

Research Article

Development and Field Test of New Environmentally Friendly Water-Rich Sand Grout Material

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The water-rich sand layer is a common source for underground engineering disasters. Considering the poor performance, high cost, and serious environmental pollution of conventional grouting materials, based on the requirements of environmental grouting treatment, a new type of environmental water-rich sand grouting material was proposed, which was mainly based on fly ash and cement and supplemented by water glass. The performance of the slurry was studied. The parameters such as the initial set time, the ratio of stone, and the compressive strength of the material under different water contents and fly ash contents were determined by experiments. The new grouting material was obtained with rapid setting, early strength, high ratio of stone formation, and strength, which were less affected by water content. The successful application of the new environmental grouting material in the Qingdao Metro not only ensures the safety of the project but also meets the requirements of environmental protection. It also verifies the scientificity of the material and will be useful for the innovation of the water-rich sand grouting material.

1. Introduction

With the rapid development of rail transit construction in China, the increasingly complex hydrogeological environment is a difficult problem for underground engineering construction in China. The water-rich sand layer is a common source of disasters for urban rail transit, which seriously threatens the safety during the construction period and operation period. Grouting is a commonly used treatment method to solve the problem of water-rich sand layer. However, the current grouting material has the following problems [1–4]. In the traditional cement grouting materials, the initial set time of the slurry was longer (6–8 h), and it was unable to meet the demand of early strong and quick setting of the grouting treatment in the water-rich sand. Cement-water glass slurry is the most widely used quick-setting grouting material [5–7]. However, cement-water glass grout stones have the following disadvantages: large solubility in water; shrinkage of late strength and volume; coagulation time being sensitive to water. Chemical grouting materials can generally meet the requirements of

grouting in water-rich sand for the strength of materials, but they are generally toxic and have high prices. Therefore, the development of new environmentally friendly water-rich sand grouting materials has become an imminent task.

In terms of improving the retention ratio of grouting materials under water-rich sand and developing high-performance grouting materials, scholars at home and abroad [8–12] have conducted relevant researches and made certain progresses. Liu et al. [13, 14] studied the VCH cement-based grouting material to improve some of the shortcomings of the traditional cement slurry, but in order to meet the pumpability of the new grouting material, adjusting the slurry ratio seriously affects the strength of grouting plus solids. In addition, there are few studies on grouting materials in the water-rich sand [15, 16].

Based on the requirements of environmental grouting treatment, this paper proposes a new type of environmental water-rich sand grouting material, which was mainly based on fly ash and cement and supplemented by water glass. The performance of the slurry was studied. Experiments determined the parameters of material, such as the initial set

time, the ratio of stone, and the compressive strength of the material under different water contents and fly ash contents. The parameters of the new grouting materials were obtained, including rapid setting, early strength, high ratio of stone formation, and less-affected strength by water. The new environmental grouting material was successfully applied in Qingdao Metro. Therefore, it has a common application prospect in the treatment of water-rich sand in underground engineering.

2. Material Development

2.1. *Test Material.* The various types of raw materials used in laboratory tests are as follows:

- (1) Cement, 425 ordinary Portland cement produced by Shandong Shanshui Cement Plant, whose quality is in line with “Portland Cement, Ordinary Portland Cement” (GB175-99) standard
- (2) Fly ash, produced by Shandong Hongyuan Building Materials (composition in Table 1).
- (3) Water glass, the parameters used for testing: m (modulus) = 3.18, Be' (Baume degree) = 40°, ω (SiO_2) = 26.25%, and ω (Na_2O) = 9.54%.

2.2. *Experiment Method*

- (1) Slurry production process: the fly ash and cement are mixed in different proportions (the mixture is called material M) and are made of different ratio of water and material M (hereinafter referred to as $W:M$) and then mixed with water glass according to the ratio of 1:1.
- (2) The ZKS-100 viscometer was used to determine the initial and final set time of the material with different components.
- (3) Samples with different components and different proportions were made into standard samples. After 3 hours, the amount of water produced and the ratio of stone formation was determined.
- (4) The test blocks of different components and proportions into cylindrical standard test blocks ($\varphi 5\text{ cm} \times 10\text{ cm}$) were prepared and placed in a constant temperature curing box at 30°C. Uniaxial compression test adopts WDW-100 universal testing machine which was provided by Jinan Lingyue Accurate Instrument Co., Ltd. The uniaxial compressive strengths of the test blocks at 1 h, 3 h, 5 h, 7 h, 1 d, 3 d, 5 d, 7 d, 14 d, and 28 d were measured via using a press.
- (5) In order to study the pumpability of the material after initial setting, a set of pumpability test instruments was designed and the corresponding pumpability test was given.
- (6) Scanning electron microscope test adopts Phenom XL provided by Phenom-China. The stone bodies of 1 d, 3 d, and 5 d were scanned by using a scanning electron microscope.

TABLE 1: Chemical compositions of raw material.

Raw materials	Percentage							
	SiO ₂	Al ₂ O ₃	F ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	Loss
Fly ash	49.32	26.38	4.15	15.78	—	0.32	2.15	1.9

3. Test Results and Analysis

3.1. *Determination of Initial and Final Settling Time.* The gelation time of the grouting material determines the fluidity and practicality of the material. The effect of the new material on the gelation time was studied. The curves of the initial and final settling time of the slurry at different ratios with the $W:M$ ratio, and the different volume occupied by the fly ash are shown in Figure 1.

The analysis shows that the water content has a significant effect on the gelation time of the new environmentally friendly grouting material (the amount of water provided here guarantees slurry workability). The figure shows that the initial and the final settling time of the sample increases with the increase of water content of the sample. When the fly ash is 10% and the ratio of $W:M$ increases from 0.8 to 1.2, the initial setting time is extended from 37 s to 76 s and the final setting time is extended from 35 minutes to 66 minutes. This shows that the content of water in the slurry has a great influence on the setting time of the new material, but when the fly ash content is about 20%, the gelation time of water and new materials does not have a significant effect.

When the fly ash is increased from 10% to 30%, the initial and final setting time of the new material will first decrease and then increase. When the amount of the fly ash is about 20%, the initial setting time will reach 20–30 s. The final settling time is basically around 20–30 mins, showing a very close correlation.

3.2. *Strength.* The strength of the grouting material is mainly described by the compressive ability of the stone body formed after the hydration and polymerization of the material components occurs. Therefore, it is of great significance for the research and development of materials to study the strength properties of grouting materials with different material ratios and different additives. The test results are shown in Table 2.

From the analysis of the table, it can be seen that the early strength of the new material increases faster than the traditional cement-water glass. When the $W:M$ ratio is 1:1 and the fly ash content is 20%, the uniaxial compressive strength of the stone after 1 h is about 0.84 MPa. When the amount of fly ash is fixed, the ratio of water to the mixture is greater, the strength of the grouting stones is slightly reduced within 12 hours, and the strength changes little after 1 day, indicating that the water content has a small effect on the strength of the material. The main reason was that the gels of the materials were not because of the hydration reaction of the traditional materials, but the reaction of the geopolymer under the alkali activation [17–22], which is less affected by the water content.

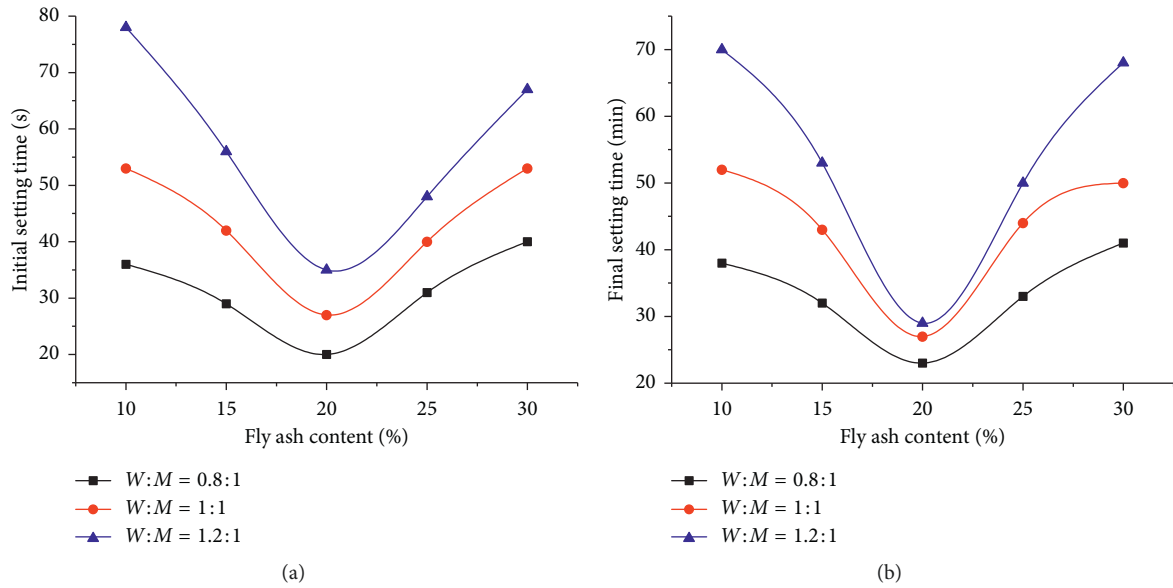


FIGURE 1: The curve of the initial and final settling time with fly ash content.

TABLE 2: Compressive strengths under different ages.

Fly ash content (%)	W:M	Compressive strength (MPa)							
		1 h	5 h	12 h	1 d	3 d	7 d	14 d	28 d
10	0.8:1	0.2	2.3	3.24	4.41	4.87	11.73	13.15	14.71
	1:1	0.06	1.96	3.07	3.96	4.48	10.92	12.62	13.71
	1.2:1	0.03	1.64	2.59	3.62	3.92	10.39	11.35	12.81
15	0.8:1	0.74	2.84	3.48	5.31	7.01	11.58	14.79	16.71
	1:1	0.59	2.49	3.24	5.05	6.71	11.48	14.35	16.32
	1.2:1	0.38	2.18	3.09	4.81	6.41	10.95	12.79	15.52
20	0.8:1	1.05	3.15	4.35	6.62	7.82	14.71	17.52	18.39
	1:1	0.84	2.74	4.09	6.48	7.79	13.96	15.92	18.01
	1.2:1	0.75	2.55	3.88	5.91	7.39	13.36	15.51	17.39
25	0.8:1	0.76	2.86	3.87	5.43	7.13	11.7	14.91	16.83
	1:1	0.55	2.48	3.27	4.97	6.63	11.4	14.27	16.24
	1.2:1	0.33	2.13	2.92	4.76	6.36	10.9	12.74	15.47
30	0.8:1	0.29	2.39	3.81	5.5	7.2	11.77	14.98	16.9
	1:1	0.18	1.98	3.01	4.91	6.57	11.34	14.21	16.18
	1.2:1	0.03	1.68	2.59	4.73	6.33	10.87	12.71	15.44

According to the above analysis, there are two characteristics of the new environmental protection grouting material: (1) early strength; (2) strength. The early strength is high, and the slurry enters into the grouting area of the water-rich sand and cannot be diluted with water. The strength is insensitive to the water content, and it solves the problem that the traditional grouting material has too large fluctuation in the strength of the stone due to the water content. The existence of these two characteristics solves the biggest problem of grouting material in the water-rich sand.

When the fly ash content increases from 10% to 30%, the strength of the grouting stones increases first and then decreases. At the same time, the strength of the new material has also found the corresponding advantages. When the content of fly ash is 20%, the compressive strength of the stone reaches the highest value. Among them, the strength of the stone is 7.79 MPa for 3 d and 18.01 MPa for 28 d. This provides an important basis for subsequent grouting parameters.

3.3. Ratio of Stone. The ratio of stone of the grouting material directly affects the stability of the grouting stone body. Especially under the water-rich sand conditions, whether the material becomes stone in a short time determines whether the material is suitable for grouting reinforcement in the water-rich sand or not. Therefore, for the development of grouting materials adopted to the conditions of water-rich sand, the determination of the ratio of stone should be limited shortly after the initial setting of the slurry. The time of this experimental study was 1 h. The change in the ratio of stone of grouting material with different water content with fly ash content is shown in Figure 2.

It can be seen from the figure that the ratio of stone of new materials decreases with the increase of water content, and it increases first and then decreases with the increase of fly ash content. At the same time, the ratio of stone of the material after 1 hour is generally above 75%. What is important is that the ratio of stone of the material also has the

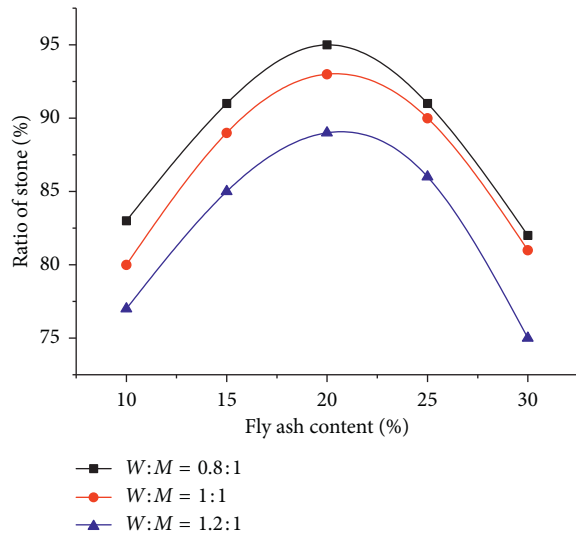


FIGURE 2: The ratio of stone changes with fly ash content.

best advantage. When the fly ash content reaches 20%, the ratio of stone of the material is generally above 90%.

3.4. Pumpability. According to the foregoing analysis, the grouting material has a shorter gel time. When $W:M$ is 0.8:1 and the fly ash content is 20%, the gel time of the slurry is only 20 s. Whether the pump can continue to pump after initial setting of the slurry seriously affects the practicability of the material. In order to study the pumpability of the material after initial setting, a set of pumpability test instruments (Figure 3) was designed and the corresponding pumpability test was given.

The $W:M$ ratio is selected to be 1:1, and the fly ash content is 10%, 20%, and 30%. Then, they were tested for pumpability. The fly ash-cement mixture and the water glass are, respectively, injected into the grouting pipeline, and then pumping is started when the mixed slurry reaches initial setting time. According to the actual situation of the project site, this test considers that the pumping time of the grouting operation is available when the pumping pressure of the mixed slurry pumping pressure is not higher than 2 MPa. The test results are shown in Figure 4.

It can be seen from the figure that the new grouting material can be pumped for a short time after initial setting. And, the strength of the new grouting material increases rapidly after gelation, indicating that the frictional resistance of the material is large. When the additive has the most advantageous material properties (20%), the slurry can be pumped for less than 11 minutes, which seriously affects the practicability of the slurry.

3.5. Water Washout. The original intention of the development of new grouting materials is focused on providing water-rich sand layer. The water in the water-rich sand layer is highly fluid, so the resistance of the material to water erosion is extremely important.

The new type of environmentally friendly grouting material with a $W:M$ ratio of 1:1 and a fly ash content of

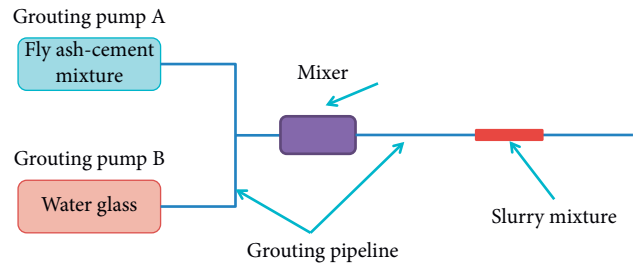


FIGURE 3: Pumpability testing principles.

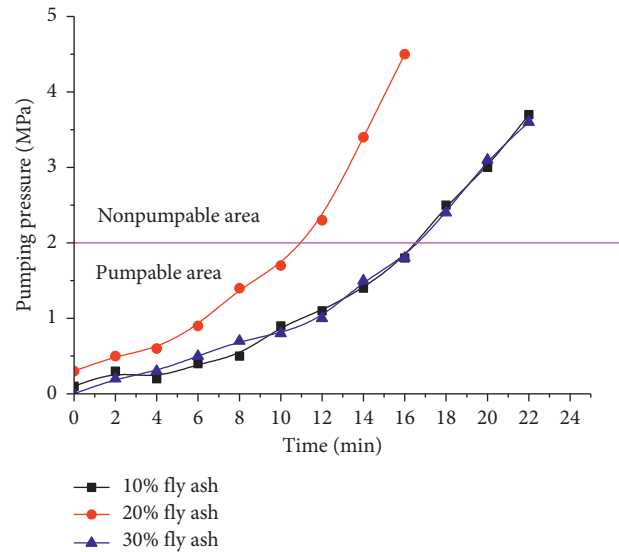


FIGURE 4: Pumping pressure changing with additive dosage curve.

10%, 20%, and 30% was tested for resistance to water washing. After the slurry and the additive are thoroughly mixed and achieve initial solidification, they were put on a marble plate (the marble plate is not polished) and placed in a pipe with different flow rates including a still water environment (the still water environment is the reference for the retention rate of the stone body). After measuring the mass M_0 of the slurry in the still water environment and the mass M_1 of the slurry in the moving water after 30 min, the retention rate of the stone material of the grouting material under the water velocity condition N is evaluated, where $N = M_1/M_0$.

The test results of the retention rate of the slurry are shown in Table 3.

Analysis shows that the new grouting material has a high retention rate in the resistance water washing test and has strong resistance to dispersibility of water. The data show that the retention rate of the slurry stone is more than 85% at a water flow rate of less than 0.6 m/s. At a water flow rate greater than 0.6 m/s, the resistance of the slurry to water erosion is significantly reduced.

3.6. Electron Microscope Scan Analysis. Taking the new grouting material fly ash, whose contents were 10%, 15%, 20%, and 30% and $W:M$ is 1:1, we did standard maintenance after the solidification of stones. The stone bodies of

TABLE 3: Stone retention rate varies with water flow rate.

Fly ash content (%)	Water flow rate (m·s ⁻¹)	M ₀ (g)	M ₁ (g)	N (%)
10	0.2	600	570	95
	0.4	600	540	90
	0.6	600	504	84
	0.8	600	390	65
	1	600	252	42
20	0.2	600	594	99
	0.4	600	564	94
	0.6	600	534	89
	0.8	600	432	72
	1	600	300	50
30	0.2	600	564	94
	0.4	600	540	90
	0.6	600	492	82
	0.8	600	402	67
	1	600	246	41

1 d, 3 d, and 5 d were scanned by electron microscopy. The test results are shown in Figure 5.

Figure 5 shows the following:

- (1) As the curing time increases, the alkali excitation reaction and the hydration reaction proceed more completely, together constituting a slurry stone body. The reaction is complete within 5 days, so fly ash will not affect the subsequent strength of the stone as a whole. The density and strength of the slurry stone body match well. When the fly ash content is 20%, the grouting reinforcement effect is the best.
- (2) The composition of fly ash shows a spatial network or beam-like shape in the stone body, which plays a role in the skeleton. Then, the composition of fly ash forms a spatial network in which the stone body is enveloped. Fly ash has better elasticity than cement stone, which can increase the tensile strength of the material stone and improve the volume stability of the stone body.

4. Field Engineering Application

4.1. Project Overview. The vaults of the tunnels in the Pi-Miao section of Qingdao Metro Line 2 are water-rich sand layers. The exposed water-rich sand is in a state of full water, has poor cementing capacity, and has no self-stabilizing ability. When the waterproof measures are improperly selected, the construction risk is extremely high. The tunnel is one of the two Class I risk sources for the construction of the Qingdao Metro Line 2. The site of tunnel collapse sand is shown in Figure 6.

A large amount of water and large thickness of sand layer are the biggest features of the tunnel. Traditional grouting materials have poor grouting effect for such rich sand layers, and chemical materials are expensive for large-scale grouting and can easily pollute the environment. To solve these problems, the new environmentally friendly water-rich sand grouting material is used to treat the tunnel.

4.2. Field Grouting Test. The following grouting parameters are used for the site of the water-rich sand:

- (1) The grouting adopts the advance-type subsection grouting technology. The length of the grouting section per cycle is 12 m, the excavation is 9 m, and a 3 m slurry area is reserved.
- (2) Based on the actual site engineering performance and new material performance, the material $W : M$ is 1 : 1, the fly ash content is 20%, and the initial setting time is about 25 seconds.
- (3) According to experience, the spacing between holes is set to 1.5 m, and the grouting pressure is set to 1.5 MPa.
- (4) After each round of grouting is completed, excavation is performed after the slurry has been solidified for 5 days.

4.3. Grouting Effect Analysis. The slurry exposed on the tunnel excavation surface is shown in Figure 7. The excavation of the tunnel exposes more slurry, and the overall stability of the excavation surface can ensure the stability of the surrounding rock before the completion of the initial support, which meets the engineering requirements.

5. Discussion

Based on the demand of environmental grouting treatment, this paper proposes a new environmentally friendly sand layer grouting material mainly based on fly ash and cement and supplemented by water glass, which is of great significance to the innovation of grouting material in sand layer. Under the catalysis of fly ash, the material depolymerizes to form oligomeric SiO₄ and AlO₄, and then SiO₄ and AlO₄ in the oligomerization state produce polycondensation reaction to form $[M_x(\text{AlO}_2)_y(\text{SiO}_2)_z \cdot n\text{MOH} \cdot \text{MH}_2\text{O}]$. Therefore, the strength of the material depends mainly on the amount of oligomeric SiO₄ and AlO₄ in the reaction. In addition, the reaction needs to be carried out under a certain amount of activator solution, that is, depending on the amount of fly ash. When the amount of fly ash is small, the amount of activator required for the reaction is small. The reaction depolymerization is weak, and the amount of reactants is small. The degree of polymerization is low, and accordingly, the gel time of the material is long, and the strength of the stone body is also low. As the amount of fly ash is increased, the content of the substance which promotes the reaction such as an activator is increased and the progress of the polymerization reaction is promoted, thereby the compressive strength of the material is increased. The study found that the best blending amount of fly ash is 20%, that is, the polymerization reaction is the most complete at this time. The setting time is the shortest, and the compressive strength of the stone body is the largest. When the fly ash continues to increase, the "passivation effect" of the fly ash reduces the amount of silicate monomer and aluminate monomer required for the polymerization reaction, reducing the material strength.

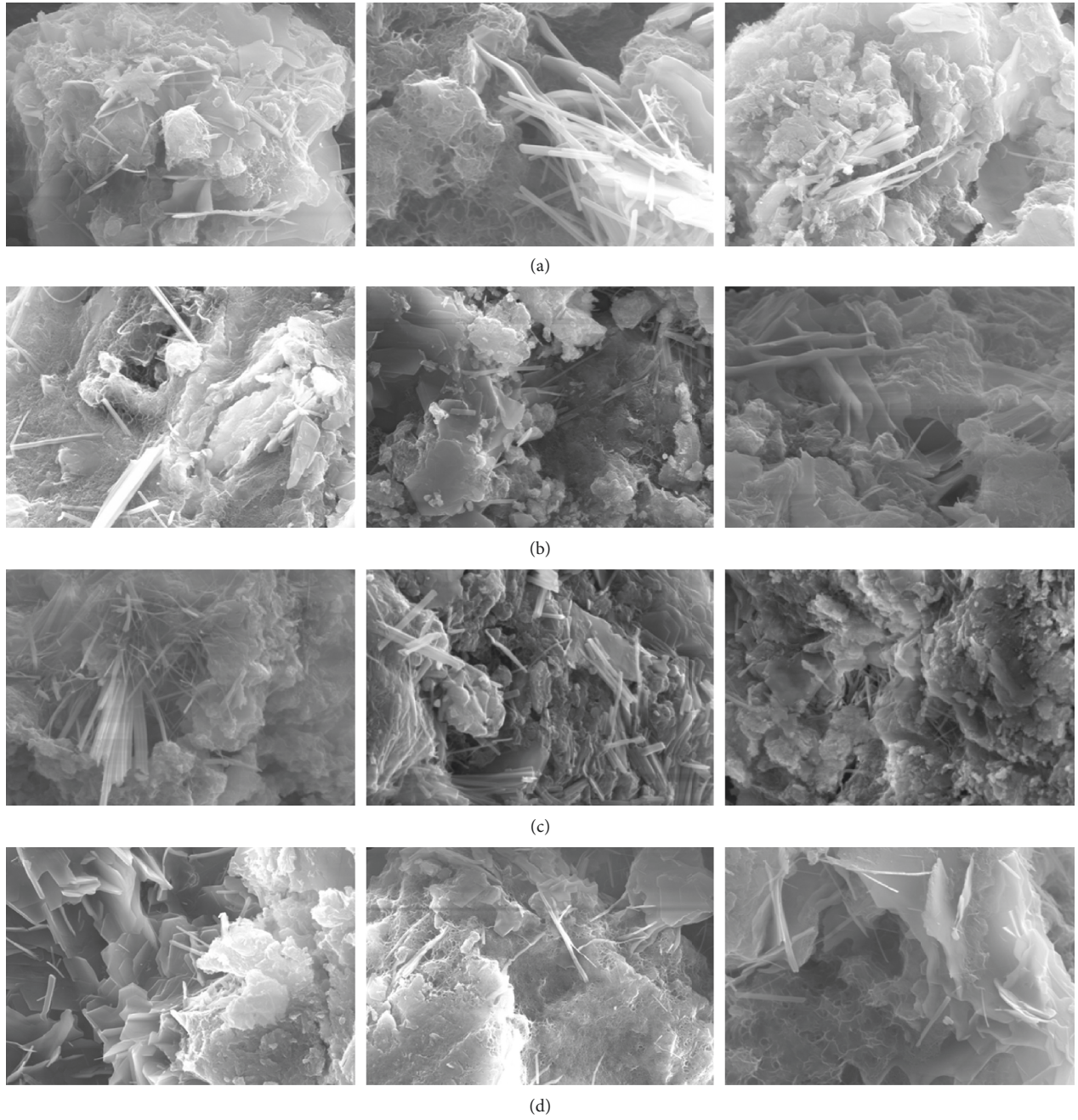


FIGURE 5: Electron microscope scan of slurry stone body 1 d, 3 d, and 5 d with fly ash content: (a) 10%. (b) 15%. (c) 20%. (d) 30%.



FIGURE 6: Site of tunnel collapse sand.

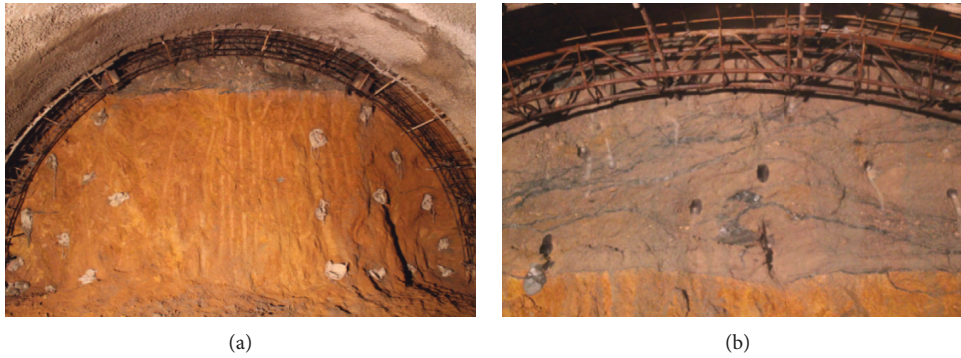


FIGURE 7: Tunnel excavation.

However, since the main component of the grouting material is cement and water glass, the pumpability of the slurry is poor. How to substantially extend the pumpability of the material in the performance of the material is the focus of the next step. At the same time, the material has the commonality of cement-water glass materials—the late strength is low. How to provide the late strength of new materials is the next step in the breakthrough.

6. Conclusion

- (1) The gel time of the new grouting material can be controlled within tens of seconds to several tens of minutes. The gel time is related to the content of fly ash and water content. When the amount of fly ash reaches about 20%, the gelling time is the shortest.
- (2) According to the study of indoor tests, the best ratio of the material was found. When the content of fly ash is 20%, the characteristics of quick setting, early strength, and high ratio of stone formation of the new material are best.
- (3) The new environmentally friendly water-rich sand grouting material has no pollution and meets the requirements of environmental protection. At the same time, the engineering practice proves that the material's practicality can meet the requirements of grouting treatment and it provides a new idea of the water-rich sand grouting treatment.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

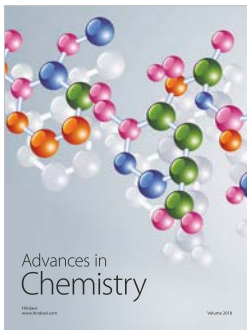
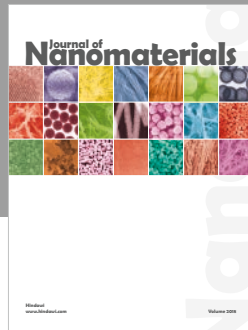
Acknowledgments

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