

Study on Similar Materials for Tunnel Lining and Sand in Water-Rich Scale Model Tests

Jian Chen^{1,*}, Yong Wang^{1,2}, Xiaojing Wang², Zengqi Zhao¹

¹ Beijing University of Technology, Beijing 100124, China

² Beijing Urban Construction Exploration & Surveying Design Research Institute Co., Ltd.,
Beijing 100101, China

*Corresponding author: 563238250@qq.com

Abstract

Addressing the challenge of similar material selection in fluid-solid coupling physical model tests for water-rich tunnels, this study systematically investigates the mix proportion optimization of similar materials for tunnel lining and sand. Through sequential testing, two lining similar material schemes based on gypsum and micro-concrete were compared. The results indicate that gypsum-based materials, although capable of matching scaled mechanical parameters, exhibit poor forming integrity and significant water softening, making them unsuitable for water-involved environments. The optimized micro-concrete proportion demonstrates good compactness and impermeability, with a strength retention rate of approximately 70% after water immersion, rendering it more adaptable to water-rich conditions. For sand similar materials, a practical scaled-down strategy of "parameter substitution" was proposed to maintain soil characteristics while strictly controlling particle gradation to ensure key parameters such as friction angle and permeability coefficient. Ultimately, a mixing scheme of river sand, barite powder, and glass fiber was selected, successfully simulating the density, internal friction angle, and permeability coefficient of the prototype medium-coarse sand layer. This research establishes a design method for similar materials in water-rich fluid-solid coupling model tests, with permeability coefficient and hydro-stability as primary control indices, providing reliable technical references for physical simulation of similar projects.

Keywords

Similar Materials; Mix Proportion Experiment; Model Test; Permeability Coefficient; Tunnel Surrounding Rock.

1. Introduction

With the rapid development of water conveyance projects, cross-river and cross-sea tunnels, and urban underground engineering in water-rich strata in China, water-involved tunnels have become an important type of underground engineering construction. Such projects face complex working conditions including groundwater seepage, which can easily trigger engineering disasters such as water and mud inrush, large deformation of surrounding rock, and lining erosion damage, seriously threatening construction and operational safety. Physical model testing is a core means of revealing the multi-field coupling disaster mechanisms in water-involved tunnels and optimizing engineering prevention and control measures. The scientific selection and precise design of similar materials is a prerequisite and key to ensuring that model test results are highly consistent with engineering reality. Particularly under water-involved conditions, similar materials must not only meet the similarity ratio

requirements of mechanical parameters but also achieve precise control of seepage-related indicators such as permeability coefficient and hydro-stability, whose performance directly determines the reliability of fluid-solid coupling model tests.

Currently, domestic and international scholars have conducted extensive research on similar materials for tunnel engineering model tests, which can be classified into two categories: tunnel lining concrete similar materials and tunnel surrounding rock similar materials. Regarding tunnel lining concrete similar materials: Wang et al. [1], relying on the quasi-static scaled test of the Xianglushan fault-crossing tunnel in the Dianzhong Water Diversion Project, used high-strength gypsum and low-strength gypsum as composite cementing agents, with barite powder and river sand as aggregates, to develop similar materials capable of simulating the elastic-plastic performance and brittle failure mode of C30 concrete through orthogonal tests and secondary refinement tests. Zhao et al. [2] used gypsum as a similar simulation material for tunnel initial support, considering the significant influence of water-gypsum ratio on gypsum mechanical properties, and prepared a series of standard specimens with water-gypsum ratios of 1:1 to 1:1.9. Ren et al. [3] targeted C30 concrete lining structures for deep-buried tunnels, using special gypsum powder as the base material to prepare lining similar materials through optimization of the water-gypsum ratio. Huang et al. [4] used cement and gypsum as cementing materials and sand as aggregate, employing orthogonal tests to optimize proportions, and developed fluid-solid coupling similar materials meeting requirements for elastic modulus, strength, and permeability coefficient.

Regarding surrounding rock similar materials: Wang et al. [1] used river sand as aggregate with high-strength gypsum and lime as composite cementing agents to develop similar materials capable of simulating tensile splitting and oblique shear failure modes of surrounding rock. Hu et al. [5] prepared fluid-solid coupling similar materials based on three-dimensional solid-fluid coupling similarity theory, measuring physical, mechanical, and hydraulic parameters of specimens with different proportions. Li et al. [6] developed three types of specialized similar materials for rock tunnel seepage tests with permeability coefficient control as the core. Yin [7] developed QBIWS fluid-solid coupling similar materials for deep tunnel engineering under high geo-stress and high permeability pressure, using quartz sand, barite powder, and refined iron powder as aggregates, white cement as cementing material, and silicone oil as regulator.

The above research has laid a solid foundation for the design and application of similar materials in tunnel engineering model tests. However, several shortcomings remain that are difficult to fully address the core needs of fluid-solid coupling model tests for water-involved tunnel engineering: (1) Existing surrounding rock similar material research primarily focuses on mechanical parameters such as elastic modulus and compressive strength as core design indices, with insufficient investigation of permeability coefficients under water-rich conditions; (2) Existing lining concrete similar material research mainly focuses on static strength and elastic modulus, generally neglecting the similarity matching of anti-seepage performance and permeability coefficients under water-involved conditions, with scarce research on the evolution of mechanical-seepage characteristics in long-term seepage environments. To address these research gaps, this study systematically investigates the selection and proportioning tests of surrounding rock and lining similar materials under water-involved conditions, forming selection schemes for tunnel lining and soil similar materials applicable to water-involved model tests.

2. Engineering Prototype and Similarity Test

2.1 Engineering Prototype

Based on the engineering background of continuous groundwater level rise in Beijing, a single-line mining-method tunnel of a Beijing subway line was selected as the prototype. The test prototype is a single-line mining-method tunnel section with a burial depth of 15 m. The initial support uses C20 shotcrete with a thickness of 250 mm; the secondary lining uses C40 waterproof concrete with an

impermeability grade of P10 and a thickness of 300 mm. The prototype tunnel passes through Class IV surrounding rock (medium-coarse sand layer).

2.2 Similarity Principle and Parameter Selection

According to the characteristics of the model test, the main purpose is to investigate the mechanical characteristics of tunnel lining structure under the combined action of seepage field and stress field, as groundwater infiltrates through the surrounding soil under groundwater level fluctuation. Due to the complexity of considering the combined action of water and soil, dimensional analysis [8-10] is adopted in the derivation of similarity criteria.

The physical quantities considered in the stress system of the surrounding soil and tunnel structure include: stress (σ), elastic modulus (E), unit weight (γ), geometric dimension (l), Poisson's ratio (μ), strain (ϵ), permeability coefficient (k), density (ρ), cohesion (c), and internal friction angle (ϕ).

According to dimensional analysis, three independent physical quantities are selected: geometric dimension (l), elastic modulus (E), and permeability coefficient (k). Setting $\alpha_l = 30$, $\alpha_E = 30$, $\alpha_k = 5.477$, the similarity constants for each physical quantity are calculated according to the pi theorem, as shown in Table 1.

Table 1. Similarity ratios for model test

Physical Quantity	Symbol	Dimension	Similarity Ratio	Remarks
Geometric length	l	L	1:30	Basic physical quantity
Time	t	T	1:5.477	—
Stress	σ	FL^{-2}	1:30	—
Strain	ϵ	—	1:1	Similarity constant
Elastic modulus	E	FL^{-2}	1:30	Basic physical quantity
Poisson's ratio	μ	—	1:1	Similarity constant
Internal friction angle	ϕ	—	1:1	Similarity constant
Force	F	F	1:27,000	—
Permeability coefficient	k	LT^{-1}	1:5.477	Basic physical quantity
Density	ρ	$FL^{-4}T^2$	1:1	—
Cohesion	c	FL^{-2}	1:30	—
Unit weight	γ	FL^{-3}	1:1	Similarity constant

The prototype and model parameters of tunnel lining and surrounding soil are shown in Tables 2 and 3, respectively.

Table 2. Physical and mechanical parameters of prototype and model for tunnel lining

Tunnel	Lining thickness (m)	Density ($kg \cdot m^{-3}$)	Elastic modulus (GPa)	Compressive strength (MPa)	Poisson's ratio
Prototype	0.55	2500	33	40	0.2
Model	0.018	2500	1.1	1.3	0.2

Table 3. Physical and mechanical parameters of prototype and model for surrounding rock soil

Stratum name	Density (kg·m ⁻³)	Cohesion (kPa)	Elastic modulus (MPa)	Friction angle (°)	Permeability coefficient (m/d)	Permeability coefficient (m/s)
Sand (engineering)	2030	0	30	35	25	2.89*10 ⁻⁴
Sand (simulation)	2030	0	1	35	4.57	5.283*10 ⁻⁵

3. Similar Material Selection for Model Test

3.1 Tunnel Similar Material Selection Scheme

The selection of test similar materials mainly involves the mechanical parameters of mining-method tunnel lining. Since the main research content is the internal force distribution variation of tunnel lining, the selection of tunnel similar materials mainly considers the unit weight, elastic modulus, Poisson's ratio, and compressive strength of the lining. According to relevant literature, two tunnel lining similar material scheme designs were proposed. Referencing other studies [11, 12], eight groups of similar materials were prepared using Scheme 1 and Scheme 2, respectively. Each group included three 100 mm x 100 mm x 100 mm specimens and three 100 mm x 100 mm x 300 mm specimens.

Scheme 1: Concrete similar materials dominated by sand, gypsum, lime, and retarder. According to existing literature [12], this scheme can effectively simulate the scaled elastic modulus and compressive strength. Gypsum, as a substitute material for scaled concrete, has lower strength and is more suitable for scaled models.

Table 4. Tunnel lining similar material selection Scheme 1

No.	Sand	Gypsum	Lime	Retarder	Moisture content
1	2.5	0.6	0.4	3%	18%
2	1.0	0.55	0.45	3%	21%

Scheme 2: Concrete similar materials dominated by cement, fly ash, yellow sand, and lime. According to relevant literature [13], this scheme can better reproduce the compressive strength of tunnel lining, but compared with the required scaled model parameters, the overall values are slightly higher.

Table 5. Tunnel lining similar material selection Scheme 2

No.	Cement	Fly ash	Yellow sand	Lime	Water
1	1 (42.5#)	0.4	5.8	0.6	1.33
2	0.8 (42.5#)	0.6	5.8	0.6	1.33
3	1 (32.5#)	0.4	5.8	0.6	1.33
4 (immersion)	0.6 (32.5#)	0.6	5.8	0.6	1.33
5 (immersion)	0.4 (32.5#)	1	6.3	0.6	1.4
6 (immersion)	0.3 (32.5#)	1	6.3	0.6	1.5
7 (immersion)	1 (32.5#)	0.4	5.8	0.6	1.33

3.2 Soil Similar Material Selection Scheme

Similar materials are generally composed of three types: aggregate, cementing material, and auxiliary materials. The functions and available materials affecting the main parameters of similar soil are as follows:

(1) Aggregate: It forms the basic framework of similar soil, maintaining the shape and stability of the soil body, enabling similar soil to withstand certain external forces, similar to the role of sand grains and gravel in natural soil. It directly affects the overall density of similar soil and is an important factor in regulating density. The pore size and connectivity of the aggregate determine the seepage path and permeability to a certain extent. Available materials include barite powder, quartz powder, iron powder, etc.

(2) Cementing material: It provides cohesion, bonding aggregate particles together to give similar soil a certain bonding strength, resisting external forces that cause particle separation and soil failure. It also regulates the elastic modulus; the elastic properties and cementing degree of cementing materials affect the overall elastic modulus of similar soil. Available materials include gypsum, cement, laundry detergent, water glass, etc.

(3) Auxiliary materials: They regulate specific parameters for certain performance requirements of similar soil. For example, silicone oil can be used to adjust cohesion and improve lubricity; bentonite can also be used to adjust permeability and friction angle. When the basic system composed of aggregate and cementing materials has certain performance deficiencies, auxiliary materials can compensate. Available materials include bentonite, silicone oil, talc powder/glass fiber, etc.

Since structural scaling and soil scaling cannot be achieved simultaneously, equal-proportion reduction of soil will result in the loss of certain soil characteristics. If sand particle size is strictly scaled down proportionally, the applicability problem of particle size scaling will be faced: if ultra-fine powder is used, the soil type will change from "sand" to "silt" or "clay," completely destroying the core characteristics of cohesionless sand ($c \approx 0$) and high permeability. Therefore, soil will use alternative materials that maintain corresponding soil characteristics for model testing.

In the typical soil layers of Beijing, medium-coarse sand is dominated by medium sand with particle size of 0.25-2 mm, with gradation characteristics of uniformity coefficient C_u 2.5-3.5 and curvature coefficient C_c 1.0-3.0. In the experiments, the similar gradation method was used to achieve geometric scaling simulation of the prototype coarse-grained soil particle system. The average particle size proportions of the medium-coarse sand layer before and after scaling are shown in Table 6.

Table 6. Average particle size distribution of medium-coarse sand layer

Particle type	Actual particle size range (mm)	Scaled particle size range (mm)	Proportion (%)
Coarse sand (minor coarse fraction)	$1.0 < d \leq 2.0$	$0.033 < d \leq 0.067$	10
Coarse sand (dominant coarse fraction)	$0.5 < d \leq 1.0$	$0.0167 < d \leq 0.033$	30
Medium sand (core component)	$0.25 < d \leq 0.5$	$0.0083 < d \leq 0.0167$	50
Fine sand (filling particles)	$0.1 < d \leq 0.25$	$0.0033 < d \leq 0.0083$	10
Silt and clay (impurities)	$d \leq 0.1$	$d \leq 0.0033$	≤ 2

Scheme 1: A certain proportion of river sand was used to simulate the sand skeleton, with gradation prepared according to Table 6. To reduce the permeability coefficient, bentonite, loess powder, and glass fiber were added.

Scheme 2: The translated gradation curve of the medium-coarse sand layer was used as the reference. Iron powder and/or barite powder were filled between river sand particles to adjust the fine particle content and density. Combined with layered compaction technology to control density and moisture content, priority was given to ensuring the mechanical properties of friction angle and permeability coefficient, achieving a practical scaling strategy of "parameter substitution" rather than "geometric replication."

4. Results Analysis and Discussion

4.1 Analysis of Tunnel Model Similar Material Schemes

For Scheme 1 dominated by gypsum, two groups of test specimens were prepared using sand, gypsum, and lime as the dominant concrete similar materials, with 3% retarder content and moisture contents of 18% and 21%, respectively. The specific test results are shown in Table 7.

Table 7. Test results of tunnel lining similar material Scheme 1

No.	Sand	Gypsum	Lime	Retarder	Moisture content	Integrity	Compressive strength
1	2.5	0.6	0.4	3%	18%	Edge detachment, insufficient density	<1 MPa
2	1.0	0.55	0.45	3%	21%	Slight edge detachment, insufficient density	<2 MPa

After specimen preparation and seven days of curing in a conventional environment, it was found that the complete forming rate of specimens was low, with all specimens showing partial damage and edge detachment. The density was relatively low with numerous pores. For similar model tests where the model itself is relatively small, the influence of pores is comparable to structural voids in the prototype, making porous proportioned materials unsuitable as tunnel similar materials. Furthermore, uniaxial compression test results showed that the compressive strength of Proportion 1 was less than 1 MPa and Proportion 2 was less than 2 MPa. Subsequent immersion tests revealed that even with waterproof coating, gypsum is prone to water seepage and softening, with this effect being particularly pronounced in low-strength similar materials.

In summary, for water-involved similar model tests, gypsum-dominated materials meet relevant parameter requirements but their softening effect significantly impacts the test, and low-strength gypsum scaled models are prone to damage. Therefore, gypsum is not the primary choice as a concrete similar material, especially for structural integrity and water-involved conditions.

Table 8. Test results of tunnel lining similar material Scheme 2

No.	Cement	Fly ash	Yellow sand	Lime	Water	Compressive strength	Density
1	1 (42.5#)	0.4	5.8	0.6	1.33	10 MPa	2400
2	0.8 (42.5#)	0.6	5.8	0.6	1.33	8-9.5 MPa	2400
3	1 (32.5#)	0.4	5.8	0.6	1.33	6 MPa	2400
4 (immersion)	0.6 (32.5#)	0.6	5.8	0.6	1.33	2.6 MPa	2400
5 (immersion)	0.4 (32.5#)	1	6.3	0.6	1.4	1.8 MPa	2400
6 (immersion)	0.3 (32.5#)	1	6.3	0.6	1.5	0.6 MPa	2400
7 (immersion)	1 (32.5#)	0.4	5.8	0.6	1.33	4.2 MPa	2400

Based on Scheme 1, Scheme 2 was revised using the sequential test method, mainly considering the impermeability, compactness, compressive strength, and model integrity of tunnel similar materials. Micro-concrete was used to simulate the scaled tunnel lining structure, which has significantly improved impermeability and waterproofing compared to gypsum materials. A total of seven groups were designed, including normal and immersed specimens. The specific test results are shown in Table 8.

In the experiments, cement and fly ash were found to be the main factors affecting strength. When cement content was too low and fly ash content too high, specimens also exhibited partial defects such as edge damage. Even when using materials with strong impermeability such as cement, water immersion still had a significant impact on strength, approximately 70%-80% of the original strength, possibly related to the short curing period. Considering that tunnel models require demolding, transportation, and long-term water immersion, certain strength is necessary for guarantee. Test 7 was ultimately selected as the tunnel model proportion.

4.2 Analysis of Soil Similar Material Schemes

For Scheme 1, the use of bentonite/loess powder was investigated. Tests with small amounts of loess powder/bentonite showed permeability coefficients that were too small, exceeding the measurement range by 1-2 orders of magnitude compared to model test requirements. For sand similar material selection tests, it was found that simply translating the relevant gradation curve could meet the simulation requirements for permeability coefficient without adding additional adjustment materials, but the gradation curve translation parameters still required multiple test adjustments. Therefore, Scheme 2 was selected as the primary research focus for soil similar materials.

Table 9. Soil similar material proportioning test results

Group	150-300 mesh	120-150 mesh	80-120 mesh	60-80 mesh	40-60 mesh	20-40 mesh	60-100 mesh Fe	100-150 mesh Fe	60-80 mesh Barite	80-120 mesh Barite	k (m/s)	Density (kg/m ³)
1	10%	30%	30%	20%	10%	—	—	—	—	—	1.59E-5	1750
2	—	10%	30%	30%	20%	10%	—	—	—	—	8.64E-5	1690
3	—	10%	15%	30%	20%	10%	10%	5%	—	—	7.45E-5	1720
4	—	10%	10%	30%	10%	10%	20%	10%	—	—	6.02E-5	1930
5	—	10%	15%	30%	10%	10%	20%	5%	—	—	6.05E-5	1860
6	—	10%	15%	30%	10%	10%	—	—	—	25%	6E-5	1930
7	—	—	10%	35%	20%	10%	—	—	—	25%	2.8E-5	1820
8	—	—	10%	10%	35%	20%	—	—	—	25%	4.34E-5	1830
9	—	10%	—	30%	25%	10%	—	—	—	25%	6.5E-5	1900
10	—	5%	—	35%	25%	10%	—	—	—	25%	6E-5	1930
11	—	10%	30%	—	20%	10%	—	—	30%	—	4.6E-5	1910
12	—	5%	30%	5%	20%	10%	—	—	30%	—	5E-5	1910
13	—	5%	20%	15%	20%	10%	—	—	30%	—	5.4E-5	1910
14	—	5%	20%	15%	20%	10%	—	—	30%	—	5.8E-5	1960
15	—	5%	20%	15%	20%	10%	—	—	30%	—	5.6E-5	1940
16	—	5%	20%	15%	20%	10%	—	—	30%	—	5.3E-5	1930

Scheme 2 employed the sequential test method, initially selecting sand with certain gradation as the test group, then using iron powder and barite powder (which do not react with water and have higher density) to replace sand of corresponding particle sizes, followed by fine-tuning based on actual

particle gradation. Detailed test results are shown in Table 9. The tests were based on the ratio of 120-150 mesh : 80-120 mesh : 60-80 mesh : 40-60 mesh : 20-40 mesh = 1:3:3:2:1, with iron powder and material replacement conducted for 60-100 mesh and 80-120 mesh particles, respectively.

In terms of material selection, iron powder showed the best simulation effect with small errors but at higher cost. Barite powder was lower in cost but required multiple sieving to ensure particle size range. The experiment ultimately adopted 0.1-0.9 mm river sand, 0.18-0.28 mm barite powder, and an appropriate amount of glass fiber. Adding glass fiber can appropriately enhance soil cohesion, thereby preventing ground shrinkage and cracking upon water contact. After multiple groups of constant head tests, the final determined ratio of river sand : barite powder : glass fiber = 0.7 : 0.3 : 0.02 (mass ratio) was established as the similar material for model soil.

5. Conclusion

To address the requirements for water-rich tunnel fluid-solid coupling physical model tests, systematic proportioning tests were conducted to optimize the selection schemes for lining and sand similar materials, establishing a targeted design method. The main conclusions are as follows:

(1) Lining concrete similar material: Anti-water erosion performance is the key selection criterion for water-involved tests. Gypsum-based materials can approximately match scaled mechanical parameters, but their forming integrity is poor, density is low, and particularly the water softening effect is significant, making them unable to meet long-term water-involved working condition requirements. In contrast, micro-concrete-based schemes demonstrate excellent comprehensive performance. By regulating the proportions of cement (binding material) and fly ash (admixture), material strength can be effectively controlled. The final optimized proportion of 32.5# cement : fly ash : yellow sand : lime : water = 1 : 0.4 : 5.8 : 0.6 : 1.33 not only meets similarity ratio requirements for mechanical parameters but also exhibits compact structure and good impermeability, with a strength retention rate of approximately 70% under water immersion conditions, enabling adaptation to water-rich environment model tests.

(2) Sand similar materials: Priority should be given to matching the permeability coefficient and friction angle to avoid gradation distortion. The "parameter substitution" strategy using heavy materials such as barite powder and iron powder to partially replace river sand, and strictly controlling particle gradation to ensure friction angle and permeability is a more effective approach.

(3) Tests showed that adding fine particle materials such as bentonite and loess powder to sand significantly reduces permeability, deviating from target values by 1-2 orders of magnitude. Although iron powder shows more stable simulation effects, based on cost-effectiveness considerations, the final determination of river sand : barite powder : glass fiber = 0.7 : 0.3 : 0.02 (mass ratio), combined with fine sieving processes, successfully simulated the density, internal friction angle, and permeability coefficient of the prototype medium-coarse sand layer.

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