Research on Solidification Ratio of Tunnel Mudstone and Experimental Verification Analysis of Karst Reinforcement Model

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Abstract: With the advancement of infrastructure development in karst regions, traditional pile foundation construction faces challenges posed by complex geological conditions, particularly under the influence of irregular cavities such as karst caves and fractures, where pile stability and load-bearing capacity often cannot be effectively guaranteed. Grouting reinforcement technology, as a commonly employed engineering measure, relies heavily on the selection and proportioning of grouting materials. Optimal slurry mixtures not only determine fluidity and strength under varying geological conditions but also directly impact the long-term durability and cost-effectiveness of pile reinforcement. With the growing adoption of resource recycling concepts, waste mudstone has garnered significant attention as a low-cost mineral admixture in grouting materials. Through optimized studies on water-to-solid mass ratios, cementitious material proportions, and admixture dosages, this research demonstrates the superior performance of modified mudstone slurry in karst pile reinforcement, particularly in enhancing slurry stability, compressive strength, and construction adaptability. Model tests further validate the feasibility of mudstone slurry grouting reinforcement. The modified mudstone slurry not only effectively reduces construction costs but also provides innovative approaches for resource utilization of waste mudstone, promoting dual advancements in environmental protection and engineering technology.

Keywords: Karst Pile Foundation; Mix Ratio Optimization; Waste Mudstone; Resource Utilization; Model Testing

1. Introduction

With the continuous advancement of urbanization, infrastructure development in karst regions faces increasingly severe challenges. Karst strata typically contain numerous irregular cavities such as karst caves and fissures, which pose significant difficulties for traditional pile foundations in terms of load-bearing capacity, stability, and deformation control [1]. During engineering construction in karst areas-particularly pile foundation installation-grouting reinforcement measures are often required to enhance the stability and load-bearing capacity of pile foundations.

The selection and proportioning of grouting materials are critical factors influencing grouting effectiveness. Proper mix design not only ensures adequate fluidity of grout under complex geological conditions but also significantly enhances compressive strength, thereby effectively improving pile foundation stability [2]. Meanwhile, tunnel excavation during infrastructure construction often generates substantial amounts of spoil and mudstone waste. Current research typically classifies these excavated materials as part of engineering waste and construction solid waste, whose storage and disposal not only consume significant resources but may also impose environmental pressures [3]. Additionally, the transportation and comprehensive disposal processes for waste materials typically incur substantial costs, further increasing resource consumption and economic burdens throughout the project lifecycle.

In recent years, with the continuous advancement of resource recycling concepts, researchers have increasingly focused on optimizing the formulation of grouting materials to enhance their performance and application effectiveness. Building upon traditional cement-clay slurry systems, an increasing number of scholars have begun experimenting with incorporating engineering waste materials (such as mudstone) as components for material modification [4-6]. For instance, Qiao Jingsheng et al. [7] investigated the strength performance of granulated blast furnace slag micro-powder used for solidifying silty soils. Their study revealed that as the dosage of granulated blast furnace slag micro-powder increased, the solidified soil strength exhibited a significant upward trend, demonstrating a stepwise increase that far exceeded that of pure silty soil. Li Yu et al. [8] successfully applied a composite material combining stone slag and mineral slag for expansive soil treatment, achieving not only improved soil strength but also enhanced durability. Liu et al. [9] developed a novel powdered geopolymers grouting material using slag powder, fly ash, alkali activators, and chemical additives, which demonstrated excellent solidification properties with outstanding performance in stabilizing soil structures. Cui et al. [10] created a high-performance synchronous grouting material by combining modified red clay with epoxy resin, providing more efficient reinforcement solutions for underground engineering projects. Liang Shihua et al. [11] formulated a cementitious system using sulfoaluminate cement and municipal solid waste incineration fly ash for leachate sludge treatment, offering new directions for solidification material development. Zhang et al. [12] investigated cave filling materials for shield tunnel construction under groundwater flow conditions using bentonite and cement as base materials with added curing agents, ensuring optimal slurry adaptability. Hu Jianlin et al. [13] utilized blast furnace slag and fly ash as precursors, employing water glass activation and nano-SiO_2 bonding to modify geopolymer-cured soil, demonstrating exceptional performance in underground soil improvement. Li et al. [14] developed cost-effective red mud-based grouting materials using ultrafine red mud. These materials extended the setting time of slag-based soil slurries while effectively reducing viscosity and thixotropy, showing promising application prospects. He Jun et al. [15] conducted flowability tests and strength experiments to study the effects of curing agent dosage and moisture content on fluidized sludge-cured soil properties, establishing flowability prediction models and strength calculation methods that provide theoretical foundations for engineering applications. Zhang Zhiyong [16] conducted research on shield tunnel slurry from Shandong Province, investigating how initial moisture content and cement dosage affect physical-mechanical properties of cured soil. Experimental studies identified optimal formulation ratios, offering practical guidance for slurry modification during tunnel construction.

This study aims to optimize the formulation ratio of mudstone grouting materials through systematic experimental investigations into parameters such as mass ratios of water to solids, cementitious material proportions, and admixture dosages affecting slurry performance, supplemented by model tests for operational validation. Results demonstrate that rational formulation design ensures optimal fluidity while maintaining adequate compressive strength and low shrinkage rates. The findings not only provide technical support for karst pile foundation reinforcement technology but also pioneer innovative approaches for resource utilization of waste mudstone. Utilizing modified waste mudstone in karst pile reinforcement materials addresses environmental concerns caused by waste accumulation while significantly enhancing resource efficiency, reducing construction costs, and promoting ecological sustainability.

2. Raw Materials

The experimental materials were sourced from the excavated mudstone of Guangxi Dazhu Tunnel Project, with specific sampling locations shown in Figure 1. The excavated unprocessed mudstone underwent solidification treatment before being applied to bridge pile foundation reinforcement projects in karst regions adjacent to the tunnel. The unprocessed mudstone was first dried and crushed, then sieved through a 4.75 mm sieve, followed by physical-mechanical property tests conducted according to relevant experimental standards. Test results indicated that the mudstone exhibited a density of 1.46 $g\cdot cm^3$, liquid limit of 20.6%, plastic limit of 13.3%, and plasticity index of 7.3. The particle size distribution curve of crushed mudstone is presented in Figure 2.

The chemical mineral composition of intact mudstone is presented in Table 1. This mudstone is primarily composed of non-clay minerals with a minor clay mineral content, predominantly consisting of illite and kaolinite, exhibiting poor cohesion. Mudstone samples excavated from tunnels predominantly display flaky or thin plate-like structures, demonstrating significant planar expansibility and showing a certain degree of directional arrangement tendency.

The cement used is 42.5 grade ordinary Portland cement with a specific surface area of 352 m²/kg. The initial setting time of this cement is 188 minutes, and the final setting time is 239 minutes. The main performance indicators are shown in Table 2.

The mineral powder used was S105 grade mineral powder, with a density of 2.93 g/cm³, specific surface area of 628 m²/kg, flowability ratio of 102%, and moisture content of 0.2%. The performance indicators of the mineral powder are shown in Table 3.

The admixture is prepared by mixing hydroxypropyl methylcellulose and early-strength agent in a specified ratio. The mixing water used in the experiment was selected from tap water in the building materials laboratory, which complies with national standards and has a pH value greater than 4.

(a) (b)

Figure 1. Mudstone Excavated During Tunnel Excavation

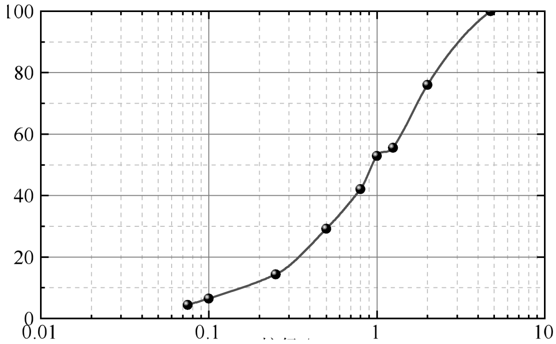

Figure 2. Particle Size Distribution Curve of Processed Mudstone

Table 1. Main Mineral Composition of Mudstone

kind	quartz	calcite	illite	dolomite	feldspar	common pyrite	hematite	kaolinite
content	23%	18.6%	21.2%	8.5%	16.5%	2.1%	5.9%	4%

Table 2. Relevant Properties of Cement

loss on ignition/%	SO3/%	MgO/%	Cl-/%	stability	3 d strength/MPa		28 d strength/MPa	
					anti-refract	resist compression	anti-refract	resist compression
3.53	2.38	1.67	0.038	qualified	5.5	28.6	8.4	51.6

Table 3. Relevant Properties of Mineral Powder

loss on ignition /%	CaO/%	SiO2/%	Al2O3/%	MgO/%	SO3/%	activity index /%	
						7 d	28 d
0.96	35.3	34.5	16.7	5.01	1.24	98	115

3. Experimental Design and Methods

3.1 Trial Protocol

Based on historical construction experience and field conditions, the performance of grouting materials is primarily influenced by factors including the type and proportion of cementitious materials, admixture composition, water content, and raw material specifications. To characterize the mix design parameters, "ratio-based indicators" were adopted as independent variables. Given the complexity of multiple influencing factors and their varying levels, this study selected four critical parameters to ensure uniform distribution of test points within the design range. Specifically, the selected parameters include: the mass ratio of cementitious materials to mudstone, the mass ratio of admixtures to cementitious materials, the mass ratio of water to total solids, and the mass ratio of mineral powder to cementitious materials. The corresponding mudstone solidified slurry test protocols are detailed in Table 4.

Table 4. Cementation Slurry Test Scheme for Mudstone

#	Mass ratio of cementitious material to mudstone	Mass ratio of admixtures to cementitious materials	The mass ratio of water to all solids	Mass ratio of fly ash to cementitious materials
A1	0.10	0.05	0.5	0.1
A2	0.10	0.05	0.5	0.2
A3	0.10	0.05	0.5	0.3

A4	0.10	0.05	0.5	0.4
B1	0.10	0.05	0.4	0.3
B2	0.10	0.05	0.5	0.3
B3	0.10	0.05	0.6	0.3
B4	0.10	0.05	0.7	0.3
C1	0.10	0.01	0.5	0.3
C2	0.10	0.05	0.5	0.3
C3	0.10	0.09	0.5	0.3
C4	0.10	0.14	0.5	0.3
D1	0.05	0.05	0.5	0.3
D2	0.10	0.05	0.5	0.3
D3	0.15	0.05	0.5	0.3
D4	0.20	0.05	0.5	0.3

The primary objective of karst pile foundation reinforcement is to prevent excessive concrete loss during pouring, thereby ensuring pile foundation quality and construction safety and effectiveness. To achieve adequate filling and reinforcement of defects such as cavities, karst caves, or fissures in karst pile foundations, grouting slurry must possess excellent fluidity compatible with cavity geometry, diffusion capacity, and filling processes. This enables the slurry to effectively penetrate cavities under high pressure conditions and form a more robust cemented mass with the filling medium, significantly enhancing foundation bearing capacity and stability. Consequently, this study conducted comprehensive testing and analysis on critical parameters including material density, flowability, shrinkage rate, and 3-day compressive strength.

3.2 Performance Indicator Testing Method

(1) Density

According to the "Standard for Test Methods of Basic Properties of Building Mortar" (JGJ/T 70-2009), first thoroughly clean the inner surface of the volume cylinder to ensure no residual impurities and accurately measure the mass of the empty cylinder. Next, pour the prepared mortar slurry into the cylinder and compact it manually to ensure uniform filling without air bubbles. Then, use a spatula to smooth the cylinder opening, ensuring a flat mortar surface. Finally, measure the total mass of the mortar-filled cylinder. The density of the mortar slurry is calculated using the following formula:

$$\rho=\frac{m_1-m_2}{V}\times 1000 \quad (1)$$

Where: ρ represents slurry density (kg/m³); m1 denotes the mass of the capacity cylinder (kg); m_2 indicates the combined mass of the capacity cylinder and sample (kg); V stands for the volume of the capacity cylinder.

(2) Mobility assay

In accordance with the "Test Methods for Air-entraining Mortar and Air-entraining Plaster" standard issued by the Japan Road Association, a glass plate measuring 400mm × 400mm × 5mm was used as the substrate during measurement. A cylindrical grinding tool with a diameter of 80mm and height of 80mm was employed for filling and measuring the mortar slurry.

(3) Shrinkage rate test

Place the ring cutter (20 mm height, 61.8 mm diameter) on a glass slide lined with filter paper, then pour in the pre-prepared slurry. Use a spatula to smooth the slurry surface and ensure uniform distribution. After measuring and recording the initial sample volume, perform standard curing under constant temperature and humidity conditions. After 3 days of standard curing, measure the sample volume again. The slurry shrinkage rate is calculated by dividing the difference between the initial volume and the volume after 3 days by the initial volume, thereby evaluating the volume change during the curing process.

$$\beta=\frac{V-V_2}{V} \quad (2)$$

Where: β represents the shrinkage rate; V denotes the initial volume of the slurry; V_2 indicates the volume of the slurry after 3 days.

(4) Compressive strength test

In accordance with the provisions of the "Geotechnical Test Method Standard" (GB/T 50123-2019), the prepared sample slurry is formed into cylindrical test blocks of standard dimensions and subjected to standard curing under specified conditions. During the curing process, the test blocks are maintained at designated temperature and humidity levels for a predetermined duration to ensure the formation and development of mechanical strength. After three days of standard curing, unconfined compressive strength tests are conducted using a strain gauge unconfined compression tester. These tests enable evaluation of strength progression during the curing process, providing reliable mechanical performance data for subsequent engineering applications.

4. Experimental Results and Analysis

According to the experimental protocol outlined in Table 4, comprehensive laboratory tests were conducted using 16 distinct mixtures of mud slurry materials. Through performance evaluation of each sample group, corresponding experimental data were obtained. The results demonstrate that the 16 mixed ratios of mud solidification slurry materials exhibit varying characteristics across multiple performance parameters. Detailed test data and performance metrics-including critical indicators such as density, fluidity, and compressive strength-are summarized in Table 5, providing comprehensive analysis of each slurry group's characteristics.

Table 5. Preliminary Compatibility Test Results of Mudstone Solidification Slurry

#	Density (g/cm³)	3D compressive strength/kPa	mobility				
			0min	20min	40min	60min	80min
A1	1.70	202.29	195	183	176	161	153
A2	1.71	248.97	221	206	192	183	169
A3	1.69	326.78	243	229	203	182	172
A4	1.72	389.02	233	216	201	191	173
B1	1.71	451.26	206	183	172	161	152
B2	1.75	326.78	217	192	179	168	159
B3	1.70	217.85	261	223	201	187	173
B4	1.65	70.02	302	285	269	226	192
C1	1.62	326.78	286	247	213	183	168
C2	1.61	342.34	213	197	183	174	163
C3	1.71	357.90	279	256	231	201	183
C4	1.46	357.90	232	296	254	224	201
D1	1.71	264.93	208	187	169	161	153
D2	1.69	326.78	216	191	179	168	159
D3	1.70	315.11	219	198	181	169	161
D4	1.68	435.70	211	190	174	163	154

Through comprehensive analysis of experimental data, this study focuses on investigating performance variations of mudstone solidification slurry under different mixing ratios, particularly in terms of density, flowability, shrinkage rate, and compressive strength. Detailed analysis of experimental data reveals the impact patterns of various factors on slurry properties, while further exploring their interactions and comprehensive effects on overall slurry performance. Based on data analysis results and practical engineering requirements, the study derives optimized mixing ratio ranges for mudstone solidification slurry under different construction environments, providing theoretical foundations and technical support for future engineering applications. Specific findings are as follows:

(1) Serous fluid density analysis

The density of mudstone solidification slurry serves as a critical parameter for evaluating its stability and construction adaptability. Experimental results demonstrate that slurry density is significantly influenced by multiple factors including the mass ratio of cementitious materials to mudstone, the mass ratio of mineral powder to cementitious materials, admixture ratios, and water-to-solid mass ratios. In this study, 16 sample groups exhibited density variations ranging from 1.46 g/cm³ to 1.75 g/cm³. Notably, density increased with elevated mass ratios of cementitious materials to mudstone and mineral powder to cementitious materials. For instance, the measured density reached 1.70 g/cm³ in formulation A1 (0.10 mass ratio cementitious materials to mudstone, 0.1 mass ratio mineral powder to cementitious materials), while rising to 1.72 g/cm³ in formulation A4 (0.10 mass ratio cementitious materials to mudstone, 0.4 mass ratio mineral powder to cementitious materials). These findings indicate that increasing mass ratios of cementitious materials to mudstone and mineral powder to cementitious materials effectively enhances slurry compactness, thereby improving overall stability and strength. However, higher admixture ratios generally lead to decreased slurry density, particularly in formulation B4 (0.05 admixture ratio, 0.10 mass ratio cementitious materials to mudstone), where density dropped to 1.65 g/cm³-significantly lower than other formulations. This phenomenon is attributed to admixture additives weakening slurry cohesion, resulting in reduced density. From a practical construction perspective, to ensure the slurry exhibits good fluidity and construction adaptability, the density should be controlled above 1.65 g/cm³. Therefore, to avoid adverse effects on construction quality caused by excessively low density, this study recommends optimizing the mix design by avoiding admixture ratios that are too high.

(2) Mobility analysis

Flowability serves as a critical performance indicator for cemented mud slurry, directly influencing its pumpability and construction adaptability. Experimental results demonstrate that slurry flowability exhibits a pronounced decline over time, with particularly significant decreases observed during the initial phase up to 20 minutes. Notably, increased mass ratio of water to solids shows a rising trend in flowability, indicating that higher water-to-solid ratios enhance fluidity. For example, Slurry B1 (0.4 water-to-solid ratio) achieves 206mm flowability at 0 minutes, while Slurry B4 (0.7 water-to-solid ratio) reaches 302mm. This confirms that elevated water-to-solid ratios improve fluidity, especially during high-pressure injection where superior flowability facilitates cavity penetration and solid cementation. However, excessively high ratios may adversely affect stability-excessive fluidity in Slurry A4 (0.5 water-to-solid ratio) demonstrates rapid decline from initial 206mm to 153mm over time. These findings suggest that while higher water-to-solid ratios enhance early-stage fluidity, their subsequent rapid decline may compromise construction stability and effectiveness during later stages. Therefore, when designing slurry mix proportions, it is essential to comprehensively consider how the mass ratio of water to all solids affects fluidity. This ensures the slurry maintains optimal flowability during construction while preserving stability, thereby guaranteeing efficient pumping performance and superior construction outcomes.

(3) Shrinkage rate analysis

Shrinkage rate serves as a critical indicator reflecting volume changes during slurry solidification, directly impacting its compressive properties and long-term stability. Experimental results demonstrate that slurry shrinkage rate correlates significantly with three parameters: mass ratio of cementitious materials to mudstone, mass ratio of mineral powder to cementitious materials, and mass ratio of water to all solids, exhibiting distinct pattern trends. Notably, higher mass ratios of water to solids (e.g., B3, C1 formulations) lead to markedly increased shrinkage rates. This phenomenon likely stems from intensified volume contraction during hydration due to elevated moisture content, which adversely affects subsequent strength development and structural integrity. For instance, formulation A1 (0.5 water-to-all solids mass ratio, 0.10 cementitious materials-to-mudstone mass ratio) shows a shrinkage rate of 0.025, while formulation A3 (0.5 water-to-all solids mass ratio, 0.10 cementitious materials-to-mudstone mass ratio) exhibits a rate increase to 0.035, indicating a positive correlation between mass ratio ratios and shrinkage rates. Additionally, excessively high water-to-all solids mass ratios (e.g., B4 formulation with 0.7 water-to-all solids mass ratio) also elevate shrinkage rates, compromising long-term stability. Excessive moisture content causes pronounced volume contraction during drying processes, further diminishing post-curing strength and structural durability. To ensure the stability of slurry during construction and its post-construction performance, practical applications require strict control over the mass ratios of water to all solids and cementitious materials to mudstone, avoiding excessive ratios to minimize slurry shrinkage and guarantee long-term stability.

(4) Compressive strength analysis

Compressive strength is one of the core properties of cemented mudstone slurry, directly determining its load-bearing capacity in engineering applications. Experimental results demonstrate that slurry compressive strength significantly increases with higher mass ratios of cementitious materials to mudstone and mineral powder to cementitious materials. For instance, in formulation A1 (mass ratio of cementitious materials to mudstone 0.10, mineral powder to cementitious materials 0.1), the 3-day compressive strength reaches 202.29 kPa, while formulation A3 (mass ratio 0.10 and 0.3 respectively) achieves 326.78 kPa. This indicates that increasing the proportion of cementitious materials and mineral powder enhances slurry compressive strength, thereby improving stability and reliability under high-pressure injection conditions. However, excessively high mass ratios may also have adverse effects-particularly when compressive strength becomes too high, which could compromise slurry fluidity and pumpability. For example, formulation B4 (mass ratio 0.10 and 0.4 respectively) exhibits high fluidity but only 70.02 kPa compressive strength, significantly lower than other formulations. These findings suggest that while increased mass ratios may improve slurry flowability and pumping performance, they simultaneously sacrifice compressive strength. Therefore, during the optimization of slurry mix proportions, it is essential to strike an optimal balance between compressive strength and fluidity. This ensures the slurry maintains adequate fluidity while delivering sufficient strength to meet construction requirements.

By comprehensively evaluating various performance indicators and integrating experimental data with practical engineering requirements, this study derives the optimal formulation parameters for mudstone solidification slurry to ensure favorable pumpability and appropriate compressive strength. During optimization, key variables included the mass ratio of cementitious materials to mudstone, the mass ratio of admixtures to cementitious materials, the water-to-solid material ratio, and the mineral powder-to-cementitious material ratio. Using the following reference values as benchmarks-0.12 for cement-to-mudstone mass ratio, 0.05 for admixture-to-cementitious material ratio, 0.58 for water-to-solid material ratio, and 0.35 for mineral powder-to-cementitious material ratio-the research systematically determined optimal ranges for each parameter. The specific optimized parameters are as follows: cement-to-mudstone mass ratio (0.08-0.16), admixture-to-cementitious material ratio (0.03-0.07), water-to-mudstone/cement/mineral powder solid material ratio (0.5-0.66), and mineral powder-to-cementitious material ratio (0.25-0.45).

The optimized mix proportions within the specified range not only meet the technical requirements for karst pile foundation reinforcement construction, but also ensure good fluidity and appropriate compressive strength of the slurry during application. These optimized formulations provide scientific basis for slurry preparation in practical engineering projects, enhance construction efficiency, guarantee reinforcement effectiveness, and deliver reliable technical support for engineering practices.

5. Model Testing

5.1 Model Test Facility

The model testing apparatus employed in this study consists of multiple functional units including a model chamber, grouting machine, pressure gauge, electromagnetic flowmeter, steel ruler, and bounded box with small karst cavities. These components work in synergy to achieve pressurization during grouting operations, slurry metering, and process visualization. The model chamber measures 120 cm × 120 cm × 60 cm (length × width × height), with its outer frame reinforced by angle steel measuring 38 mm × 38 mm × 1.8 mm to ensure structural stability and strength. The chamber comprises four side panels, a base plate, and a top panel, all constructed with 6 mm thick tempered glass on the side panels and base plate, while the top panel features 5 mm thick tempered glass. The top panel incorporates two functional holes: a 20 mm diameter central hole for grouting operations and a 50 mm diameter hole for pile drilling.

Figure 3. Schematic Diagram of the Model Test Apparatus

This design ensures precise positioning and alignment between grouting and pile-forming models within the same experimental system. The grouting power system utilizes a multifunctional grouting machine with a rated power output of 2.2 kW, capable of delivering required grouting pressure and flow rates to meet experimental demands. As shown in Figure 3, the overall layout of the apparatus aims to provide accurate experimental data and intuitive observation methods for simulating grouting processes under karst environments, facilitating detailed evaluation and analysis of grouting effectiveness.

5.2 Slurry Materials Used in Model Testing

The primary objective of the model test was to validate the practical applicability of fluidized solidified mud slurry grouting materials in karst pile foundation reinforcement. For this purpose, the slurry materials used in the experiment were selected from the optimal formulation developed in Chapter 4 of this study. Specifically, a range of mix proportions was adopted: the mass ratio of cementitious materials to mudstone (0.08-0.16), the mass ratio of admixtures to cementitious materials (0.03-0.07), the mass ratio of water to solid components (mudstone, cement, and mineral powder) (0.5-0.66), and the mass ratio of mineral powder to cementitious materials (0.25-0.45). Detailed specifications of this formulation are presented in Table 6. These parameters were optimized to enhance slurry performance, ensuring optimal operational characteristics and construction outcomes during karst pile foundation reinforcement processes.

Table 6. Slurry Mix Proportion Used in Model Test for Karst Pile Foundation Reinforcement

#	Mass ratio of cementitious material to mudstone	Mass ratio of admixtures to cementitious materials	The mass ratio of water to all solids	Mass ratio of fly ash to cementitious materials
content	0.13	0.06	0.60	0.36

5.3 Model Testing Method

The simulation conditions in this study primarily replicate anhydrous karst cave environments, with experimental procedures conducted as follows: First, grouting materials for karst pile foundation reinforcement were prepared according to optimal mix ratios for drilled solidified soil, followed by measurement of slurry flowability during initial injection phases. Pressure grouting was then employed to inject slurry into model cavities, with continuous observation of slurry accumulation morphology evolution within the voids. Grouting operations were immediately terminated upon reaching the top layer or when the upper diameter reached preset control thresholds. Post-injection, consolidation of accumulated masses was monitored. To further assess stability, electric drills were used to create 50mm-diameter boreholes penetrating downward from the mass surface. Glass tubes (simulated piles) were vertically inserted into these boreholes with controlled depths of 1-2cm. Cement slurry with a water-to-solid mass ratio of 0.5 was prepared and injected through funnel into the boreholes. Real-time monitoring recorded slurry-induced stability effects during infusion. Upon complete cementation, cutting tools were employed to section the mass structure for internal integrity assessment. Borehole expansion radii were measured to quantify impacts of slurry injection on wall integrity and mass structure. This experimental protocol provides comprehensive data support for evaluating slurry performance in practical engineering applications.

5.4 Model Test Analysis

The results of the grouting reinforcement model test for karst pile foundations conducted in an anhydrous karst cave are illustrated in Figure 4. The filling body formed using fluid-solidified mud slurry exhibits excellent compaction characteristics, with an overall diffusion pattern resembling conical accumulation. This deposition morphology not only meets the roof connection requirements but also effectively prevents ineffective slurry diffusion within cavities, ensuring precise slurry distribution in target areas. This approach enhances material utilization efficiency and construction controllability. The fluid-solidified mud slurry demonstrated remarkable stability and controllability under the unique conditions of an anhydrous karst cave, maintaining stable geometric morphology in complex geological environments while effectively achieving wall protection and sealing objectives.

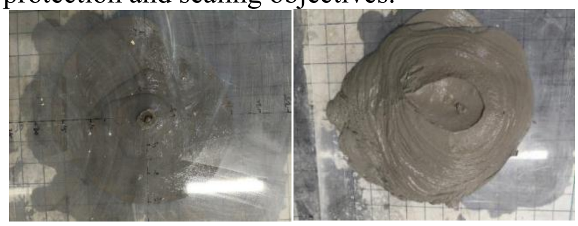

Figure 4. Post-Grouting Effect of Anhydrous Karst Cave

After completing grouting reinforcement in karst caves, the cement slurry is poured into pile holes once the slurry has reached final setting state and the hole profile is formed, simulating the construction process of bored pile installation.

As shown in Figure 5, the filled body formed by fluid-solidified mudstone slurry exhibits excellent overall continuity after slurry injection, with no visible cracks, penetration failures, or leakage channels. This demonstrates that during the critical drilling and pouring phase, the filled body maintains structural stability while effectively encapsulating and supporting the surrounding pile hole area. Further analysis reveals that the prepared fluid-solidified mudstone slurry demonstrates superior formability and setting characteristics under these conditions, providing sufficient disturbance resistance post-final setting while delivering effective wall protection. These findings establish relatively closed and stable boundary conditions for subsequent pile-forming processes, ensuring controlled quality management throughout the cement pile formation procedure.

Figure 5. Effect Diagram of Anhydrous Grouting

6. Conclusion

This study systematically optimized the mixing ratios of grouting materials for karst pile foundation reinforcement and explored the resource utilization of waste mudstone in grouting applications. Through experimental analysis, we elucidated the performance variation patterns of mudstone grouting materials under different water-to-solid mass ratios, cementitious material proportions, and admixture contents. Model tests further validated the practical applicability of these formulations in karst pile foundation reinforcement, yielding the following key conclusions:

(1) By appropriately adjusting the mass ratio of water to solid materials, the proportion of cementitious materials, and the dosage of admixtures, the fluidity, compressive strength, and shrinkage properties of mudstone grouting materials can be significantly improved. The optimized slurry formulation not only enhances construction performance during karst pile foundation reinforcement but also effectively improves reinforcement outcomes, strengthening pile foundations' load-bearing capacity and stability. This optimization approach provides theoretical basis and technical support for engineering applications under similar geological conditions, ensuring slurry adaptability and long-term stability in complex karst environments.

(2) The application of modified waste mudstone as grouting material not only effectively reduces material costs but also addresses environmental issues caused by mudstone accumulation. The modified mudstone slurry demonstrates excellent fluidity and compressive strength, meeting all technical requirements for construction applications. Moreover, this eco-friendly material complies with environmental regulations and facilitates resource recycling, promoting sustainable material utilization. This innovative material provides a novel solution for waste management during construction processes, advancing green building practices and sustainable development goals.

(3) Mud slurry demonstrates remarkable adaptability during construction, particularly under complex karst geological conditions, effectively filling cavities and ensuring long-term structural stability. Regardless of varying operational conditions or construction environments, this material consistently exhibits excellent stability and performance characteristics that meet practical engineering requirements, guaranteeing reliable construction outcomes. With its outstanding properties, mud slurry holds broad application prospects in engineering projects such as karst pile foundation reinforcement, offering significant technical and economic value while providing effective solutions for structural reinforcement in challenging geological environments.

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