis was undertaken to discern the synergistic influences of geotextile thickness and the nuances of geotextile material on the rate of sediment loss per unit area. The methodology entailed the development of a partial correlation framework, within which this study computed partial correlation coefficients to ascertain the unique contribution of each predictor to the response variable, with a systematic adjustment for the perturbations introduced by concomitant predictors. The integrity of this analysis hinged on the data's adherence to the foundational prerequisites of linearity, autonomy, multivariate normal distribution, and homogeneity of variance. The fidelity of the model's representation was gauged by the statistical significance vested in the partial correlation coefficients, thereby providing a robust measure of the model's concordance with empirical observations.

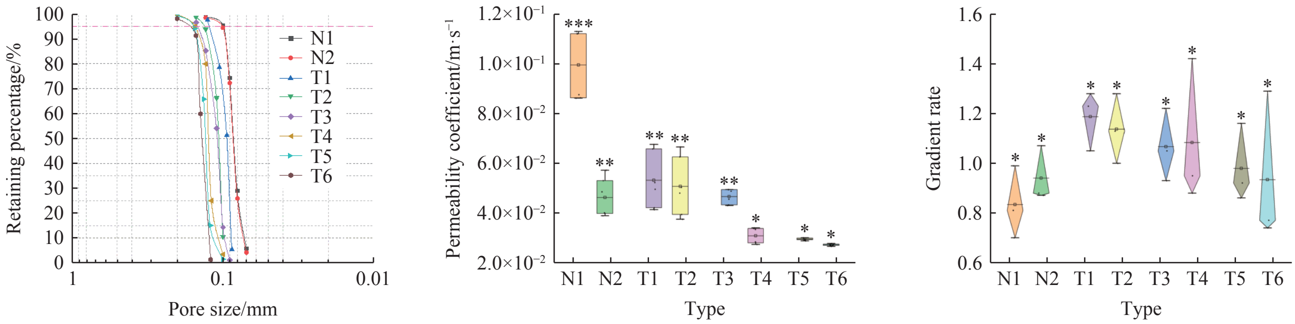
For the implementation of one-way ANOVA, Origin 2021 graphic and data analysis software (Origin Lab, Massachusetts, USA) can be used for analysis and visualization, while partial correlation analysis and its interaction effects may be conducted using the R Project for Statistical Computing.

3 Results

3.1 Comparison and evaluation of basic drainage performance of nonwoven geotextiles

Through the use of cubic spline interpolation to fit the distribution curves of retention rate and opening size observed in the experiments, as delineated in Figure 4a, the apparent opening size (AOS) for N1, N2, T1, T2, T3, T4, T5, and T6 were determined to be 0.100, 0.103, 0.126, 0.133, 0.147, 0.152, 0.163, and 0.174 mm, respectively. Based on calculations of sediment particle size distribution at the experimental site, for the remediation of coal-mined subsided lands filled with Yellow River sediment, the AOS of the sediment-retaining and drainage geotextile should be less than one time the particle size distribution coefficient (B_s), namely 0.158 mm, to theoretically achieve an optimal soil conservation effect. Given the experimental results for the AOS, it can be seen that N1, N2, T1, T2, T3, and T4 all had AOS less than 0.158 mm, indicating their superior capability in sediment retention and soil conservation.

Based on the analysis of permeability coefficients (k_n) (Figure 4b), it was observed that the permeability coefficients of the seven types of nonwoven geotextiles, namely N1, N2, T1, T2, T3, T4, and T5, were greater than ten times that of the Yellow River sediment[11]. Among them, N1 exhibited a significant difference compared to the other six types of nonwoven geotextiles, while N2, T1, T2, and T3 showed no significant differences. On the other hand, T4 and T5 exhibited significant differences from the others, albeit approaching ten times the permeability coefficient of the Yellow River sediment, and showed no significant difference from T6, which had a permeability coefficient lower than that of the Yellow River sediment. To ensure that the nonwoven geotextiles maintain sufficient permeability after stable filling and drainage, nonwoven geotextiles with a mass per unit area exceeding 200 g/m^2, such as N1, N2, T1, and T2, are theoretically preferred.



a. Pore size distribution of the geotextiles b. Permeability coefficient (k_n) of geotextile c. Gradient ratio (GR) of geotextile

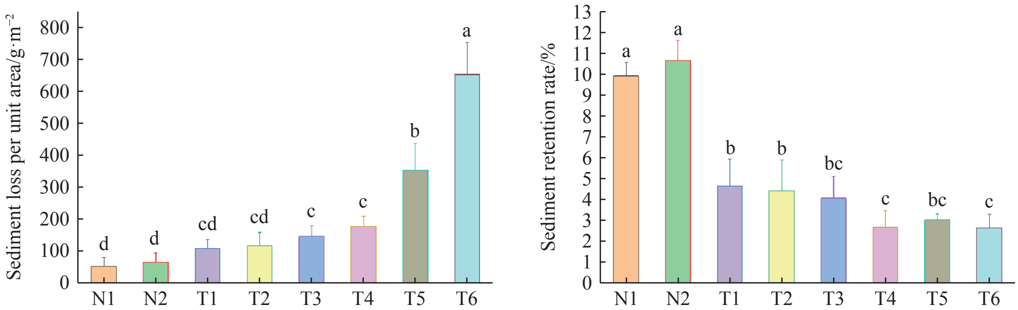
Note: Different numbers "*", "**", and "***" represent significant differences at the 0.05 level.

Figure 4 Basic drainage performance of geotextiles

The results from the standard gradient ratio test method revealed that the long-term gradient ratios (GR) for nonwoven geotextiles N1, N2, T1, T2, T3, T4, T5, and T6 were all below 3 (Figure 4c). Theoretically, this indicates that utilizing these nonwoven geotextiles for drainage meets the requirements of the filtration layer, with clogging being highly unlikely to occur. Consequently, this suggests that these nonwoven geotextiles demonstrate commendable anti-clogging performance and are theoretically capable of effectively maintaining the unimpeded functionality of the drainage system.

3.2 Efficacy of nonwoven geotextiles in sand interception and drainage performance

When mixed water and sand enter the drainage system, clean water and fine sand particles will flow through the nonwoven geotextile, resulting in a certain degree of sediment loss. According to the sand interception and drainage test results (Figure 5a), the sediment loss rates for nonwoven geotextiles N1, N2, T1, T2, T3, and T4 were all below 200 g/m^2. This figure indicates that these geotextiles have good sediment interception and soil retention capabilities. In particular, the soil retention performance of N1, N2, T1, and T2, among the four nonwoven geotextiles, did not exhibit significant differences, showing excellent performance. While the performance of T3 and T4 did not significantly differ from the aforementioned four types, it was notably better compared to T5 and T6. Taking all factors into consideration, from the perspective of controlling the sediment loss per unit area, it is theoretically recommended to select nonwoven geotextiles with a mass per unit area exceeding 160 g/m^2, such as N1, N2, T1, T2, T3, and T4, to ensure the efficient operation and long-term stability of the drainage system.



a. Unit area sediment loss, reflecting soil retention b. Sediment retention rate, reflecting the effective opening area of the nonwoven geotextile

Note: Different letters a, b, and c represent significant differences at the 0.05 level.

Figure 5 Results of nonwoven geotextile sand filtration and drainage test

When mixed water and sand pass through the drainage nonwoven geotextile, clean water and fine sand particles flow through the nonwoven geotextile, while some particles are retained on the nonwoven geotextile. According to the sand filtration and drainage test results, the sediment retention rates of N1 and N2 were 9.92% and 10.67%, respectively, which were significantly higher than the other six nonwoven geotextiles, T1-T6. This indicates a significant difference in sediment retention rates among nonwoven geotextiles produced using different manufacturing processes. Specifically, the sediment retention rates of T1, T2, and T3 were 4.64%, 4.42%, and 4.07%, slightly higher than T4, T5, and T6, which were 2.68%, 3.03%, and 2.68%, respectively. Lower sediment retention rates reflect the stability of the effective opening area of the drainage system. Therefore, it is recommended to use thermal-bonded nonwoven geotextiles to ensure the efficient operation and stability of the drainage system.

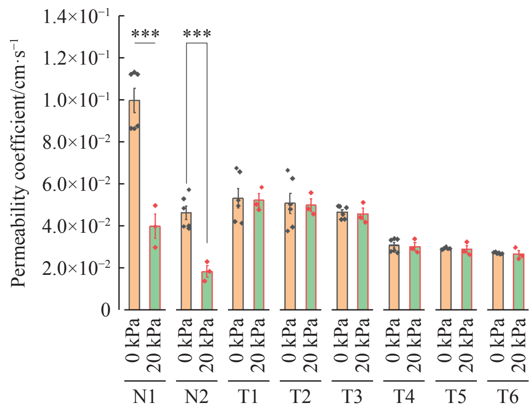
3.3 Permeability coefficient of nonwoven geotextiles under load

In the prevailing scenarios of land reclamation and the specifications for producing nonwoven geotextiles, drainage systems customarily employ nonwoven geotextiles that span a width of 1 m. Empirical evidence indicates that under such a width, the maximal lateral pressure that the nonwoven geotextiles are likely to withstand approximates 20 kPa[11]. Under the influence of this perpendicular pressure, two varieties of nonwoven geotextiles, designated N1 and N2, exhibited varying degrees of permeability reduction. Specifically, the permeability coefficients for N1 and N2 diminished by nearly half; yet, the coefficient for N1 persistently exceeded that of the Yellow River sediment by more than an order of magnitude, whereas the coefficient of N2 dwindled to less than one tenth that of the sediment. In stark contrast, nonwoven geotextiles labeled T1 through T6 demonstrated no significant alteration in their permeability coefficients under analogous pressures (Figure 6).

This phenomenon sheds light on the profound implications of construction techniques on the stability of nonwoven geotextile performance. The marked decline in the permeability coefficient of needle-punched nonwoven geotextiles under vertical pressure alludes to their suboptimal stability. Conversely, thermal-bonded nonwoven geotextiles retain a high degree of permeability stability under equivalent conditions. Consequently, in the design and execution of drainage systems, it is imperative to give precedence to those nonwoven geotextiles that uphold a stable permeability coefficient when subject to vertical pressure, thereby ensuring the long-term efficacy and dependability of the drainage infrastructure.

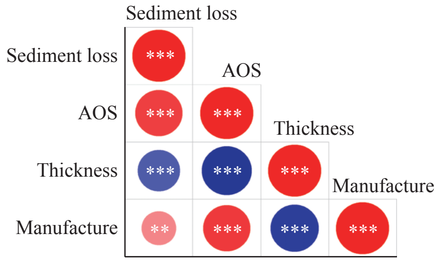
3.4 Interplay between the soil retention properties of nonwoven geotextiles and their apparent opening size (AOS), thickness, and manufacturing process

In the experiment of sediment interception and drainage using nonwoven geotextile, the lower the unit area sediment loss of the nonwoven geotextile, the better the soil protection effect of the nonwoven geotextile drainage system. To analyze the correlation between the unit area sediment loss of the nonwoven geotextile and its apparent opening size (AOS), thickness, and production process, a correlation analysis was conducted. Based on the data inspection (see Figure 7b), the normal quantile-quantile plot indicates that the data approximately followed a normal distribution. The results (Figure 7a) demonstrated a strong correlation between the unit area sediment loss of the nonwoven geotextile and its AOS, thickness, and production process. Specifically, the unit area sediment loss of the nonwoven geotextile was positively correlated with its AOS, with a correlation coefficient of 0.805; negatively correlated with the thickness of the nonwoven geotextile, with a correlation coefficient of –0.648; and positively correlated with the production process classification, with a correlation coefficient of 0.445.

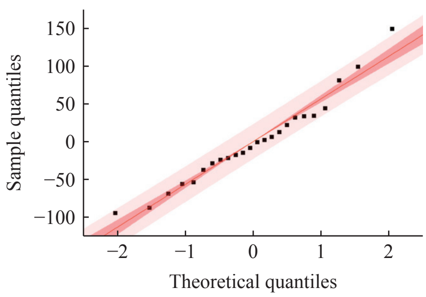


Note: Different numbers "*", "**", and "***" represent significant differences at the 0.05 level.

Figure 6 Permeability coefficient of nonwoven geotextiles under load 0-20 kPa



a. Correlation heatmap of unit area sediment loss



b. Normal Q-Q plot in the multivariate regression analysis

Note: Different numbers "*", "**", and "***" represent significant differences at the 0.05 level.

Figure 7 Correlation and multivariate regression analysis of unit area sediment loss of nonwoven geotextiles with apparent opening size (AOS), thickness, and material manufacturing process

To analyze their interactions further, a partial correlation analysis was carried out (Table 2). Controlling for the thickness of the nonwoven geotextile and the production process, the AOS of the nonwoven geotextile showed a significant positive correlation with sediment loss (r=0.742, p=0.001). Controlling for the AOS of the nonwoven geotextile and the production process, the correlation between the thickness of the nonwoven geotextile and sediment loss was weak and not significant (r=0.059, p=0.758). Controlling for the AOS of the nonwoven geotextile and its thickness, the production process of the nonwoven geotextile exhibited a significant negative correlation with sediment loss (r=–0.504, p=0.004). Therefore, the partial correlation analysis suggests that the AOS and production process of the nonwoven geotextile have a significant impact on sediment loss, while the thickness of the nonwoven geotextile also influences sediment loss, albeit to a lesser extent.

Table 2 Partial correlation analysis of sediment loss in relation to apparent opening size (AOS), thickness, and manufacturing process

Control Variables	Independent Variable	Dependent Variable	Correlation (*r*)	Significance (*p*)
Thickness: Manufacture	AOS	Sediment loss	0.742	0.001
AOS: Manufacture	Thickness	Sediment loss	0.059	0.758
AOS: Thickness	Manufacture	Sediment loss	–0.504	0.004

4 Discussion

4.1 Validity and significance of detection indicators and simulation tests

In the application of drainage in the reclamation of Yellow River sediment filling, soil retention, permeability, and anti-clogging are the key performance indicators[10]. The apparent opening size (AOS) is a critical indicator for measuring soil retention, as its size directly affects the particle retention capacity[28]. In this study, sediment interception and drainage experiments showed a strong correlation between the sediment loss per unit area and the AOS. The permeability coefficient measures the permeability of geotextiles, reflecting their ability to allow water flow under ideal conditions, which is particularly important for Yellow River sediment filling and rehabilitation areas[29]. In this study, the permeability coefficients of most specifications exceeded the permeability coefficient of Yellow River sediment tenfold, demonstrating strong permeability. Anti-clogging is commonly evaluated using the gradient ratio, which reflects the drainage capacity of geotextiles under particle blockage[17,24]. In this study, the gradient ratio remained below 1.2 for an extended period, far below the standard 60%, theoretically indicating good drainage capacity under blockage.

However, in actual working conditions, the sediment transported through pipelines is approximately 200-300 kg/m^3[9]. This means there are two key processes in drainage: the interception and drainage of the sediment slurry and the continued drainage and stabilization of the remaining moisture after sediment settlement. These two processes subject the geotextiles to certain lateral pressures. To fully reflect these two stages, sediment interception and drainage experiments, as well as geotextile permeability coefficient tests under load, were conducted accordingly. In addition to basic testing, supplementing the detection of soil retention, anti-clogging, and permeability of geotextiles through sediment interception and drainage experiments and geotextile permeability coefficient tests under load can more comprehensively meet actual working conditions. These experiments can more accurately simulate the performance of geotextiles in actual applications, ensuring that the selected geotextiles can maintain their functionality when subjected to particle and water flow, thereby ensuring the stability and sustainability of Yellow River sediment-backfilled reclaimed coal-mined subsided lands.

4.2 Critical factors affecting clogging of drainage nonwoven geotextiles

The clogging of drainage geotextiles is influenced by their own structure and working environment. Sand trapping and drainage tests have shown a significant correlation between the AOS and thickness of geotextiles and the amount of sediment loss, with an increase in thickness potentially leading to aggravated clogging[29]. Additionally, permeability coefficient tests under load have demonstrated a significant decrease in the permeability of geotextiles within a certain load threshold, which is an important factor in the clogging of needle-punched nonwoven geotextiles[20,26,27]. However, the vertical load that geotextiles bear in drainage is often overlooked in current engineering designs.

Research indicates that the thickness of geotextiles affects their soil retention, but this effect is not linear[29]. Within applicable working conditions, the thickness of geotextiles has a considerable impact on soil retention. Thicker geotextiles have longer opening channels, so within the opening size range of geotextiles, the thickness of geotextiles has a certain impact on sediment loss[29]. However, although there is a strong correlation between sediment loss and thickness, the variation in geotextile thickness shown in tests is not significant compared to the AOS; therefore, the effect of thickness on sediment loss is not significant. Furthermore, in actual working conditions under lateral soil pressure, the permeability coefficient of geotextiles will significantly decrease[20,26,27], a factor not considered in traditional permeability criteria. Therefore, when selecting geotextiles, it is necessary to consider the lateral compression conditions to ensure that their permeability coefficient does not decrease significantly or that it remains within a safe range even after a decrease. The clogging of geotextiles is closely related to the size of the geotextiles themselves and the soil particles[30]. Although the gradient ratio is a commonly used anti-clogging index[24,17], its performance in dynamic water-sand mixtures may differ from that under static conditions. In actual working conditions, when geotextiles trap sand and drain water, they are subjected to lateral pressure from soil particles. Under water flow conditions, soil particles are intercepted on the surface of the geotextiles, reducing their effective opening area[30,29], and the natural filter cake structure formed becomes less permeable under lateral compression[30].

Under the same material, different types of geotextiles, such as needle-punched nonwoven geotextiles and thermal-bonded geotextiles, will affect the clogging of geotextiles. The influencing factors of clogging in terms of soil retention, water permeability, and anti-clogging properties include the AOS and thickness of geotextiles, permeability coefficient, load-bearing capacity, gradient ratio, and sediment retention capacity. Therefore, in practical applications, it is necessary to consider the differences in various geotextiles through indoor tests and comprehensive screening to minimize clogging and ensure the long-term effectiveness of the drainage system.

4.3 Recommendations for drainage geotextile selection based on application scenarios

Generally, geotextiles can be divided into woven geotextiles and nonwoven geotextiles. Among drainage geotextiles, nonwoven geotextiles are widely used. Different applications require different performance indicators for geotextiles. For instance, in water conservancy and hydropower engineering, geotextiles are primarily used for riverbank protection and erosion control, necessitating considerations of mechanical strength, tensile properties, and abrasion resistance[31]. Conversely, in landscaping and greening construction, geotextiles are utilized for vegetation coverage and slope protection, emphasizing permeability and durability[32]. Therefore, it is essential to establish an evaluation system and propose appropriate technical indicators based on specific engineering requirements and usage scenarios, and to formulate corresponding standards to select the most suitable geotextile materials.

In previous studies and practices related to Yellow River sediment-backfilled reclaimed coal-mined subsided lands, attempts were made to evaluate geotextile performance based on soil retention, permeability, and anti-clogging properties[10,33]. However, considering only AOS, hydraulic conductivity, gradient ratio (GR), and other indicators, it is still difficult to fully apply them in engineering practices. Based on research findings, it is recommended to augment the evaluation criteria for soil retention, permeability, and anti-clogging with additional indicators such as geotextile thickness, vertical hydraulic conductivity under safe load, and soil retention rate to comprehen sively and accurately assess geotextile material performance.

By analyzing the application scenarios and evaluating the importance weights of each performance indicator, specific evaluation criteria tailored to the specific requirements of the scenario can be developed. This approach can effectively screen geotextile products that fully meet the technical requirements and are economically viable[30]. When formulating specific evaluation criteria, factors such as engineering requirements, cost-effectiveness, and environmental impact in the given scenario should also be taken into consideration.

5 Conclusions

Based on the evaluation of two different production processes of geotextile, needle-punched and thermal-bonded, in terms of basic indicators such as apparent opening size (AOS), permeability coefficient (k_n), and gradient ratio (GR), and through the simulation and analysis of actual causes of clogging based on Yellow River sediment drainage experiments and geotextile permeability tests under load, the following conclusions can be drawn: 1) Through the evaluation of AOS, permeability coefficient (k_n), and GR, experiments have shown that nonwoven geotextiles N1, N2, T1, T2, T3, and T4 exhibit suitable AOS, superior permeability, and good anti-clogging performance, making them suitable for long-term stability in soil protection and drainage systems. 2) The key factors contributing to clogging in drainage geotextiles include the geotextile's AOS, thickness, permeability, load-bearing capacity, GR, and sediment retention efficiency. These factors need to be comprehensively considered through indoor experiments to optimize material selection in practical applications. 3) The selection of geotextiles for Yellow River sediment-filled drainage should be based on the specific engineering requirements of the application scenario. It is essential to establish a comprehensive evaluation system covering soil retention, permeability, anti-clogging, and supplementary performance indicators to ensure that the selected materials meet specific technical requirements and are economically viable.

Acknowledgements

This study was funded by the National Natural Science Foundation of China (Grant No. 41771542). The authors would like to acknowledge Freudenberg Performance Materials (Changzhou) for providing the thermal-bonded geotextiles used in this study.

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