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Research Article

Experimental Study on Simulation Filling of New Underwater Cementitious Filling Material (NWC-FM)

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To solve the problem of waste slag treatment of slurry shields, a reuse scheme in which waste shield mud is used to replace traditional karst cave grouting filling material which is proposed; thus, a new type of underwater cementitious filling material (NWC-FM) is developed. NWC-FM is convenient, inexpensive, and environmentally friendly. Its mix proportion is designed, and its mechanical performance is tested. According to the characteristics of karst caves, a semiclosed and pressurized karst cave simulation box is designed and manufactured to simulate grouting filling processes at construction sites, and an NWC-FM grouting simulation test is carried out. The results show that the fluidity of the NWC-FM slurry is good, and the strengths of the samples in the three groups of designed mix proportions meet the requirements of field construction. The underwater poured NWC-FM shows good fluidity, cohesion, nondispersibility, self-leveling, and self-compacting. After each pouring of NWC-FM material, a 2~3 cm isolation layer eventually forms on the surface due to the action of the additives, which can effectively block the contact between water and NWC-FM and ensure the flatness of the underwater poured surface of the NWC-FM material. The average compressive strength of the NWC-FM consolidated core samples at 7 d, 14 d, and 28 d are 0.56 MPa, 0.72 MPa, and 0.79 MPa, respectively, meeting the technical strength requirements of construction sites. NWC-FM has strong underwater nondispersibility and moderate strength, which can well meet the requirements of karst cave filling treatment during shield construction of urban subways. Additionally, as a low-cost and environmentally friendly material, NWC-FM will greatly reduce the project cost and minimize environmental pollution.

1. Introduction

In the process of subway tunnel shield construction, foaming agents and other lubricants are usually applied to the shield cutter head, which makes the soil difficult to consolidate, drain, and recycle because it becomes a kind of muddy waste [1–3]. The slurry output of a slurry shield is generally 2~3 times the tunnel excavation volume. At present, the disposal of waste shield mud is mainly transported to the designated spoil ground. The transportation volume is large, and its disposal cost accounts for approximately 10% of the cost of the shield tunnel. It is also difficult to find a suitable spoil ground. Due to limited urban storage sites and high personnel density, improper disposal will cause environmental pollution, land occupation, and other issues. Therefore, research on the treatment of waste shield mud has very important practical significance.

Karst commonly causes hydrogeological engineering failure in the process of subway construction in China. When a shield crosses the karst strata, it is necessary to preprocess the karst cave in advance to ensure the safety of shield construction. The traditional karst cave treatment methods mainly include the pressure-injection double-liquid slurry [4], sand grouting [5], and concrete grouting methods [6, 7], which consume large amounts of building materials. Therefore, the cost of construction cost is high, and the strength is difficult to control. Moreover, traditional backfill construction is difficult, the backfill period is long, and the backfill quality is difficult to guarantee. It is urgent to find a low-cost, convenient, and green environmental protection material to meet the needs of karst backfill treatment.

The use of waste shield mud as an in situ prepared cave grouting filling material is one of the ways of utilizing waste shield mud as a resource, greatly saving resources, reducing urban pollution, reducing the cost of engineering construction, and realizing green construction. Scholars have studied the working performance and physical and mechanical properties of recycled slurry from abandoned shield sediment and have prepared grouting materials with a fluidity of 230 mm and a 28 d compressive strength that is greater than 2.5 Mpa; thus, this recycled slurry has achieved good comprehensive utilization results [8–12]. However, the existing research on recycled slurry of waste shield sediment mainly focuses on subgrade materials [13], slurry film-forming [14], and slurry shield synchronous grouting raw materials [15–17]. There are few reports on the use of the recycled slurry of waste shield sediment as the filling material of karst caves. Moreover, for water-filled karst caves, the filling material needs to consider the underwater dispersion resistance and other issues. In view of this, this study takes the karst cave treatment of Guangzhou metro construction as the background and takes abandoned shield mud as the main raw material. After the addition of a certain proportion of admixtures, it is fully mixed with water to form a new type of underwater cementitious filling material (NWC-FM) with pumpability and strong fluidity. Based on the characteristics of karst caves and considering the groundwater pressure, a semiclosed and pressurized karst cave simulation box is designed and manufactured, and an NWC-FM grouting simulation test is carried out to study its underwater fluidity and cohesion, thereby evaluating the engineering effect of NWC-FM karst grouting.

2. Mechanical Performance Test of NWC-FM

2.1. Raw Materials and Mix Proportions of the NWC-FM Samples. NWC-FM takes waste shield mud (taken from a shield tunnel construction site of Guangzhou Metro, the sampling depth is 5~10 m, Figures 1(a) and 1(b)) and cement as the main basic materials and selects UWB-II anti-washout admixtures of underwater concrete [18] (developed and produced by CNPC Engineering Technology R&D Company Limited, it is mainly made of sugar polymer thickener, concrete fluidizing agent, concrete setting time regulator, etc, Figure 1(c)) as the flocculating agent. An early-strength chlorine salt agent and polycarboxylate superplasticizer are added to improve the performance of NWC-FM, achieve the effect of water reduction and enhancement, and increase the strength of NWC-FM so that it meets the engineering requirements after a certain number of days of maintenance while also remaining fluid. In addition, fly ash and mineral powder are used to reduce the amount of cement, realize waste utilization, and protect the environment while saving costs. Our research group determined three groups of NWC-FM mix proportions through a large number of laboratory tests in the early stage, as shown in Table 1. The basic requirements of the design include the following four aspects:

(1) The water-binder ratio is 0.45~0.6, and the water consumption is 270~310 kg/m^3
(2) Water consumption should cause the slump of the NMC-FM mixture to reach 220 ± 20 mm, and the slump expansion should reach 350 ± 20 mm
(3) The underwater strength of NWC-FM material is 0.5 MPa
(4) When pouring the NWC-FM material, the free drop-in water is 30~50 cm

2.2. Test Process

2.2.1. Samples Preparation and Curing. NWC-FM samples were prepared according to the Chinese standard GB/T50080-2016 [19] and the Chinese standard DL/T5117-2000 [20]. Nine samples were prepared in each group. The geometric size of the sample was 70.7 mm × 70.7 mm×70.7 mm, and curing ages of 7 d, 14 d, and 28 d were used. The samples preparation steps are as follows:

(1) Configure the slurry: the original shield mud used in the test was dried, crushed, and screened, and large soil particles were removed. Then, it was mixed with cement, fly ash, mineral powder, flocculant, and other additives. Finally, this mud was with water to prepare the mixed mud.
(2) Sample preparation: to facilitate later demolding, a layer of Vaseline was evenly coated on the inner wall of the mold before loading the mixture. The prepared mixed mud was slipped into one side of the mold wall three times, poured into a 1/3 mold volume once, and vibrated for a period of time after each pouring; thus, small bubbles were released from the surface to prevent the influence of the internal bubble gap on the strength of the sample. After filling, the sample was scraped flat with a scraper and then sealed with a cover film.
(3) Sample curing: the test samples were numbered and placed in the water curing protection box of the standard curing room (20 ± 3°C, humidity >95%) for curing. Demould after 48 hours. After demoulding the test samples, continue water curing until the design age is reached (Figure 2(a)).

2.2.2. Unconfined Compressive Strength Test. After the curing of the sample was completed, unconfined compressive strength tests were performed with the consolidated bodies after 7 d, 14 d, and 28 d using a microcomputer-controlled electronic universal testing machine (Figure 2(b)) with a measuring range of 200 kN (axial strain rate of 1 mm/min). When analyzing the test strength of each group, the mean value of three horizontal samples was first calculated. If the deviation between the sample strength and mean value was greater than 10%, it was eliminated. Finally, the mean value of no less than two samples was taken as the test strength value.

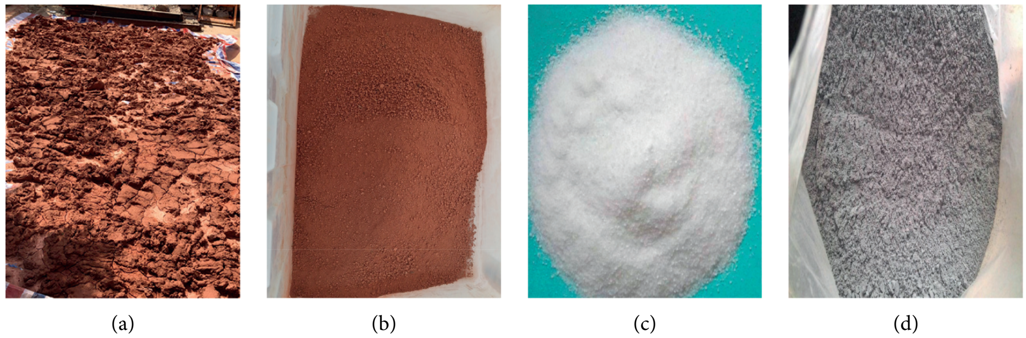


Figure 1: Photos of the undisturbed shield mud (a), shield mud sample after drying, crushing and screening (b), UWB-II anti-washout admixtures of underwater concrete (c), and fly ash (d).

Table 1: Mix proportions of the NWC-FM samples.

Number	Materials (kg)							
	Shield mud	Cement	Fly ash	Mineral powder	Flocculating agent	Early-strength agent	Water reducing agent	Water
NWC-1	1.000	0.286	0.057	0.021	0.014	0.010	0.010	0.429
NWC-2	1.000	0.357	0.071	0.021	0.014	0.010	0.010	0.357
NWC-w	1.000	0.141	0.041	0.010	0.0032	0.003	0.0045	0.351

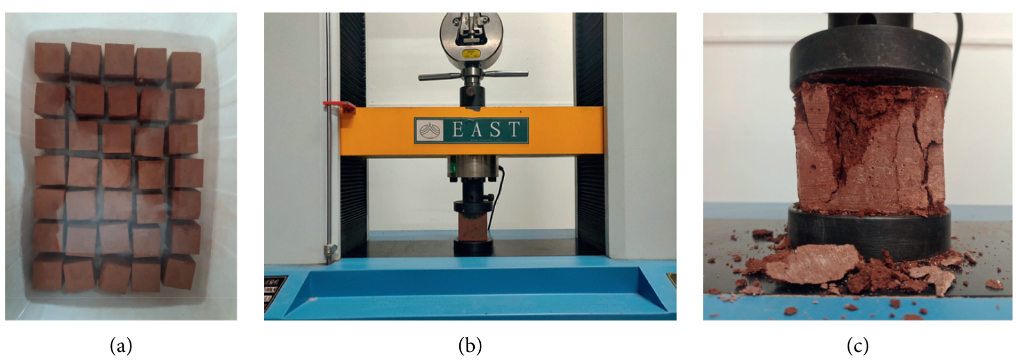


Figure 2: Photos of the stored samples (a), compression testing machine (b), and sample destruction (c).

2.3. Test Results and Analysis. The unconfined compressive strength of the NWC-FM sample is shown in Figure 3. It can be seen from the figure that the strength of the NWC-FM sample gradually increases with increasing curing time. Since the technical requirements of NWC-FM are to ensure the smooth advancement of the shield machine while ensuring the nondispersibility of underwater filling, the strength after filling is required to be greater than or equal to the strength of undisturbed soil, that is, the strength after the filling is approximately 0.5 MPa. The strength of the NWC-FM samples configured according to the design mix proportion of each group is higher than 0.5 MPa, meeting the engineering requirements. Moreover, the strength of the NWC-1 and NWC-2 samples is higher than that of the NWC-w sample, indicating that the strength of the NWC-FM materials is greatly affected by the amount of admixtures. The greater the amounts of additives, such as cement, the greater the strength of NWC-FM and the better the performance. Considering that many kinds of admixtures are required for the NWC-FM configuration and that too high of a strength will cause considerable waste, NWC-w is selected as the optimal mix proportion for the test based on the configuration cost and strength requirements.

3. NWC-FM Simulation Filling Test

Karst caves are underground closed spaces formed by karst in soluble rocks. The formation of karst caves is the result of the long-term dissolution of groundwater in limestone areas, which often contain a large amount of groundwater. Based on the characteristics of karst caves and considering the groundwater pressure, a semiclosed karst cave simulation box with pressure is designed and manufactured to simulate the grouting filling process at the construction site, carrying out a simulation test of grouting with NWC-FM, and study the fluidity and cohesion underwater. The engineering effect of karst grouting with NWC-FM is evaluated.

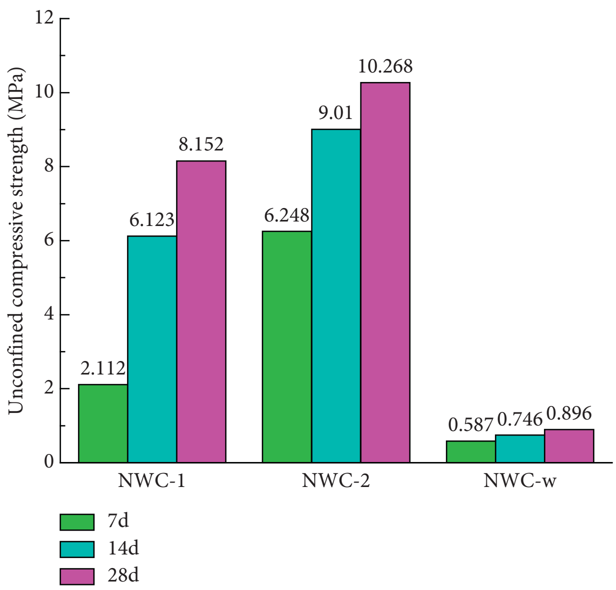


Figure 3: Unconfined compressive strength of the NWC-FM samples with different proportions and at different ages.

3.1. Design and Installation of the NWC-FM Simulation Filling Test Device. A simulation box is designed and manufactured with dimensions of 1500 mm × 800 mm × 500 mm (length × width × height); this box is filled with water to simulate a real water-filled cave. The material of the simulation box is organic glass, each side is fixed with steel strips, and the joint of the organic glass plate is blocked with a waterproof and weather-resistant silicone adhesive to ensure that the simulation box is sealed and does not leak. Three circular holes with a diameter of 100 mm are opened on the roof of the simulation box. As shown in Figure 4, holes A and B are grouting holes and hole C is a drainage hole.

The NWC-FM simulation filling test device is shown in Figure 5, which is composed of a karst cave simulation box and a pulp feeding and water drain system. The pulp feeding and water drainage system is composed of a slurry inlet pipe, a funnel, a drainage pipe, and a water holding tank. The funnel is set on the NWC-FM material feeding platform, approximately 3 m from the ground. The grouting pipe directly penetrates into the bottom of the simulation box through the reserved grouting hole in the roof, which is 200 mm from the bottom of the box; additionally, the drainage pipe is 100 mm from the roof. After reaching the roof, it is connected to the water collecting tank through the conversion elbow. Before the test, clear water is injected into the simulation box through the grouting pipe. Water is added until filling the simulation box and drainage pipe; then, the addition of water is stopped to ensure that there is a certain water pressure in the simulation box when the material is poured. In the process of NWC-FM grouting, the grouting pipes on both sides are alternately grouted to ensure the filling rate of NWC-FM. The installed karst cave simulation box is shown in Figure 6.

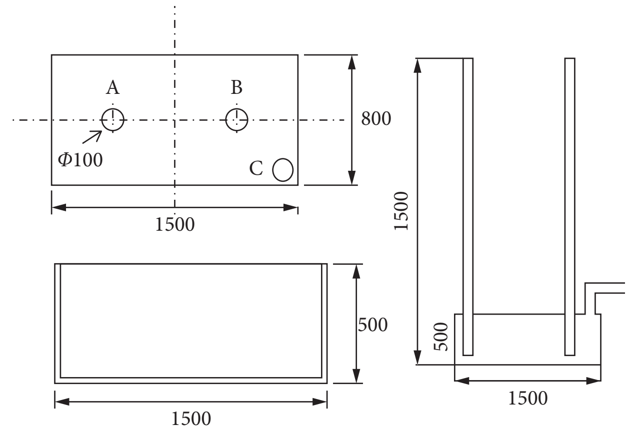


Figure 4: Schematic showing the dimensions of the simulation box. 1 and 2, slurry inlet pipe; 3, drain pipe; 4, plexiglass box; 5, funnel; 6, PVC water injection pipe; 7, water pump; 8, water holding tank; 9, floating ball; 10, traction line with scale; 11, lower floating ball.

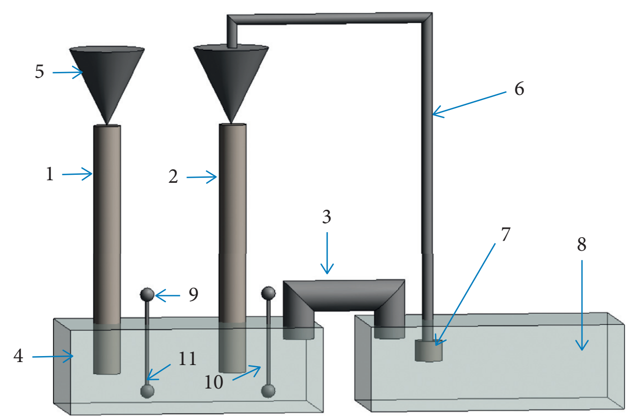


Figure 5: 3D schematic showing the simulated filling test device.

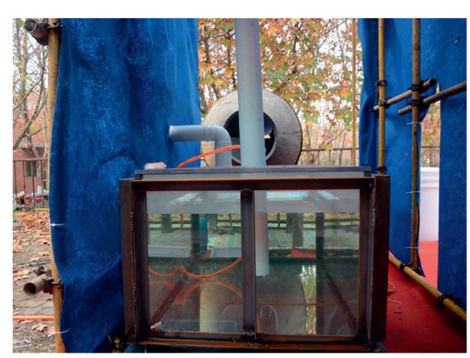


Figure 6: Completed installation of the karst cave simulation box.

3.2. Test Scheme. The NWC-w mix proportion is selected for the NWC-FM simulation test. Before the test, the shield mud and various admixtures after drying are divided into four parts and weighed for use. The test mixer with 0.3~0.5 m^3 discharge per plate ensures a continuous mixing supply of filling materials.

(1) Before the test, the grouting pipe is first inserted into grouting hole A; moreover, the drainage pipe is fixed in the simulation box. The grouting pipe is 200 mm from the bottom of the box, and the drainage pipe is 100 mm from the top surface to ensure compliance with construction at project sites.

(2) Water is injected into the simulation box through the grouting pipe. Water is added until completely filling the simulation box drainage pipe. At this point, the addition of water is stopped to ensure that there is the certain water pressure in the simulation box.

(3) After the preparation work is completed, the NWC-FM premixed shall be penetrated into the grouting pipe through the funnel to observe the decline of the new underwater agglomerating filling material in the grouting pipe. Additionally, attention should be given to the change in the liquid level of the drainage pipe, and the drainage pipe should be connected to the water collecting bucket to facilitate the smooth discharge of water.

(4) The behavior of the NWC-FM entering the water is observed, including the falling process in the water, the shape when reaching the bottom of the simulation box, and the diffusion process, fluidity, and coverage of the filling material at the bottom of the simulation box. Moreover, the changes in the surface of the filling material in the simulation box and of the water in the simulation box are observed.

(5) First, grouting is achieved through grouting pipe A. When the material filling rate drops, grouting pipe A is replaced with grouting pipe B to continue filling, and grouting pipe A is raised by 10–15 cm.

(6) The above process is repeated until all the water in the simulation box is discharged. During the test, attention is given to recording and observing the working properties of NWC-FM at each stage.

(7) After pouring, the surface treatment is carried out in time, and the test piece is wrapped for thermal insulation and moisture conservation.

The simulation filling test flowchart is shown in Figure 7.

3.3. Test Phenomena and Analysis. The NWC-FM material simulation filling test is performed by pouring continuously 4 times. When the first batch of NWC-FM materials touches the bottom plate of the simulation box, due to the impact, the NWC-FM materials will be diluted by the water and begin to slowly rise. The amount of rising slurry will increase slowly. Then, a small part of the NWC-FM is diluted, and most of it diffuses around the bottom and produces a small amount of bubbles. When the amount of NWC-FM material continues to increase, the diffusion speed of the material increases and the slurry continues to rise after touching the bottom, reaching the top of the simulation box and then moving back down to the bottom of the simulation box. At this point, the diluted slurry has diffused to half of the volume of the simulation box, the upper and left colors are light, and the color around the grouting pipe is dark due to the accumulation of the NWC-FM material. The color of the accumulated material gradually becomes lighter outward, and the slurry does not diffuse to the right side of the simulation box; thus, there is still clean water on the right side of the box (Figure 8(a)).

As the pouring is continued, NWC-FM at the grouting pipe is gradually deposited. When the deposition amount increases to a certain extent, the newly poured material squeezes the deposited NWC-FM at a certain pressure to make it evenly move around. The NWC-FM at the bottom of the box presents a distribution pattern of uniform decrease around the grouting pipe. Since grouting pipe A is located on the left side of the simulation box, when the amount of NWC-FM continues to increase, the material close to the left side first touches the sidewall of the simulation box and accumulates on the left wall. The material on the right side continues to move until they contact the right wall, and the speed at which NWC-FM accumulates on the left is significantly higher than that on the right (Figure 8(b)).

When the first pouring is complete, the distribution of NWC-FM material on the left side of grouting pipe A is basically the same, the distribution on the right side decreases gradually with increasing distance from grouting pipe A, and the overall trend is that the left side is high and the right side is low. Although the NWC-FM material that initially enters the simulation box is diluted and the whole simulation box is filled with diluted NWC-FM material, this process develops slowly. With continuous pouring, the integrity of the NWC-FM material is maintained well, and this underwater filling material, with its high fluidity and cohesiveness, forms and moves throughout the simulation box. Two minutes after the completion of the first pouring, a thin layer of white flocculent precipitates appears on the surface of the NWC-FM material at the bottom of the simulation box, and the distribution is relatively uniform. With increasing time, the white precipitates gradually increase, thicken, and clear layer. After 5 min, the thickness of the precipitates reaches approximately 1 cm, forming a milky white isolation layer (Figure 8(c)). The bottom of the simulation box is obviously divided into three layers: diluted NWC-FM solution, the white precipitate isolation layer, and the NWC-FM material from top to bottom, respectively. The isolation layer effectively isolates water from the NWC-FM material and maintains its cohesion and nondispersibility.

While NWC-FM is poured, the mixer continues to work to mix the next batch of material. There is a thick isolation layer above the NWC-FM material before the third pouring (Figure 8(d)). When the NWC-FM material falls, it must first pass through the isolation layer, which disturbs this layer at the grouting pipe and causes the material to rise; however, the isolation layer is still continuous and not dispersed. With the increase in pouring materials, the upper material and lower material gradually push the isolation layer to move around at the same time, and the isolation layer is slowly dispersed after this continuous and strong disturbance. Two minutes after the second pouring, a thin layer of white precipitates is formed on the material surface of NWC-FM. After five minutes, the amount of precipitates increases and

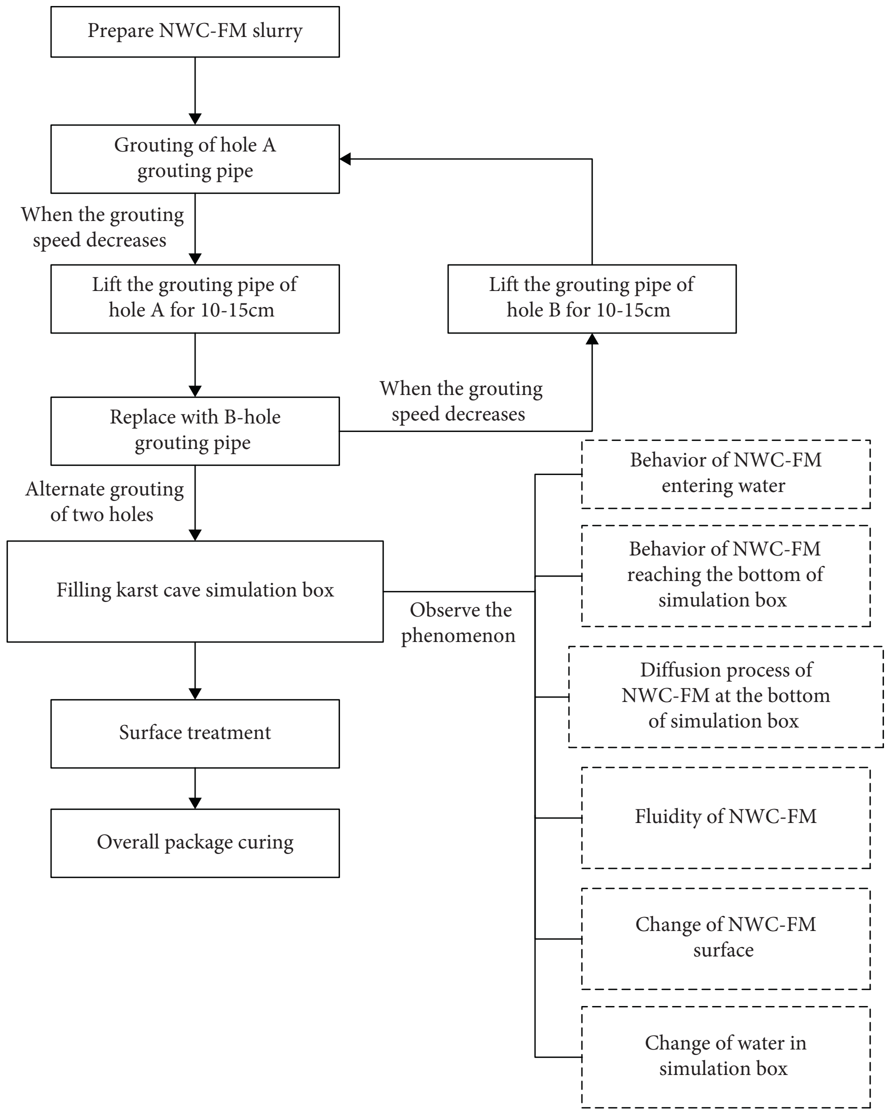


Figure 7: Flowchart of the simulation filling test.

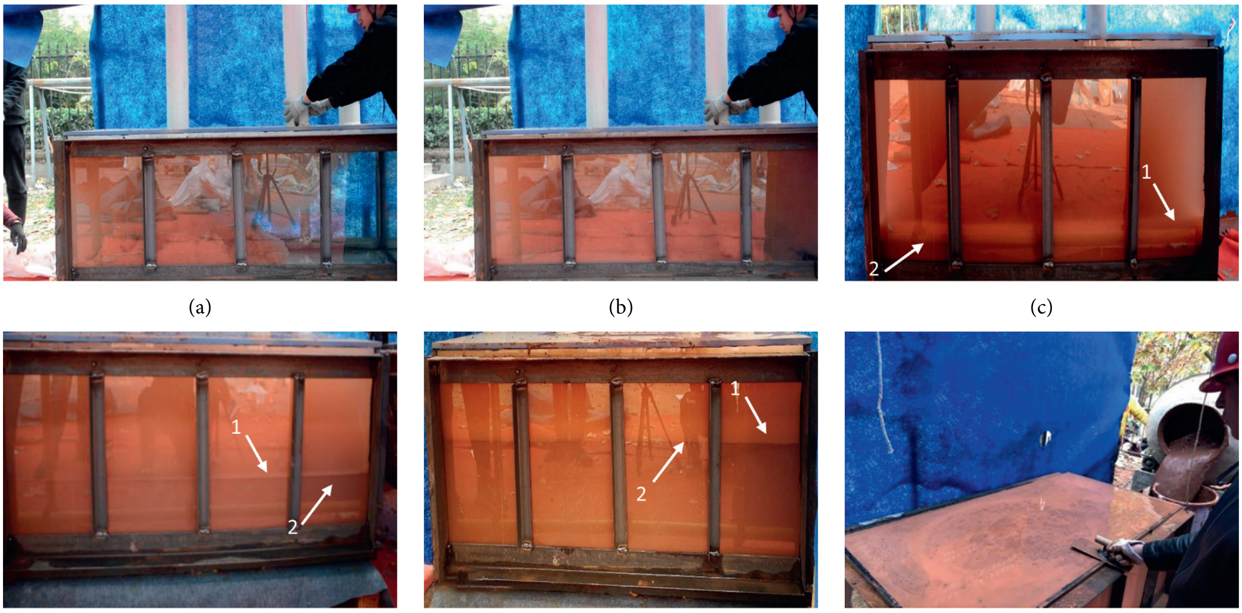
finally forms a new isolation layer. The situation in the third and fourth pouring simulation boxes is basically the same as that in the second time. The material first passes through the isolation layer, which causes the isolation layer to slowly disperse. Then, the NWC-FM material gradually moves around and tends to be stable. Finally, a new isolation layer is formed on the surface of the NWC-FM material. The fourth pouring stops 1 cm from the top surface, completing the simulated pouring test (Figure 8(f)).

During underwater pouring, the isolation layer formed by NWC-FM can prevent the lower NWC-FM from contacting water and maintain the nondispersibility of the material. Additionally, the cementitious material of the isolation layer is continuously distributed and has a certain viscosity, which is not easily affected by the water flow. It can better maintain the cohesion and fluidity of NWC-FM and give full play to the excellent performance of NWC-FM. It can be seen from the above test phenomena that NWC-FM has strong nondispersibility underwater. Thus, even if it were to flow in the water-filled cave simulation box, there is little material separation due to water washing. Moreover, NWC-FM is viscous and plastic, and the water can gradually deposit due to its weight. Furthermore, NWC-FM has self-leveling and self-compaction properties, satisfactorily meeting the requirements of karst cave filling.

4. Mechanical Property Test of the NWC-FM Consolidated Core Sample

To study the strength performance of the NWC-FM simulated filling materials, core samples with a diameter of 100 mm and a length of 150~2200 mm are taken at 7, 14, and 28 d after the simulated filling test by the core drilling sampling method. An unconfined compressive strength test is carried out on the core samples, and the test results are shown in Table 2 and Figures 9 and 10.

At the initial stage of test loading, the deformation of each sample is small. With increasing load, fine cracks appear vertically along with the core sample, and the cracks are evenly distributed along the circumference of the core



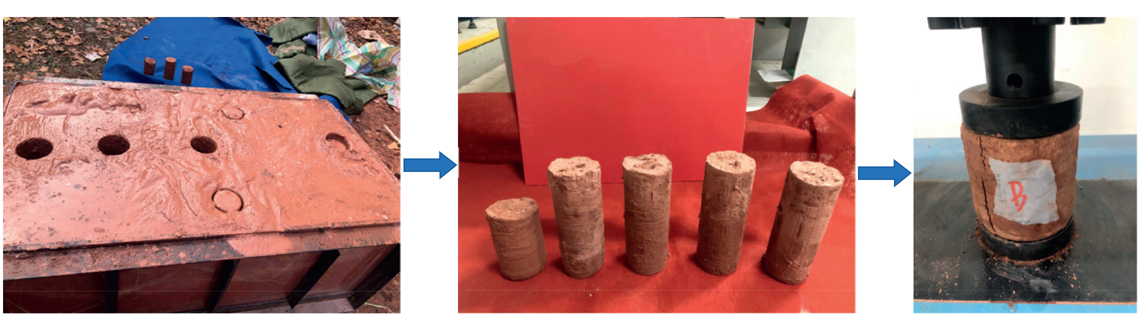
(a) (b) (c)

(d) (e) (f)

Figure 8: Photos of NWC-FM entering the simulation box (a). NWC-FM diffuses in the simulation box (b). Five minutes after the first pouring (c). Five minutes after the second pouring (d). Five minutes after the third pouring (e). After completing the pouring (f).

Table 2: Compressive strength of the core samples.

Curing age (d)	Number	Failure load (kN)	Compressive strength (MPa)	Mean value (MPa)
	1	4.580	0.58	
7	2	4.378	0.56	0.56
	3	4.214	0.54	
	1	5.915	0.75	
14	2	5.920	0.75	0.73
	3	5.291	0.67	
	1	6.745	0.86	
28	2	6.036	0.77	0.79
	3	5.884	0.75	



(a) (b) (c)

Figure 9: Photos of the core sampling positions (a), removed core samples (b), and sample destruction (c).

sample. As the load continues to increase, the cracks gradually extend through the top and bottom surfaces of each sample. The sample is damaged and loses its bearing capacity. The failure mode is shown in Figure 9(c). Table 2 and Figure 10 show that the strength of the consolidated core sample of the NWC-FM simulation filling test gradually increases with increasing curing time. The average compressive strength at 7, 14, and 28 days is 0.56, 0.72, and

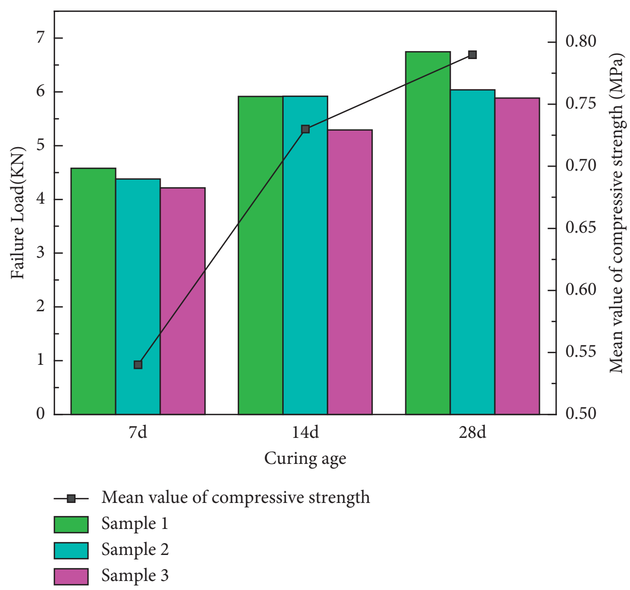


FIGURE 10: Test results of the unconfined compressive strength of the NWC-FM consolidated core samples.

0.79 MPa, respectively, which represents moderate strength. Therefore, this material can better meet the requirements of underwater karst cave filling at project sites.

5. Conclusions

Aiming at the resource utilization of waste shield mud and the treatment of water-filled karst caves in urban subway shield construction, a new underwater cementitious filling material that is convenient to obtain (NWC-FM), low cost, and environmentally friendly is developed. Its mix proportion is designed, and its basic properties are tested. A karst grouting simulation test is performed to study the fluidity, cohesion, and nondispersibility of NWC-FM during underwater pouring. After curing, core samples are drilled out, the strength index of the NWC-FM material is tested, and the karst grouting effect of the NWC-FM material is evaluated. The main conclusions are as follows:

(1) Through laboratory tests, NWC-FM is developed with waste shield mud, cement, flocculant, and fly ash as raw materials. The minimum 7 d-compressive strength of the three groups of mix proportion samples is 0.587 MPa, which meets the technical requirements of construction sites.

(2) The NWC-FM material initially entering the simulation box will be diluted by water, but the process is slow. Notably, the integrity of the material is maintained, and material separation due to water washing rarely occurs. Furthermore, NWC-FM has strong fluidity and cohesion and can flow in any direction underwater.

(3) After each pouring of NWC-FM material, a 2~33 cm isolation layer will eventually be formed on the surface due to the action of the admixture. The cementitious material of the isolation layer is continuously distributed and has a certain viscosity that is less affected by water flow. This layer can effectively block the contact between the water and NWC-FM material, maintain the nondispersibility, cohesion, and fluidity of the NWC-FM material, ensure the leveling of the underwater poured surface of the NWC-FM material, and prevent material loss. Thus, the NWC-FM material has good underwater service performance and meets the requirements of underwater filling.

(4) The strengths of the NWC-FM consolidated core samples at 7 d, 14 d, and 28 d are 0.56 MPa, 0.72 MPa, and 0.79 MPa, respectively, meeting the technical strength requirements of construction sites. NWC-FM has strong underwater nondispersibility and moderate strength, which can satisfactorily meet the requirements of karst cave filling treatment during urban subway shield construction. Additionally, as a low-cost and environmentally friendly raw material, NWC-FM will greatly reduce the project cost and minimize environmental pollution.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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