

Feasibility study on waste silty clay as a recycled slurry material for slurry shield tunneling

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Feasibility study on waste silty clay as a recycled slurry material for slurry shield tunneling

Abstract:

To expand the options for recycling the waste silty clay generated during shield tunneling, a feasibility study was conducted on the use of modified silty clay slurry as slurry material for shield tunnels. First, the optimal formulation for the modified slurry was determined through physical and rheological property tests. Subsequently, using a proprietary slurry filtration and filter cake formation testing system, vertical permeability tests were conducted on the optimized slurry in three types of formations: medium-coarse sand, coarse sand, and gravel. The results indicate that the modified drilling fluid meets construction specifications. In medium-coarse sand and coarse sand strata, the slurry can form a filter cake or a composite structure of filter cake and permeable zone, with a pressure conversion efficiency above 85% and controllable API fluid loss and penetration depth. In gravel strata, however, effective filter cake formation is unattainable due to excessively large pore sizes, leading to a pressure conversion efficiency below 40% that cannot meet excavation face support requirements. The mechanism of filter cake formation was elucidated by combining double-layer theory, zeta potential, and FTIR and SEM analyses. Sodium carbonate modification increased the negative surface potential and hydration capacity of the clay particles through ion exchange, thereby bringing the colloidal stability of the modified silty clay slurry close to that of bentonite slurry. Research has confirmed that modified waste silty clay is a viable material for use in shield tunneling slurry, offering significant economic and environmental benefits.

Keywords: Slurry shield tunneling; Filtration and filter cake formation performance; Modified waste silty clay slurry; Filter cake type; Recycling

Highlights

1. The optimal mix proportion of modified waste silty clay slurry is determined as 3:5, 60 g fine sand, and 0.5% sodium carbonate. Its physical, rheological, and filtration properties all meet field construction requirements.
2. The modified waste silty clay slurry is suitable for medium-coarse sand and coarse sand strata. It can form Type I and Type II effective filter cakes, and the pressure conversion efficiency is above 85%.
3. After sodium carbonate modification, the surface negative charge density and hydration ability of silty clay particles are significantly improved, and the colloidal stability is close to that of bentonite slurry.
4. The filter cake type of modified silty clay slurry is controlled by the ratio of slurry characteristic particle size d_{85} to formation average pore size D_0 . Pure filter cake forms when $d_{85}/D_0 > 1$, filter cake-permeation zone forms when $0.5 < d_{85}/D_0 < 1$, and no filter cake forms when $d_{85}/D_0 < 0.5$.
5. Modified waste silty clay slurry shows potential as a slurry material for slurry shield tunneling. It broadens the resource utilization channel of shield spoil, reduces material cost, and achieves significant economic and environmental benefits.

1. Introduction

The rapid development of urban underground rail transit in China has established shield tunneling as a primary construction method (Guo et al., 2024; Liu et al., 2024; Shen et al., 2023; Yang et al., 2023), valued for its high construction speed, minimal environmental impact, and enhanced safety (Jin et al., 2023; Wang et al., 2023; Wang et al., 2023; Xu et al., 2020). In slurry shield tunneling, pressurized slurry is injected to form an impermeable filter cake on the excavation face, which stabilizes the face by balancing earth and water pressures (Wu et al., 2025; Yin et al., 2021). The cutterhead then excavates this filter cake and the native ground in a cyclical process to advance the tunnel boring machine (Liu et al., 2024; Mao et al., 2020; Zizka et al., 2021). The grouting material must therefore possess specific properties, including appropriate specific gravity, effective filter-cake formation, stability, viscosity, and rheology to ensure face stability and counteract subsurface pressures (Guo et al., 2023). Bentonite is a mineral with finite reserves, and its extraction and processing are costly (Wang et al., 2022). Concurrently, the management of excavated waste slurries containing bentonite particles and additives presents a significant challenge, as they are difficult to treat and separate, leading to serious environmental pollution (Guo et al., 2024). This issue is particularly relevant in the context of China's dual-carbon strategic goals, which emphasize sustainable development. Earth Pressure Balance Shield (EPBS) tunneling, for instance, generates substantial spoil (Liu et al., 2025; Liu et al., 2025). Conventional disposal methods like open-air stockpiling or landfilling risk contaminating soil and groundwater and can damage local landscapes and ecosystems (Cao et al., 2025; Hu and Wu, 2023). In China alone, the annual production of shield spoil exceeds 119 million tons, yet the utilization rate remains below 1% (Zhang et al., 2022). The resource utilization of shield spoil presents considerable environmental and economic benefits. Given that bentonite slurry is the predominant grouting material in slurry shield tunneling, researchers are investigating silty clay, a major component of EPBS spoil, as a potential substitute (Liu et al., 2024; Wang et al., 2023; Wang et al., 2023). Determining the efficacy of modified silty clay in replacing bentonite is therefore of

strategic importance, as it could create new recycling pathways for excavated materials and advance sustainable tunnel construction.

During the tunneling and grouting process of slurry shields in water-rich gravel strata and other formations with high water content and permeability, the slurry often experiences deep filtration, resulting in significant API fluid loss (Min et al., 2013). This phenomenon inhibits the formation of an effective filter cake, which is essential for providing adequate support pressure to the excavation face and consequently increases the risk of engineering incidents. Previous studies have demonstrated that modified waste silty clay slurry can achieve physical and rheological properties comparable to those of bentonite slurry. However, for slurry shield tunneling applications, the filtration behavior of the slurry within the formation remains a critical indicator for evaluating its engineering applicability (Cui et al., 2019; Zhang and Bezuijen, 2025). However, research on the filtration and membrane-forming performance of modified waste silty clay slurry in soil formations remains limited. Therefore, conducting laboratory-scale filtration and membrane-forming tests is essential to investigate the slurry's performance in highly permeable strata and to evaluate the feasibility of utilizing modified waste silty clay slurry as a grouting material for slurry shield tunneling.

The most prevalent method for investigating the filtration performance of slurry in permeable strata is the three-dimensional permeation column test (Jin et al., 2025). This approach enables direct correlation between parameters such as slurry mix proportion, stratum gradation, and slurry rheological properties with filter cake performance (Min et al., 2019; Xu and Bezuijen, 2019). The fundamental principle of slurry shield tunneling relies on forming an effective filter cake on the excavation face to ensure stability. The efficacy of filter cake formation is fundamentally governed by the slurry properties, stratum performance, and the underlying interaction mechanisms between the slurry and the stratum (Xu and Bezuijen, 2018, 2019; Xu and Bezuijen, 2019). Furthermore, by optimizing the particle gradation or incorporating additives such as sand or polymeric agents, the slurry's filtration behavior can be effectively controlled, promoting the formation of a thin and impermeable filter cake (Cao et al., 2025; Wang

et al., 2022). To gain deeper insight into the slurry filtration performance, some researchers have used pore pressure transducers embedded within the formation to reveal that filter cake formation is a dynamic process. During this process, slurry pressure is gradually transformed into effective stress resisting earth pressure. The filter cake formation time, API fluid loss volume, and dissipation degree of excess pore water pressure can serve as key indicators for evaluating its quality (Xu et al., 2024; Yuan et al., 2024). Min et al. (2013) conducted a systematic investigation into the relationship between slurry mix proportions, formation gradation, and the performance of the resulting filter cake. Through a series of permeation tests with different slurry formulations in various strata, they proposed a discrimination criterion based on the ratio of the slurry's characteristic particle size (d_{85}) to the average pore diameter of the formation (D_0). This criterion classifies filter cake formation into three types: filter cake, filter cake with penetration zone, and penetration zone, providing a quantitative theoretical framework for matching slurry properties to formation conditions. Subsequent research has further elucidated the critical control mechanisms of filter cake formation from a rheological perspective. The viscosity performance of a slurry can be represented by a critical aperture under a specific pressure gradient, and the incorporation of coarse-grained materials has been shown to significantly enhance the filter cake formation performance of bentonite slurries (Wang et al., 2023). Regarding precise control of slurry viscosity during filtration, studies have identified a clear critical threshold (10.56 MPa·s). Below this value, ineffective slurry penetration occurs, hindering filter cake development, while exceeding it promotes the rapid formation of a shallow, impermeable filter cake that effectively controls API fluid loss (Lu et al., 2022; Lu et al., 2022). Extensive permeation column testing has progressively clarified the mechanisms and influencing factors of slurry filtration and filter cake formation. However, most current permeation tests focus on bentonite slurries, with limited research on modified silty clay. The filtration performance of modified waste silty clay slurry in strata remains unclear, and how its filtration behavior differs from that of bentonite slurry requires further investigation.

To this end, waste silty clay derived from the shield tunneling project of Shenyang

Metro Line 6 was adopted as the raw material, and sodium carbonate was used as an alkaline modifier to prepare a total of 45 batches of modified silty clay slurry. Based on systematic measurements of the physical and rheological properties of these slurries, the optimal mix proportion satisfying field construction criteria was determined. A self-developed vertical slurry filtration and filter cake formation test system was employed to conduct vertical permeability tests on the optimized modified slurry and conventional bentonite slurry in three typical strata: medium-coarse sand, coarse sand, and gravel. A comprehensive comparative analysis was performed on their filtration characteristics, transient pore water pressure evolution, API fluid loss, pressure conversion efficiency, and filter cake types across different geological conditions. Combined with electric double layer theory, zeta potential tests, Fourier-transform infrared (FTIR) and scanning electron microscopy (SEM), the modification mechanism and filter cake formation mechanism were revealed at the microscopic scale, which further validates the feasibility of using modified waste silty clay slurry as a shield tunneling slurry material. This study provides experimental evidence and theoretical support for the resource utilization of waste silty clay from shield tunneling and the design of low-cost, eco-friendly slurries for slurry shield tunneling.

2. Materials and methods

2.1 Test materials

(1) Stratum materials

The stratum materials employed in this study were natural river sand obtained from Shijiazhuang, Hebei Province. The sand particles exhibited uniform gradation within the designed particle size ranges, as illustrated in Fig. 1. In accordance with the Code for Geotechnical Investigation (GB 50021), soil is classified as coarse sand if more than 50% of its total mass comprises particles larger than 0.5 mm, whereas gravel refers to crushed stone particles with an average diameter ranging from 2 mm to 60 mm. To evaluate the applicability of modified waste silty clay slurry in various geological conditions, three types of permeable strata were selected: medium-coarse sand (0.25–0.5 mm), coarse sand (0.5–1.0 mm), and gravel (2–5 mm). Their key physical properties

are summarized in Table 1. To minimize the influence of variable compaction on test results and ensure uniform initial porosity and comparable test conditions for strata with different particle sizes, the sand filling mass and specimen volume were strictly controlled during sample preparation. This guaranteed identical dry density and porosity for all graded sandy soils, thus enhancing the reproducibility and reliability of comparative analyses.

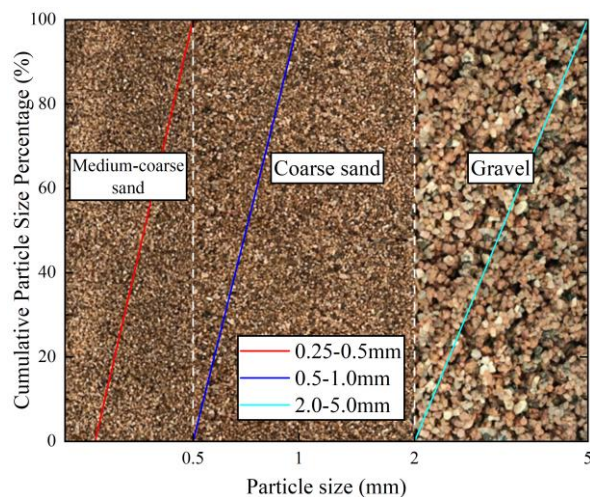


Fig.1. Distribution of sand gradation

Table 1
Physical properties of sand.

Properties	Test methods	Particle size (mm)	Results
Permeability coefficient (cm/s)	Steady-state permeation test	0.25-0.5	1.01×10^{-4}
		0.5-1.0	4.16×10^{-4}
		2.0-5.0	1.41×10^{-3}
Dry density (g/cm ³)	Oven test	0.25-0.5	1.59
		0.5-1.0	
		2.0-5.0	
Specific gravity	Burette test	0.25-0.5	2.65
		0.5-1.0	
		2.0-5.0	
Porosity	Drying test	0.25-0.5	0.40
		0.5-1.0	
		2.0-5.0	
Cohesion (kPa)	Direct shear test	0.25-0.5	0.60
		0.5-1.0	0.42
		2.0-5.0	0.25
Internal friction angle (°)	Direct shear test	0.25-0.5	38.2
		0.5-1.0	41.7
		2.0-5.0	44.5

(2) Slurry materials

The slurry investigated in this study mainly consisted of water, anhydrous sodium carbonate, bentonite, waste silty clay, and fine sand. Anhydrous sodium carbonate used was of analytical reagent (AR) grade, supplied by Sinopharm Chemical Reagent Co., Ltd. The bentonite was sourced from Weifang, Shandong Province, and its chemical composition is presented in Table 2. The waste silty clay was excavated from the construction site of Nanguan Road Station, Shenyang Metro Line 6. Its fundamental physical and mechanical properties were measured in accordance with the Standard for Geotechnical Testing Methods (GB/T 50123-2019), with detailed parameters listed in Table 3. The fine sand adopted was natural river sand with a particle size range of 0.1–0.2 mm, also sourced from Shijiazhuang, Hebei Province.

Table 2

Chemical composition of bentonite.

Composition	SiO ₂	Al ₂ O ₃	MgO	K ₂ O	Na ₂ O	Fe ₂ O ₃	TiO ₂	Loss on ignition
Content (%)	63.21	17.76	3.21	0.92	0.98	2.01	0.11	11.8

Table 3

Physical and mechanical parameters of silty clay.

Properties	Test methods	Results
Percentage of saturated water content (%)	Oven drying method	37.28
Specific gravity	Pycnometer method	2.83
Liquid limit (%)	Liquid-plastic limit combined method	30.68
Plastic limits (%)		19.5
Cohesion (kPa)	Direct shear test	8.52
Internal friction angle (°)		11.48

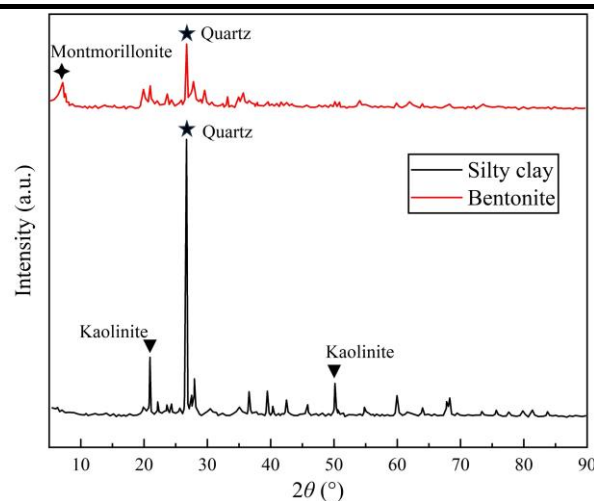


Fig.2. XRD test results

Bentonite and silty clay were characterized by X-ray diffraction (XRD) using a Japanese Rigaku D/MAX-2600 diffractometer. The XRD patterns are presented in Fig.

2. Montmorillonite is the dominant clay mineral in bentonite, accompanied by quartz as the main non-clay mineral. By contrast, kaolinite constitutes the primary mineral phase in the silty clay, with quartz also present.

Laser particle size analysis was carried out using a Mastersizer 2000 laser diffraction analyzer to determine the volume fraction of particles within the range of 0.01–3000 μm . The corresponding particle size distribution curves are presented in Fig. 3. Overall, the silty clay exhibits a finer particle size distribution than bentonite. The specific surface area of silty clay is 0.688 m^2/g , with the 25 μm fraction being the most dominant. By comparison, bentonite has a specific surface area of 0.363 m^2/g and is dominated by the 60 μm particle fraction. The representative particle size d_{85} of the modified silty clay is 35 μm , whereas that of bentonite is 109 μm .

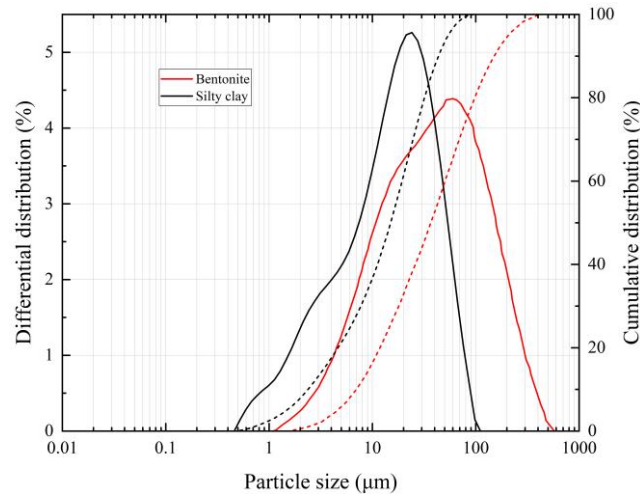


Fig.3. Laser granulometry test results

2.2 Test methods

2.2.1 Slurry performance tests

(1) Test Protocol

Previous studies have validated that sodium carbonate-modified waste silty clay slurry can attain physical and rheological properties comparable to those of conventional bentonite slurry in shield tunneling spoil recycling applications (Liu et al., 2024). To further broaden the resource utilization approaches for waste silty clay, this study extends the application of such modified slurry to slurry shield tunneling. A core functional requirement for slurry used in slurry shield tunneling is the rapid formation of a dense filter cake upon injection onto the excavation face, which generates effective

support pressure to guarantee excavation face stability. Nevertheless, in highly permeable strata, slurries commonly fail to form a continuous and dense filter cake within a short period, potentially triggering engineering hazards including insufficient face support and ground instability. Accordingly, fine sand particles were introduced into the modified silty clay slurry in this study. The particle gradation and pore-filling effects of fine sand were utilized to block large pore channels in highly permeable strata, thereby accelerating filter cake formation (Dong et al., 2024; Xu et al., 2024). The waste silty clay used for testing was obtained from a shield tunneling site. After oven-drying and grinding, the soil was sieved through a 0.1 mm standard sieve to remove impurities and obtain a uniform powder. A total of 45 groups of modified silty clay slurry were prepared, with detailed mix proportions listed in Table 4.

Table 4

Experimental design plan.

Soil water ratio	Sodium carbonate content	Fine sand content	Number of groups
1:2			15
3:5	0.5%、1%、2%、3%、4%	0g、60g、120g	15
9:10			15

(2) Experimental procedure

The modified slurries were prepared in accordance with the target mix proportions specified in the test design. After complete mixing, each slurry was allowed to hydrate undisturbed for 24 h to ensure full chemical reaction and particle dispersion. Physical property tests were then performed on all 45 slurry groups following standardized procedures (Liu et al., 2024), with key indicators measured including funnel viscosity, slurry density, colloid fraction, and API fluid loss. Slurry mix proportions satisfying field construction requirements were selected using the performance criteria of typical on-site slurries as the benchmark. The detailed threshold parameters are listed in Table 5.

Table 5

Slurry performance indicators.

Slurry properties	Range
Funnel viscosity (s)	20~35
API fluid loss (ml)	<20
Specific gravity (g/cm ³)	1.1~1.5

Slurry rheological properties do not have a single fixed indicator and change with shear rate. For this reason, bentonite slurry with a concentration ratio of 1:8 to 1:12, which is widely used in slurry shield tunneling, was chosen as the control group. A rotational viscometer was used to test the rheological properties of the optimized slurry and the bentonite slurry. The detailed procedure of the slurry performance test is presented in Fig. 4.

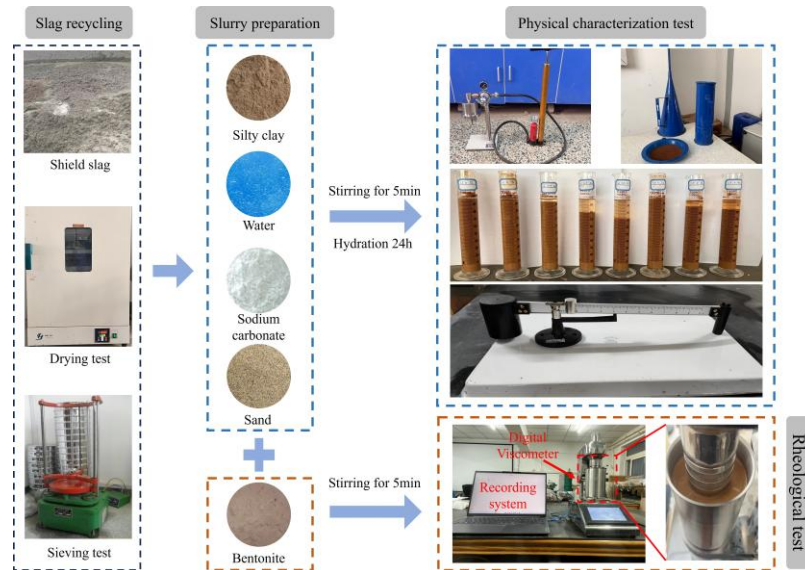


Fig.4. Slurry performance testing procedure

2.2.2 Vertical permeability test

(1) Test protocol

This study aims to investigate the seepage and filter cake formation behavior of modified waste silty clay slurry in strata with different permeability, to clarify its filter cake formation performance, and to verify its feasibility as a substitute for bentonite slurry in grouting. The S6 bentonite slurry proposed by Min et al. (2013) was adopted as the control group. The mix proportion of the control slurry is 100 g in total, with bentonite, silty clay, fine sand and water at a ratio of 6.32:11.9:46.48:35.3. Meanwhile, the optimal mix proportion of modified waste silty clay slurry determined in the previous slurry performance tests was used to carry out filtration and filter cake formation tests in three kinds of strata with different permeability, including medium-coarse sand (0.25–0.5 mm), coarse sand (0.5–1.0 mm) and gravel (2.0–5.0 mm). A slurry pressure of 50 kPa, which is commonly adopted in engineering practice (Cui et

al., 2019; Qin et al., 2023), was applied in the tests to simulate the face support condition on site.

(2) Test system

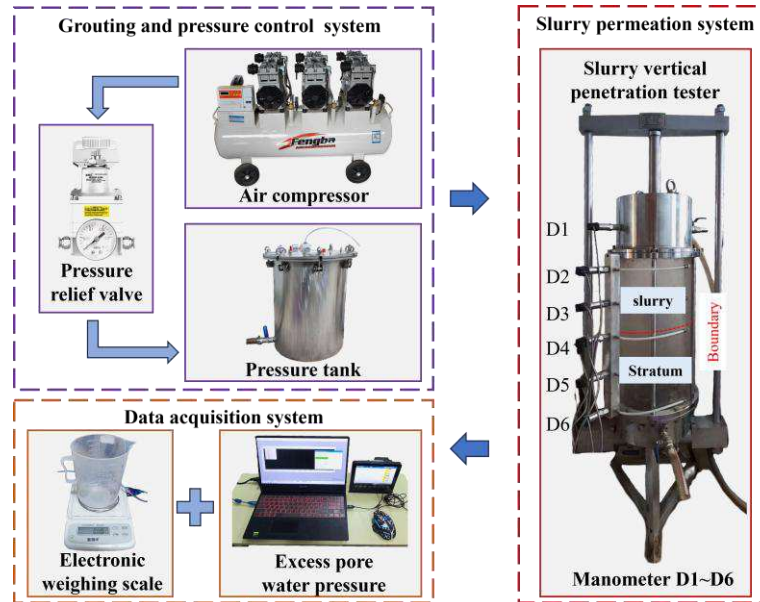


Fig.5. Schematic diagram of the slurry penetration and filter cake formation test system

This paper presents an independently developed slurry filtration and filter cake formation test system, as illustrated in Fig. 5. The system mainly includes a grouting pressure control system, a slurry infiltration system, a pore water pressure and filtrate loss data monitoring system, and a data acquisition system. (i) a pressure control unit that delivers stable grouting pressure (0–0.8 MPa, regulation precision ± 0.5 kPa) via an air compressor and precision regulator. (ii) a vertical permeameter with a plexiglass chamber (300 mm diameter, 600 mm height, 1 MPa pressure rating), conforming to Chinese standards for coarse-grained soil permeability testing. (iii) a monitoring unit consisting of six pore pressure transducers (D1–D6, 15 cm spacing, with D4 at 3 cm below the slurry–soil interface) and a precision electronic balance for real-time filtrate measurement. Their specific installation locations are detailed in Table 6. (iv) a synchronized data acquisition system.

Table 6

Pore water pressure gauge placement locations.

Number	1	2	3	4	5	6
Depth (cm)	-47	-27	-12	3	18	33
Location	Air	Slurry	Slurry	Soil layer	Soil layer	Soil layer

	chamber	chamber	chamber
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Note: The labels -47 and +3 indicate the installation positions of the pore pressure transducers, located 47 cm above and 3 cm below the surface of the sand specimen, respectively.

(3) Experimental procedure

The slurry filtration test was conducted using a self-developed system. Compressed air from an air compressor drove the modified waste silty clay slurry to infiltrate a saturated sand layer, enabling real-time monitoring of the spatiotemporal evolution of pore water pressure. As filtration proceeded, the migration and retention of slurry particles progressively altered the permeability of the sand layer. By analyzing changes in pore water pressure and API fluid loss, the filtration and filter cake formation performance of the slurry in strata of varying permeability were determined. The specific test procedure is as follows:

1. Slurry preparation. Sodium carbonate was first dissolved in water under continuous stirring, after which predetermined masses of silty clay and fine sand were added and mixed thoroughly. The slurry was hydrated for 24 h to ensure complete reaction and homogeneity, and re-agitated with an electric mixer immediately before testing to prevent particle sedimentation.

2. Specimen preparation. To ensure consistent compaction, the dry sand was compacted in layers into the permeameter at a controlled dry density of 1.58 g/cm³ (target porosity = 0.40). Each lift was uniformly compacted, and the process was repeated until the specimen surface reached 2 cm below the D4 pressure transducer.

3. Specimen saturation. After installing the upper cap, the specimen was saturated from the bottom upward using de-aired water. This reverse saturation sequence promotes uniform water distribution and effective air expulsion. Water injection was terminated when the water level exceeded the specimen surface, and the system was allowed to stabilize for 30 min.

4. Slurry placement. Preliminary tests revealed significant pressure loss during slurry transfer from the pressure tank, with the grouting pressure dropping from 50 kPa to 22.5 kPa in the slurry chamber. To mitigate this issue, the procedure was modified: the slurry was directly placed into the test chamber. The pressure tank was repurposed solely for

pressure stabilization and augmentation. The upper cover plate was removed, and the thoroughly mixed slurry was directly poured into the chamber above the prepared specimen to a height of approximately half the specimen thickness.

5. Pressurized filtration. The air compressor, pressure tank, and vertical permeameter were connected. The air compressor was started, and the exhaust valve was opened to initiate pressurization. The pressure regulator was adjusted to maintain a stable inlet pressure of 50 kPa. The inlet valve of the vertical permeameter was then opened. Once the slurry chamber pressure stabilized at 50 kPa, the water inlet valve was opened to initiate slurry filtration. After the filtrate flow rate stabilized, the filtrate outlet valve was closed. Throughout the test, the data acquisition system monitored and recorded pore water pressure and API fluid loss in real time.

6. Analysis of test data. When the API fluid loss gradually stabilizes or remains unstable after 10 minutes of permeation, with significant slurry penetration into the saturated sand layer, close the water drainage valve, open the vent ports of the slurry tank and vertical permeameter, and terminate the filtration and filter cake formation test. Subsequently, remove the top plate and securing screws from the vertical permeameter, extract excess slurry, and use a ring knife to obtain soil samples from the interface between the slurry and the formation. Observe the morphology of the filter cake. Analyze the variation performance of key parameters such as excess pore water pressure and API fluid loss during the slurry filtration process.

3 Analysis of slurry performance test results

3.1 Physical properties of the slurry

Fig. 6 shows four core physical properties of sodium carbonate modified silty clay slurry. These properties include specific gravity, funnel viscosity, colloid content, and filtration loss. Specific gravity directly determines the support pressure provided by the shield and the difficulty level of slurry pumping. Funnel viscosity describes the flow behavior of the slurry. Colloid content reflects the suspension stability and sedimentation resistance of the slurry. Filtration loss controls the water retention capacity of the slurry and the quality of filter cake formation on the excavation face.

These four indicators determine density, flowability, stability and impermeability of the slurry. They jointly define whether the slurry can satisfy the application requirements of slurry shield tunneling. Therefore, comprehensive analysis and proper adjustment of these physical properties are necessary to obtain the optimal mix ratio of modified slurry for engineering use.

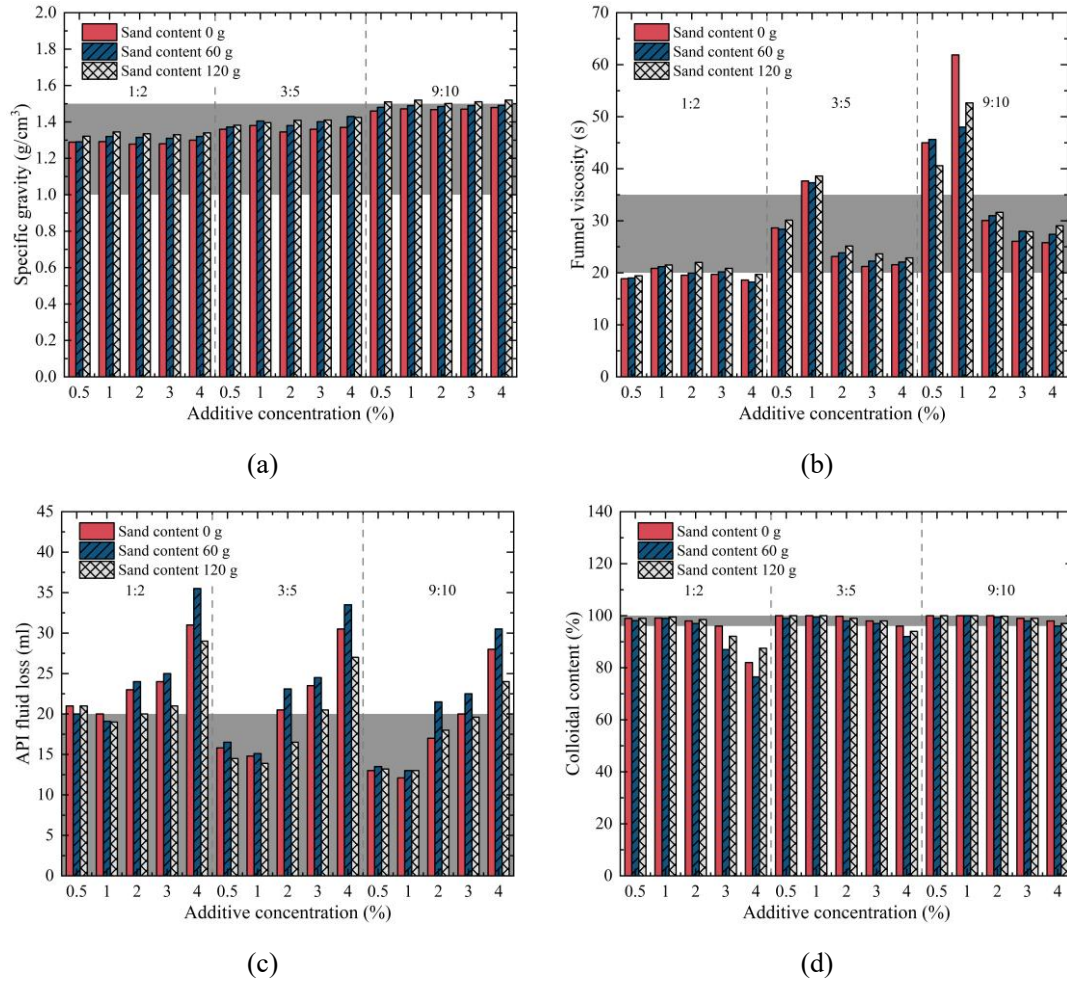


Fig. 6. Physical properties of modified silty clay slurry: (a) specific gravity; (b) funnel viscosity; (c) API fluid loss; (d) colloidal content

As shown in Fig. 6(a), slurry density increases monotonically with soil water ratio and fine sand content. A higher volume fraction of solid phase directly increases the density of the system. This change helps meet the support pressure requirements in shield tunneling. At a fixed soil water ratio, slurry density first increases slightly and then remains stable with increasing sodium carbonate content. This result shows that sodium carbonate can optimize particle distribution at low dosage. Further increase in sodium carbonate content no longer causes significant change in density. As presented

in Fig. 6(b), slurry viscosity increases significantly with rising soil water ratio. At a soil water ratio of 1:2, viscosity is generally below 20 s because of insufficient solid phase. Such low viscosity makes it difficult to satisfy construction requirements. This observation indicates that solid phase content is the basis for slurry to reach target viscosity. The influence of sodium carbonate dosage on viscosity shows a typical trend of increase first and decrease later. The best viscosity performance appears at a dosage of 1%. Fine sand plays a two way regulatory role. It reduces viscosity at low sodium carbonate content and increases viscosity at high sodium carbonate content. This means the effect of fine sand on flow properties depends on the dispersion state of the slurry system. For colloidal stability, Fig. 6(c) shows that the change in colloid content is highly consistent with that of funnel viscosity. Colloid content increases significantly with rising soil water ratio. Higher solid phase concentration helps maintain a uniform suspension state. At the same soil water ratio, colloid content increases first and then decreases with increasing sodium carbonate content. This result indicates that excessive sodium carbonate weakens the stability of the system. The increase in fine sand content causes colloid content to decrease first and then increase. A small amount of fine sand disturbs the original suspension balance. Higher fine sand content raises the total solid phase concentration and allows the system to regain stability. For filtrate control, Fig. 6(d) shows that filtrate volume is inversely related to viscosity and colloid content. Higher soil water ratio leads to lower filtrate volume. Higher solid phase concentration promotes the formation of a dense colloidal structure. With increasing sodium carbonate content, filtrate volume decreases first and then increases. Moderate dosage delivers the best water retention performance. Fine sand also shows a two way regulatory effect. A small amount of fine sand increases filtrate volume. Further increase in fine sand content reduces filtrate volume. Such a pattern helps meet the filter cake formation requirements in high permeability strata.

Based on the four physical performance indicators, together with field pumpability and construction stability of slurry, four optimal mix proportions of modified silty clay slurry are selected for slurry shield tunneling. These proportions are 3:5 0.5%, 3:5 60 0.5%, 3:5 120 0.5%, and 3:5 120 2%. The above results fully prove that modified silty

clay slurry can reach engineering performance similar to bentonite slurry through reasonable adjustment of soil water ratio, sodium carbonate content and fine sand content. This conclusion provides reliable experimental data and mix proportion support for resource utilization of shield tunneling waste soil.

3.2 Slurry rheological properties

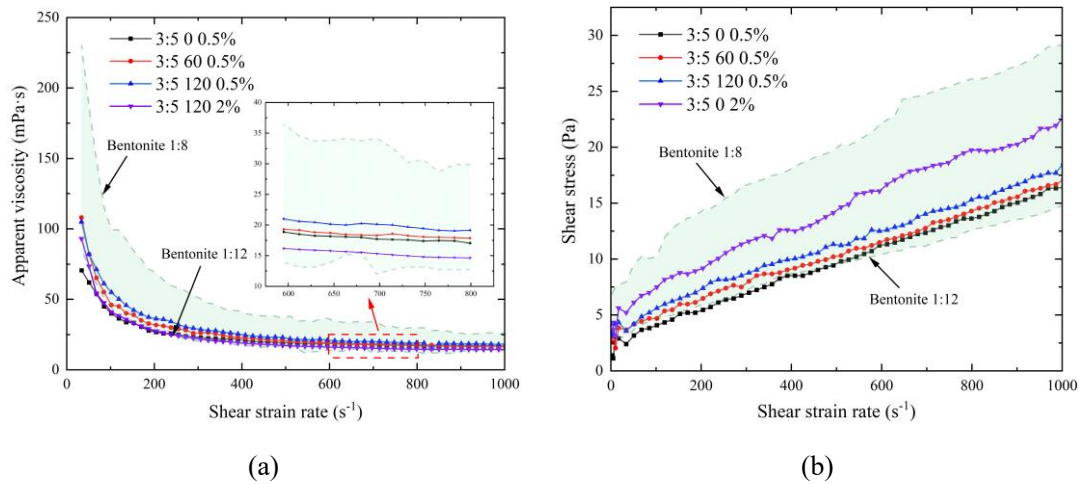


Fig. 7. Rheological properties of modified silty clay slurry: (a) apparent viscosity; (b) shear stress

Slurry rheological properties reflect dynamic flow behavior and support performance. These properties are critical in evaluating pumpability, cuttings carrying capacity and working stability during shield tunneling. Rheological tests must be carried out for the optimized mix proportions to verify their applicability in engineering projects. Based on the previous physical property tests, four groups of modified silty clay slurries are selected for rheological tests. The proportions are 3:5 0.5%, 3:5 60 0.5%, 3:5 120 0.5%, and 3:5 120 2%. Test results are compared with those of bentonite slurry commonly used in engineering practice.

Fig. 7 shows the apparent viscosity and shear stress curves of modified silty clay slurry as functions of shear rate. The shaded region represents the range of rheological curves that satisfy recommended engineering performance standards. The rheological properties lie between those of 1:8 and 1:12 bentonite slurries. Modified silty clay slurry behaves as a pseudoplastic shear thinning fluid. It shows high viscosity at low shear rates to help maintain excavation face stability. Viscosity decreases at high shear rates to meet the needs of field pumping and circulation. This behavior is consistent with that

of bentonite slurry. Under the same shear rate, apparent viscosity and shear stress of the modified slurry generally increase with higher fine sand content and sodium carbonate dosage. The addition of fine sand raises the solid phase content of the system. It strengthens interactions between particles and significantly improves rheological parameters. Increasing sodium carbonate content further optimizes the structural stability of the slurry. It greatly enhances structural viscosity at low shear rates and improves suspension stability under static construction conditions. Compared with bentonite slurry, the rheological curves of the four modified slurry groups generally fall within the range of 1:8 to 1:12 bentonite slurries. Key rheological parameters including apparent viscosity and shear stress are comparable to those of conventional bentonite slurries used in shield tunneling. These parameters meet the construction requirements for flowability, cuttings carrying capacity and static stability. In summary, the modified silty clay slurry with a mix proportion of 3:5 60 0.5% is finally selected as the slurry material for slurry shield tunneling. This selection takes into account field pumping pressure and material cost.

4 Analysis of vertical permeation test results

To further verify the filtration and filter cake formation characteristics of the selected modified silty clay slurry with a mix proportion of 3:5 60 0.5% in real geological strata, and to evaluate its ability to form dense filter cake on the excavation face to prevent water seepage and maintain stratum stability, this section carries out vertical filtration and filter cake formation tests on three kinds of strata with different permeability using the optimized slurry and bentonite slurry. An in depth analysis is performed on the filter cake formation characteristics and filtration mechanism of the slurry.

4.1 Filtration and filter cake formation characteristics in 0.25–0.5 mm sand layer

(1) Variation of excess pore water pressure and pressure conversion efficiency

The ability of slurry pressure to be rapidly and efficiently converted into effective stress in the stratum is a core factor affecting the stability of the excavation face in slurry

shield tunneling. To quantitatively evaluate the effective effect of slurry pressure on the stratum, this paper introduces the index of slurry pressure conversion efficiency. It is defined as the proportion of grouting pressure that is converted into effective stress, as shown in Eq. 1 (Wang et al., 2025).

$$\delta = \frac{P_p - P_s - P_e}{P_p - P_s} \times 100\% \quad (1)$$

Where, δ represents the grouting pressure conversion rate; P_p , P_s , and P_e denote the grouting pressure, hydrostatic pore pressure (0 kPa under the experimental conditions), and excess pore water pressure, respectively. This parameter reflects the ability of the grout pressure to provide effective support to the formation skeleton after overcoming the pore water pressure: a higher conversion rate indicates that the grout pressure is more effectively converted into effective stress, resulting in a stronger stabilizing effect on the excavation face. D1-D3 are arranged in the slurry chamber, and the measured pressure is basically equal to grouting pressure, not involved in the analysis of stratum pressure transfer law.

Fig. 8 shows the evolution of super-pore water pressure and pressure conversion rate over time for the modified silty clay slurry and the S6 bentonite slurry under a permeation pressure of 50 kPa. The response of both slurries exhibits a distinct two-stage pattern, indicating that the film-forming mechanisms of the modified silty clay slurry and the natural silty clay slurry are fundamentally similar, although differences remain in their specific macroscopic behavior.

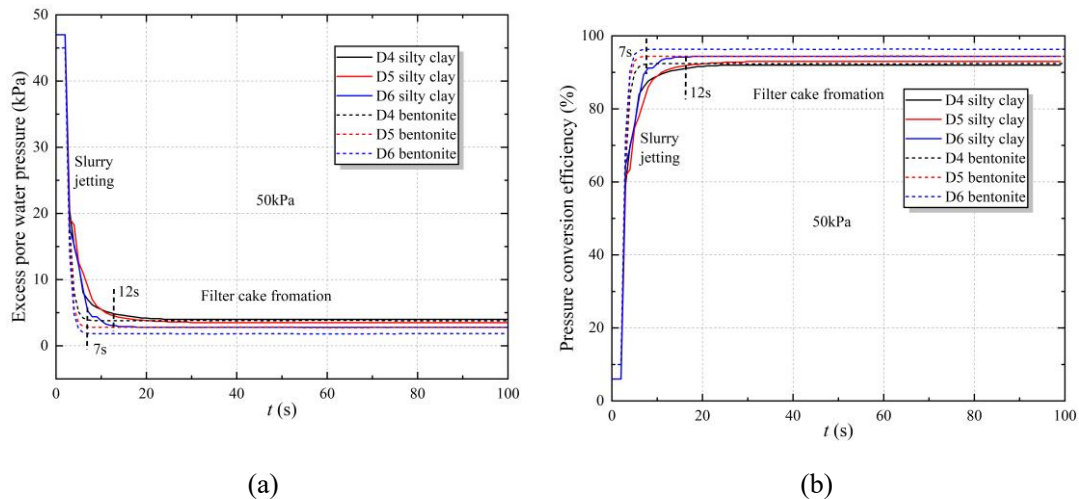


Fig. 8. Pressure changes during slurry permeation in a 0.25 – 0.5 mm sand layer: (a) excess pore water pressure; (b) pressure conversion efficiency

During the slurry injection stage, excess pore water pressure of both slurries dissipates rapidly. At the same time, pressure conversion efficiency increases. This trend reflects the dynamic processes of slurry infiltration, particle retention and filter cake formation. It is worth noting that excess pore water pressure of bentonite slurry dissipates much faster. The pressure tends to be stable within about 7 s. Modified silty clay slurry needs about 12 s to reach stability. As a result, pressure conversion efficiency of bentonite slurry rises above 90% in a shorter time. The final stable value ranges from 93% to 97%. This value is significantly higher than the 90% to 93% of silty clay slurry. The residual excess pore water pressure of bentonite slurry is also lower, which is about 1 to 3 kPa. In addition, the initial pore water pressure of modified silty clay slurry is higher than that of bentonite slurry. In this test, physical and rheological properties of modified silty clay slurry and bentonite slurry are basically consistent. Therefore, the above phenomenon mainly comes from the mineral characteristics of the two materials. Bentonite slurry takes montmorillonite as the main component. It has strong hydration expansion ability and high specific surface area (Jalal et al., 2025). Once it contacts water, particles expand quickly and form a dense microscopic pore structure. A low permeability water blocking layer can be formed rapidly on the sand surface. It greatly shortens the dissipation time of excess pore water pressure and helps achieve higher pressure conversion efficiency. Modified silty clay slurry takes kaolinite as the main component. Although its macroscopic properties are close to bentonite slurry after sodium carbonate modification, some differences still exist. The impermeable filter cake formed in the early infiltration stage is slightly weaker than that of the bentonite slurry. As a result, grouting pressure is mostly borne by pore water in the stratum. The initial excess pore water pressure of modified silty clay slurry reaches 47 kPa, which is higher than the 45 kPa of bentonite slurry, as shown in Fig. 8.

When entering the filter cake formation stage, excess pore water pressure of both slurries tends to be stable. Pressure conversion efficiency remains at a high level. This result shows that the formation of dense filter cake effectively blocks further filtrate

infiltration. It realizes the stable transfer of grouting pressure to the effective stress of the stratum. However, the stable pore pressure of modified silty clay slurry is slightly higher than that of bentonite slurry. Its pressure conversion efficiency is 1% to 2% lower than bentonite slurry. Even so, the stable pressure conversion efficiency of modified slurry is still above 90%. It can meet the engineering requirements for excavation face stability in slurry shield tunneling.

(2) Evolution characteristics of filtration loss and permeation distance

Before slurry grouting and infiltration, the sandy stratum is already in a saturated state. Under the condition that stratum compression is not considered, the volume of slurry entering the stratum is equal to the volume of filtrate discharged.

$$V_s = V_L = nAL \quad (2)$$

The permeation distance of slurry in the stratum can be roughly calculated by the volume balance method.

$$L = \frac{V_L}{nA} \quad (3)$$

Where, n represents the stratum porosity (0.4), V_s is the volume of slurry entering the stratum, V_L is the volume of filtrate discharged, and A is the cross-sectional area of the vertical permeation column ($A = 706.85 \text{ cm}^2$).

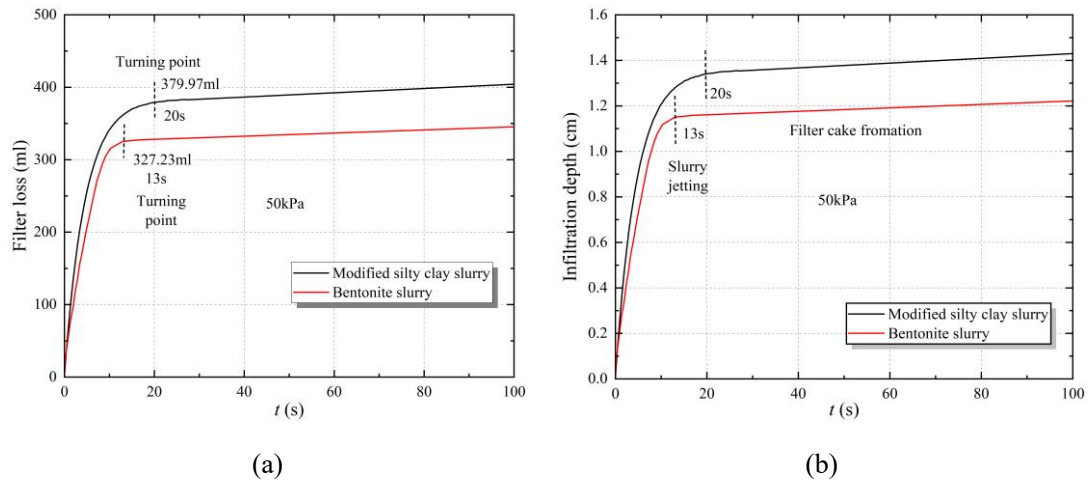


Fig. 9. Patterns of filter loss and penetration depth during slurry permeation in a 0.25 – 0.5 mm sand layer: (a) filter loss; (b) infiltration depth

Fig.9 shows the variation of filtrate loss and slurry permeation depth with time for the modified silty clay slurry and S6 bentonite slurry under a pore pressure of 50 kPa. These variation trends are highly consistent with the previously observed changes in

excess pore water pressure and pressure conversion efficiency. The filtration processes of both slurries show typical two stage characteristics. The inflection point of the filtrate loss curve for bentonite slurry appears at about 13 s, corresponding to a filtrate loss of 327.23 mL. After that, the filtration rate decreases significantly and enters a steady state stage. In contrast, the inflection point of modified silty clay slurry is delayed to about 20 s, with a corresponding filtrate loss of 379.97 mL. This is an increase of about 16.1% compared with bentonite slurry. This result indicates that the modified slurry has a longer initial open flow stage and greater filtrate loss. Correspondingly, bentonite slurry completes the initial permeation process at about 13 s, with a maximum permeation depth of about 1.15 cm. The inflection point of the permeation depth increase of modified silty clay slurry occurs at about 20 s, with a final permeation depth of about 1.4 cm. This is an increase of about 21.7% compared with bentonite slurry. This phenomenon also shows that bentonite slurry forms a dense gel filter cake instantly at the entrance of stratum pores through the rapid hydration and expansion of montmorillonite particles. It effectively restricts filtrate infiltration and particle intrusion, resulting in low filtrate loss and shallow permeation depth. In contrast, the formation of dense filter cake in modified silty clay slurry is slow in the early stage, which cannot achieve effective sealing. This leads to continuous filtrate seepage and particle migration into the stratum, resulting in delayed filter cake formation, significantly increased filtrate loss and greater permeation depth. These results are highly consistent with the aforementioned variation patterns of pore water pressure and pressure conversion efficiency.

4.2 Filtration and filter cake formation characteristics in 0.5–1.0 mm sand layer

(1) Variation of excess pore water pressure and pressure conversion efficiency

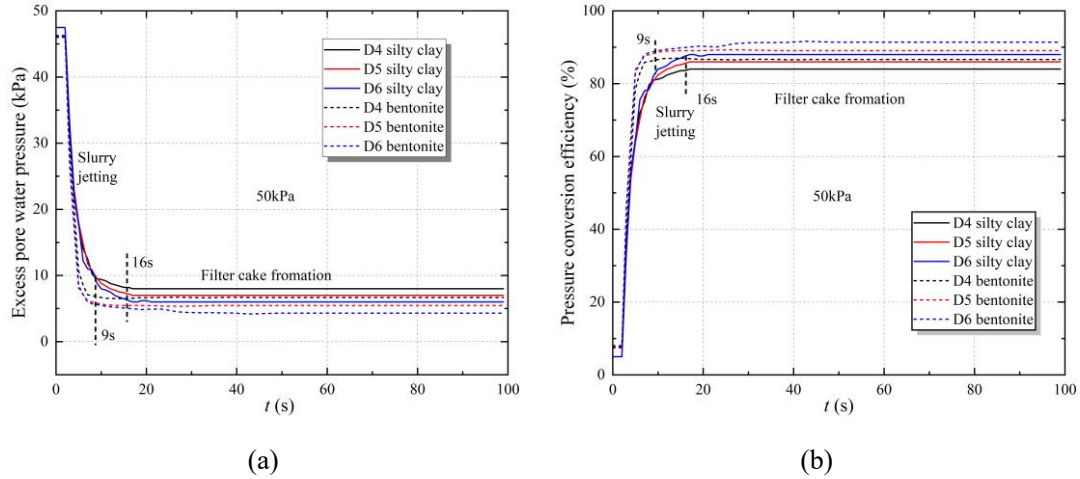


Fig. 10. Pressure changes during slurry permeation in a 0.5 – 1.0 mm sand layer: (a) excess pore water pressure; (b) pressure conversion efficiency

In the 0.5–1.0 mm sand stratum with larger pore size, the filtration and filter cake formation characteristics of modified silty clay slurry and S6 bentonite slurry show a more significant performance gradient, as shown in Fig. 10. Under 50 kPa permeation pressure, the evolution of excess pore water pressure and pressure conversion rate of both slurries still follows the two-stage law, but the filter cake formation response time is longer than that in 0.25–0.5 mm stratum.

The initial excess pore water pressure of both modified silty clay slurry and bentonite slurry increases, indicating that the plugging effect of both slurries on the stratum decreases with the increase of stratum pores. The excess pore water pressure of bentonite slurry attenuates rapidly to equilibrium within 9 s, the residual excess pore water pressure is as low as 5 kPa, and the pressure conversion rate reaches more than 85%. The initial excess pore water pressure and pressure conversion rate inflection point of modified silty clay slurry lag, and it takes 16 s to enter the stable stage, with a conversion rate of 83%–85%, 2%–3% lower than bentonite slurry. Although the performance of both slurries in this medium-coarse sand stratum is lower than that in fine sand stratum, the filter cake formation law of modified silty clay slurry is basically consistent with that of bentonite slurry, and the pressure conversion efficiency is stable above 80%.

(2) Variation of filtration loss and permeation distance

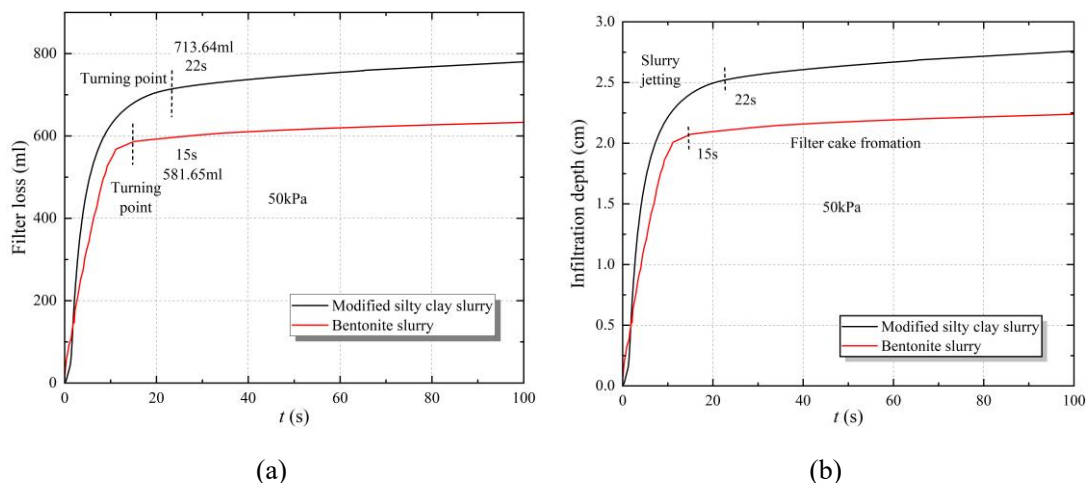


Fig. 11. Patterns of filter loss and penetration depth during slurry permeation in a 0.5 – 1.0 mm sand layer: (a) filter loss; (b) infiltration depth

Fig. 11 shows the variation of filtration loss and permeation depth of modified silty clay slurry and S6 bentonite slurry with time in 0.5–1.0 mm sand layer under 50 kPa permeation pressure. The results show that in the stratum with large pore size, the filtration characteristics of the two slurries show significant differences, which are highly consistent with the aforementioned changes in pressure conversion characteristics.

The filtration and permeation processes of both slurries show typical two stage characteristics: the inflection point of the filtration loss curve of bentonite slurry appears at about 15 s, corresponding to a filtration loss of 581.65 mL, after which the filtration rate decreases significantly and enters a steady-state stage. The inflection point of modified silty clay slurry is delayed to about 22 s, corresponding to a filtration loss of 713.64 mL, an increase of about 22.7% compared with bentonite slurry; the final permeation depth is about 2.7 cm, an increase of 22.7%. This further confirms that in the coarse sand layer, modified silty clay slurry lacks the efficient hydration expansion ability of montmorillonite, so it must go through a longer slurry injection stage to complete plugging through physical accumulation and colloid bonding of coarse particles deep in the stratum. Modified silty clay slurry shows higher filtration rate and deeper permeation distance before filter cake formation, which is mutually causal with its low initial pressure conversion rate. In the large pore stratum, the deeper permeation

distance (2.7 cm) means a larger permeation range of slurry to the stratum. Although the filtration loss and permeation depth of modified slurry are slightly higher than those of bentonite slurry, the seepage tends to stabilize rapidly (22 s) after filter cake formation, and filtrate loss and particle intrusion are effectively controlled, indicating that modified slurry can finally build a dense filter cake with stable structure.

4.3 Filtration and filter cake formation characteristics in 2.0–5.0 mm gravel layer

(1) Variation of excess pore water pressure and pressure conversion efficiency

In the 2.0–5.0 mm gravel stratum, the filter cake formation and pressure transfer behavior of both slurries undergo fundamental changes (as shown in Fig. 12). The excess pore water pressure of bentonite slurry attenuates rapidly within 10 s, but can only drop to 27–31 kPa, corresponding to a maximum pressure conversion efficiency of only 40%–45%. The pore pressure attenuation process of modified silty clay slurry is more lagged, taking about 21 s to stabilize, with a residual pore pressure as high as 32–35 kPa and a steady-state pressure conversion efficiency of only 30%–39%, showing a significant performance gap compared with bentonite slurry. The essential reason for this phenomenon is that the pore throat size of the 2.0–5.0 mm graded stratum is much larger than the effective particle size of fine particles in the slurry, resulting in the failure of both slurries to form an effective plugging filter cake on the stratum surface. The pressure conversion efficiency of both slurries is far lower than the critical value of 80% required by engineering, indicating that even bentonite slurry cannot realize the stability control of excavation face in this graded stratum, and modified silty clay slurry is limited by the filter cake formation mechanism, showing worse adaptability.

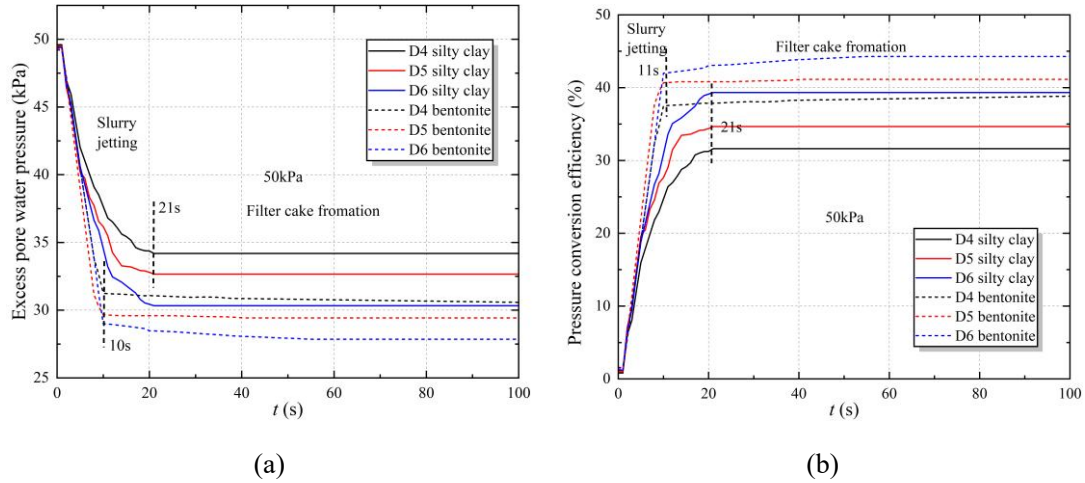


Fig. 12. Pressure changes during slurry permeation in a 2.0 – 5.0 mm gravel layer: (a) excess pore water pressure; (b) pressure conversion efficiency

(2) Variation of filtration loss and permeation distance

Fig. 13 shows the evolution of filtration loss and slurry permeation distance in 2.0–5.0 mm gravel stratum. It is concluded that neither slurry can form an effective filter cake. The filtration loss of both slurries increases linearly with time without obvious slowdown or stabilization stage. At 40 s, the filtration loss of modified silty clay slurry is as high as 3525.03 mL, and that of bentonite slurry also reaches 2885.92 mL, far higher than the filtration level when filter cake can be formed in fine sand stratum. Correspondingly, the permeation distance of slurry also shows a synchronous linear growth trend. At 40 s, the permeation depth of modified silty clay slurry exceeds 12 cm, and that of bentonite slurry also reaches about 10 cm, indicating that slurry particles continue to migrate deep into the stratum with filtrate, and no effective filter cake that can inhibit filtration loss is formed on the stratum surface. The filtration rate and permeation depth of modified silty clay slurry are slightly higher than those of bentonite slurry, which is consistent with the aforementioned results of excess pore water pressure dissipation and pressure conversion efficiency. Since slurry cannot form an effective filter cake on the stratum surface, and slurry particles are difficult to retain and block pores in oversized pores, filtrate and particles continue to migrate deep into the stratum, and the filtration process cannot be inhibited. In contrast, bentonite slurry has certain advantages. Although montmorillonite colloid particles in bentonite slurry can hydrate and expand, the particle size after expansion is still much smaller than stratum pores,

but can form plugging in stratum with small local pores, with slightly lower filtration rate, which cannot change the overall continuous permeation trend. The linear growth characteristics of filtration loss and permeation distance. Under the condition of no filter cake formation, grouting pressure continuously pushes slurry to migrate deep into the stratum, unable to form a stable pressure transfer interface on the surface, which is the fundamental reason for failing to meet the requirements of excavation face stability.

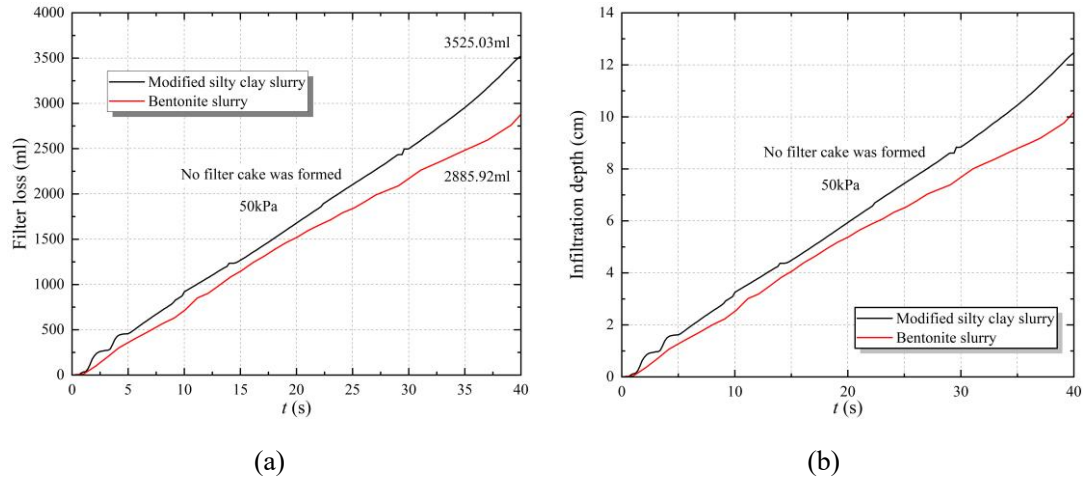


Fig. 13. Patterns of filter loss and penetration depth during slurry permeation in a 2.0 – 5.0 mm gravel layer: (a) filter loss; (b) infiltration depth

4.4 Filter cake type analysis

Existing research results show that the filter cake formation type of slurry shield slurry can be divided into three types: Type I filter cake type, Type II filter cake + permeation zone type, and Type III no filter cake type. At present, the criterion for filter cake type is not unified. Referring to the classic research of scholars such as Min Fanlu, this paper takes the ratio of slurry characteristic particle size to stratum average pore size d_{85}/D_0 as the core criterion: when $d_{85}/D_0 \geq 1$, it is Type I filter cake type; $0.5 < d_{85}/D_0 < 1$, it is Type II filter cake + permeation zone type; $d_{85}/D_0 \leq 0.5$, it is Type III no filter cake type (Min et al., 2013). Combined with the particle gradation test results of slurry and stratum in this paper, the characteristic particle size d_{85} of unmodified silty clay slurry is 35 μm . Since 60 g fine sand uniformly distributed in the range of 0.1–0.2 mm is added to the modified slurry, its overall particle gradation curve shifts to the direction of coarse particles, and the d_{85} of modified silty clay slurry is calculated to be 40.1 μm . First, calculate the average pore size of the stratum according to the following formula:

$$D_0 = \sqrt{\frac{k}{31 \times 1.5n}} \quad (4)$$

Where, k is the initial permeability coefficient of the stratum, and n is the initial stratum porosity. The average pore sizes of the three strata are calculated to be 23.3 μm , 47.3 μm and 87.1 μm respectively. The corresponding ratios are 1.72 (Type I), 0.85 (Type II) and 0.46 (Type III) in turn.

Fig. 14 shows the comparison of filter cake types between modified silty clay slurry and S6 bentonite slurry. The filter cake formation type of modified silty clay slurry still follows the criterion of particle gradation ratio d_{85}/D_0 . The theoretical analysis results are highly consistent with the filter cake type obtained from the test, and the macroscopic morphology characteristics of filter cake form a good internal confirmation with the aforementioned pressure conversion law, filtration characteristics and slurry permeation behavior. Combined with the analysis of average pore size of different strata, modified silty clay slurry forms Type I filter cake type in 0.25–0.5 mm sand layer. Slurry particles are fully retained on the stratum surface, forming a continuous and dense surface filter cake, corresponding to low filtration loss, permeation distance and high pressure conversion rate in the test. In 0.5–1.0 mm sand layer, due to the increase of stratum pore size, the surface rapid plugging ability is limited, forming Type II filter cake + permeation zone type. Modified silty clay slurry is difficult to quickly block and form a dense filter cake on the stratum surface. In the early stage of filtration, slurry particles permeate and migrate deep into the stratum. After the surface dense filter cake is gradually formed, the slurry permeation process tends to be stable and stops migrating. Compared with 0.25–0.5 mm stratum, all indicators are deteriorated to a certain extent. In 2.0–5.0 mm gravel large pore stratum, the pore scale is far larger than the slurry particle size, unable to form a continuous and stable surface filter cake, showing Type III no filter cake type. Slurry particles and filtrate continue to migrate deep into the stratum, filtration loss and permeation depth increase linearly, completely losing pore plugging ability, and difficult to meet the requirements of excavation face stability.



Fig. 14. Modified silty clay of filter cake

In summary, modified silty clay slurry has good filter cake formation performance and support capacity in medium-fine sand and coarse sand strata. Its filter cake formation characteristics and plugging effect can meet engineering application requirements. However, in large pore gravel strata, its filter cake formation adaptability is insufficient, and further improvement is needed by optimizing slurry particle gradation, adding large particle solid phase particles, etc., to improve filter cake formation and water blocking performance under large pore stratum conditions.

5 Microscopic mechanism analysis

Through physical performance, rheological performance tests and vertical filtration and filter cake formation tests of slurry, the previous chapters have clarified the macroscopic filter cake formation characteristics and pressure transfer law of modified waste silty clay slurry in different permeability strata, confirming that it can form effective filter cake in medium-coarse sand and coarse sand strata to meet shield support requirements, but cannot form filter cake in gravel strata. However, the above macroscopic phenomena only reveal the macroscopic performance of whether filter cake is formed and performance advantages and disadvantages, and have not clarified the internal mechanism of why modified slurry has engineering applicability similar to bentonite, the microscopic root of filter cake quality differences in different strata, and the mechanism of sodium carbonate modification to improve slurry performance.

Therefore, based on the electrical double-layer theory, zeta potential, and FTIR, this chapter conducts a mechanistic analysis of the aforementioned macroscopic test results. Specifically, three key aspects are investigated: the electrochemical properties of particle interfaces, the evolution of surface functional groups, and the mechanisms of colloidal dispersion and stabilization. This study aims to reveal the fundamental principles governing the filtration and film-forming behavior of the modified waste silty clay slurry, thereby providing microscopic theoretical support for its engineering feasibility as a substitute for bentonite slurry.

5.1 Electric double layer structure analysis

Fig. 15 shows the electric double layer structure differences between bentonite and modified silty clay, providing a direct microscopic basis for explaining the interface electrochemical behavior and macroscopic engineering performance differences between the two. As a typical 2:1 layered silicate clay mineral, bentonite has a high permanent negative charge density due to the widespread isomorphous substitution in its crystal structure (such as Si^{4+} replaced by Al^{3+} , Al^{3+} replaced by Mg^{2+}), prompting a large number of exchangeable cations (Na^+ , Ca^{2+} , Mg^{2+}) in the solution to form significant Stern layer and diffuse layer on the particle surface, forming a thick electric double layer and strong hydration film structure. Its electric double layer shielding effect is weak and the absolute value of Zeta potential is high, consistent with the results in Table 7. Therefore, bentonite has strong hydration expansion and colloid stability, which is the core source of its excellent filter cake formation ability. However, this high charge density electric double layer structure also leads to high viscosity and excessive thixotropy of bentonite slurry, which is easy to cause problems such as pumping difficulty and filter cake cracking in practical engineering, so the concentration of bentonite slurry in engineering needs to be reasonably regulated. Compared with original silty clay, sodium carbonate modification replaces high-valent cations such as Ca^{2+} and Mg^{2+} adsorbed on the particle surface with Na^+ through ion exchange, weakening the compression effect of high-valent cations on the electric double layer. At the same time, alkalization promotes the dissociation of Si-OH and Al-OH hydroxyl

groups on the surface of clay particles, improving the variable negative charge density of particle surface and enhancing the electrostatic repulsion between particles. After modification, the electric double layer thickness of silty clay particles increases moderately, the cation gradient distribution in the diffuse layer is more stable, the particle agglomeration behavior is significantly inhibited, and the slurry dispersion uniformity and colloid stability are significantly improved. Although sodium carbonate modification significantly improves the colloid stability and dispersibility of original silty clay, its electric double layer thickness, charge density and hydration film strength still do not reach the level of bentonite, and are still slightly inferior to bentonite in core performance indicators such as colloid stability and filter cake compactness, consistent with the macroscopic test law. However, from the perspective of engineering application requirements, all performance indicators of modified silty clay slurry can meet the basic requirements of slurry shield construction for slurry rheology, permeation control ability and pumping performance, and has the advantages of low cost and easy availability of raw materials, it is feasible to use it as a slurry material in slurry shield tunneling.

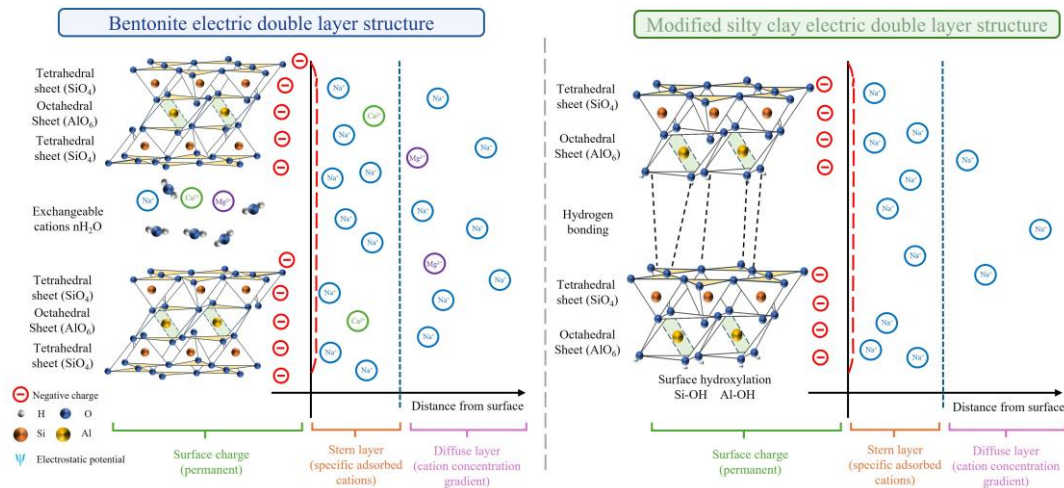


Fig. 15: Electric double layer structure of modified silty clay and bentonite

5.2 Zeta potential analysis

Zeta potential is an index to measure the attraction or repulsion between particles. Its absolute value represents stability, and positive and negative only represent the charge of particles. The higher the absolute value of Zeta potential, the more stable the dispersion system and the better the slurry performance. Therefore, to study the

interaction force between slurry particles after modification of silty clay slurry, a British Zetasizer Nano ZS90 nanoparticle size potentiometer was used for measurement. Table 7 shows the Zeta potentials of S6 bentonite slurry, 3:5 60 0.5% modified silty clay slurry, and 3:5 60 0% silty clay slurry.

Table 7

Zeta potential of different slurries.

Slurry types	Zeta potential (mV)
S6 bentonite slurry	-28.6
3:5 60 0% silty clay slurry	-1.5
3:5 60 0.5% modified silty clay slurry	-26.1

From the perspective of charge properties, the Zeta potentials of the three slurries are all negative, indicating that the surfaces of the three slurry particles are all negatively charged, which is consistent with the mechanism that the surface of clay particles produces negative charge due to isomorphous substitution and hydroxyl dissociation as mentioned above, further verifying the charge characteristics of clay particles.

From the perspective of dispersion stability, according to the core law that the higher the absolute value of Zeta potential, the more stable the dispersion system and the better the slurry performance, the stability of the three slurries shows significant differences. The absolute value of the Zeta potential of 3:5 60 0% silty clay slurry is only 1.5 mV, which is extremely low, indicating that the electrostatic repulsion between particles is extremely weak, far insufficient to overcome the van der Waals attraction between particles, leading to easy agglomeration and flocculation of particles, and an extremely unstable dispersion system. This also explains one of the core reasons why original silty clay is difficult to use directly as a shield slurry material. After modification with 0.5% sodium carbonate, the absolute value of Zeta potential of 3:5 60 0.5% modified silty clay slurry increases significantly to 28.6 mV, nearly 19 times higher than that of original silty clay slurry, indicating that sodium modification effectively enhances the negative charge density of particle surface, significantly increases the electrostatic repulsion between particles, inhibits particle agglomeration, and greatly improves the stability of slurry dispersion system. This is in precise

correspondence with the mechanism of increased electric double layer thickness and improved colloid stability of silty clay particles after modification as mentioned above. The stability of 3:5 60 0.5% modified silty clay slurry is close to that of S6 bentonite slurry, further confirming the feasibility of modified silty clay as shield slurry material.

5.3 FTIR analysis

Based on the analysis of the electric double layer structure and Zeta potential, the interface electrochemical level has revealed why sodium carbonate-modified silty clay slurry can replace bentonite slurry. However, direct microscopic evidence of the evolution of surface functional groups of clay particles, hydration film strengthening, and mineral skeleton changes during the modification process needs to be further supplemented. Therefore, Fourier transform infrared testing was carried out on S6 bentonite slurry, 3:5 60 0% silty clay slurry, and 3:5 60 0.5% modified silty clay slurry. Considering that water peaks may interfere with sample peaks and affect test results, slurry powder was selected for testing. Before testing, the slurry was dried in an oven at 105°C for 12 hours. Then, the slurry cake was ground into powder with an agate mortar and tested using a Thermo Scientific Nicolet iS20 Fourier transform infrared spectrometer from the United States.

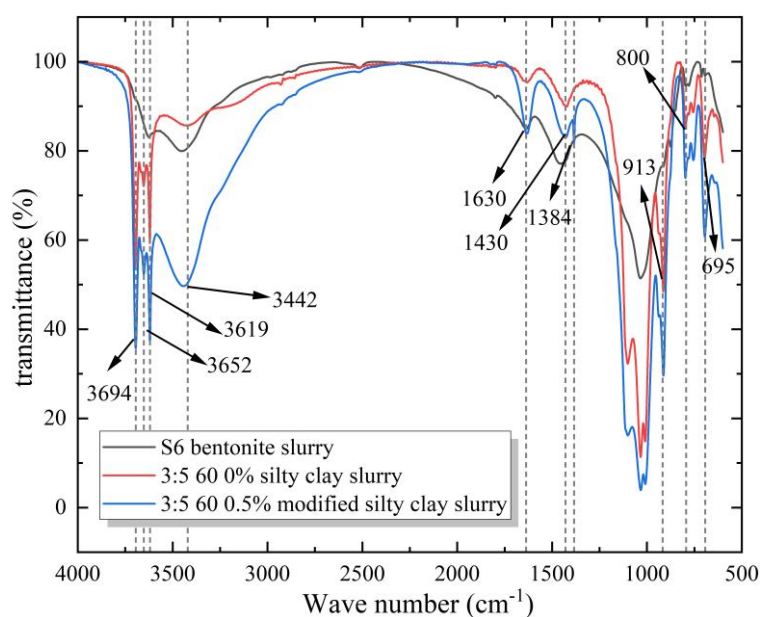


Fig. 15: Electric double layer structure of modified silty clay and bentonite

In the range of 3700–3600 cm^{-1} , the three curves show characteristic absorption peaks at 3694 cm^{-1} , 3652 cm^{-1} , and 3619 cm^{-1} , corresponding to the stretching vibration

of structural hydroxyl (-OH) of clay minerals. Among them, the peak shape of bentonite slurry is wide and strong, reflecting the abundant interlayer hydroxyl content of montmorillonite minerals, while the peak intensity of silty clay slurry is significantly weaker, indicating insufficient active sites of primary mineral structural hydroxyl. After modification, the peak intensity of silty clay slurry increases significantly, indicating that sodium carbonate modification promotes the dissociation and exposure of surface hydroxyl groups of particles, providing more active sites for hydration film formation. The broad absorption peak at 3442 cm^{-1} corresponds to the O-H stretching vibration of free water and adsorbed water. The peak intensity of the modified silty clay slurry is significantly higher than that of the silty clay slurry and close to that of the bentonite slurry, directly confirming that the hydration film thickness on the particle surface increases and the water holding capacity of the system improves after modification, which is highly consistent with the result of improved colloid stability of the modified slurry in the Zeta potential test. The absorption peak at 1630 cm^{-1} corresponds to the H-O-H bending vibration of adsorbed water. The peak intensity of the modified silty clay slurry is significantly higher than that of the original slurry, further indicating that sodium modification significantly strengthens the hydration of clay particles and enhances the colloid hydration capacity of the slurry. In the range of $1430\text{--}1384\text{ cm}^{-1}$, modified silty clay slurry shows obvious characteristic absorption peaks of carbonate (CO_3^{2-}). The double peak structure of 1430 cm^{-1} and 1384 cm^{-1} corresponds to the active groups introduced by sodium carbonate, while silty clay slurry and bentonite slurry have no such characteristic peaks, directly proving that sodium carbonate modifier is successfully attached to the surface of clay particles through ion exchange and surface adsorption, introducing exchangeable cations, and providing direct evidence at the functional group level for the increase of electric double layer thickness and electrostatic repulsion between particles. In the range of $1100\text{--}900\text{ cm}^{-1}$, bentonite slurry shows a characteristic stretching vibration peak of the Si-O-Si bond of montmorillonite at 1030 cm^{-1} , while the peak shape of original silty clay slurry is dominated by Si-O bond vibration of primary minerals such as quartz and feldspar. After modification, the peak intensity of the silty clay slurry increases significantly, and

the peak position shifts to the characteristic peak of bentonite. At the same time, an absorption peak corresponding to Al-OH bending vibration appears at 913 cm^{-1} , indicating that the modification does not destroy the clay mineral skeleton, but promotes the exposure of mineral active sites by improving dispersibility, enhancing the electrostatic repulsion and hydration between particles. In the range of $900\text{--}695\text{ cm}^{-1}$, the absorption peaks at 800 cm^{-1} and 695 cm^{-1} correspond to the characteristic vibrations of clay minerals and quartz. The peak shape of the modified silty clay slurry is closer to that of the bentonite slurry, indicating that the modification effectively optimizes the microstructure of particles, making their colloid behavior consistent with that of the bentonite slurry.

In summary, the microscopic test results reveal that the microstructure characteristics of modified silty clay slurry are consistent with those of bentonite slurry, providing direct microscopic evidence for the similar engineering applicability of modified slurry to bentonite, and also explaining the microscopic root of modified slurry forming an effective filter cake in different strata and meeting shield support requirements.

5.4 SEM analysis

To characterize the filtration and filter cake formation behavior of modified silty clay slurry and S6 bentonite slurry, the filter cakes produced by these two slurries were observed using scanning electron microscopy (SEM), as shown in Fig. 16.

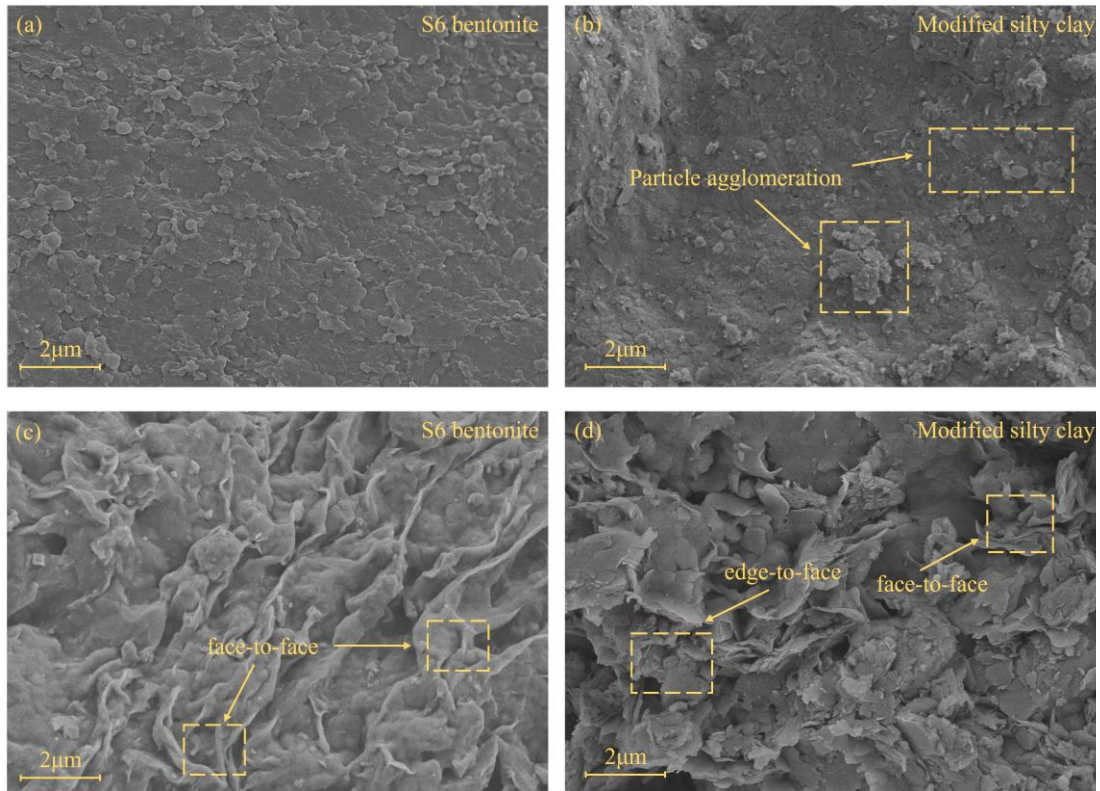


Fig. 16. SEM images of modified silty clay and bentonite filter cakes: (a)(c) overview; (b)(d) from the perpendicular direction of infiltration

As shown in Fig. 16(a), the bentonite filter cake features a remarkably smooth, continuous, and compact surface microstructure. Upon hydration, montmorillonite platelets become fully dispersed and assemble into a planar, membrane-like structure dominated by face-to-face particle contacts. With virtually no observable pores or defects, the bentonite forms an impermeable filter cake layer. The corresponding cross-section (Fig. 16(c)) further elucidates its internal architecture: driven by osmotic pressure gradients, montmorillonite lamellae align highly preferentially perpendicular to the infiltration direction, yielding a continuous, wavy layered stacking structure. Interlayer voids are substantially compressed, and interlayer bonding occurs mainly via face-to-face contacts, creating a tight, low-permeability barrier. In contrast, the surface of the filter cake formed by sodium carbonate-modified silty clay (Fig. 16(b)) displays greater surface roughness, accompanied by minor particle agglomeration and sparse micropores, indicative of lower compactness. In the cross-sectional view (Fig. 16(d)), both the preferential alignment of clay lamellae and the continuity of the layered fabric are inferior to those of bentonite. The lamellae are distributed relatively randomly, interlayer pores are enlarged, and a loose card-house stacking structure appears locally.

Nevertheless, the overall microstructural framework remains analogous to that of bentonite. These microstructural discrepancies between the two filter cakes translate into distinct macroscopic performance. Benefiting from its highly compact and oriented layered structure, the bentonite filter cake achieves faster formation, lower filtration loss, and higher pressure conversion efficiency. Although the modified silty clay filter cake is slightly weaker in compactness and structural ordering, it can still form effective Type I/II filter cakes in medium-coarse sand strata. It satisfies the fundamental requirements for support pressure transmission and excavation face stability in slurry shield tunneling, confirming its engineering feasibility as a viable alternative to bentonite slurry.

6 Conclusions

This paper aims to expand the recycling channels of silty clay and verify the feasibility of replacing bentonite slurry with modified waste silty clay slurry as a slurry shield slurry material. The slurry optimization, filtration, and filter cake formation tests and microscopic mechanism analysis are systematically carried out, and the main conclusions are as follows:

(1) Through systematic tests of physical and rheological properties of multiple groups of modified waste silty clay slurry, the regulation law of soil water ratio, sodium carbonate dosage, and fine sand content on slurry working performance is clarified. Finally, the optimal mix proportion is determined as a soil water ratio of 3:5, sodium carbonate dosage 0.5%, and fine sand dosage of 60 g. The core indicators, such as funnel viscosity, specific gravity, and colloid content of the slurry with this mix proportion, meet the specification requirements of slurry shield construction. The rheological characteristics show shear thinning behavior, which is highly consistent with bentonite slurry with common engineering concentration of 1:8–1:12, and has excellent static stability and dynamic pumping and conveying capacity.

(2) The optimized modified waste silty clay slurry strictly follows the classic criterion of bentonite slurry based on the characteristic particle size ratio d_{85}/D_0 . The filter cake formation type and stratum adaptability show a high degree of regularity, and

its applicable stratum range is clear and definite. In a 0.25–0.5 mm medium-coarse sand stratum, $d_{85}/D_0=1.72$, the slurry forms a Type I filter cake type, and the pressure conversion rate is stable above 90%. In a 0.5–1.0 mm coarse sand stratum, $d_{85}/D_0=0.85$, the slurry forms a Type II filter cake + permeation zone type, and the pressure conversion rate remains above 85%. Both indicators meet the requirements of excavation face stable support. In a 2.0–5.0 mm gravel stratum, $d_{85}/D_0=0.46$, the average stratum pore size reaches 87.1 μm , far exceeding the effective plugging scale of slurry particles, unable to form a continuous and effective filter cake. The pressure conversion rate is lower than 40%, filtration loss and permeation depth continue to increase linearly, without engineering support capacity, requiring the addition of large particle clay particles. The optimized modified waste silty clay slurry shows potential as shield tunneling slurry material, expanding the recycling channels of shield waste clay, significantly reducing material costs, and meeting the requirements of green construction and dual-carbon strategy.

(3) The property enhancement of the modified silty clay slurry arises from the synergistic effects of interfacial electrochemical modification and microstructural optimization. Ion exchange induced by sodium carbonate transforms calcium-enriched raw soil particles into sodium-dominated particles, raising the absolute zeta potential from 1.5 mV to 26.1 mV (nearly 17 times increase). This drastically strengthens interparticle electrostatic repulsion and effectively counteracts van der Waals attraction, thereby fundamentally inhibiting flocculation and agglomeration of the original soil particles. Meanwhile, the pronounced intensification of adsorbed water vibration bands at 3442 cm^{-1} and 1630 cm^{-1} elevates particle hydration capability, allowing the slurry system to form a uniform, stable hydrated film and electrical double-layer structure. Moreover, the filter cake formed by the modified silty clay slurry is dominated by face-to-face stacking and edge-to-face bridging, with a global microstructure essentially identical to that of bentonite filter cake. The modified silty clay exhibits dispersibility, colloidal stability, and filter-cake formation potential comparable to bentonite, offering decisive microscopic theoretical support for its application as a substitute for conventional bentonite slurry and for the resource utilization of shield

tunneling spoil.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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