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Geotechnical Model Testing with High-Strength Gypsum Similar Materials: A Case Study on Quartzite-Like Formulations

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Abstract: This paper explores the formulation and optimization of high-strength gypsum-based similar materials for geomechanical model tests, with a specific focus on their application in simulating conditions analogous to quartzite. Employing an orthogonal experimental design, key factors such as quartz sand-to-gypsum ratio, cement-to-gypsum ratio, and barite content were systematically varied. Through a series of indoor experiments, comprehensive assessments of physical and mechanical properties, including density and compressive strength, were conducted for diverse material ratios. The results reveal a broad spectrum of physical and mechanical indicators, aligning with the requisites for model tests across varying similarity ratios. Notably, a high-strength gypsum formulation yielding a uniaxial compressive strength within the precise range of 10~20 MPa was identified, providing valuable insights for researchers engaged in hard rock model tests using similar materials. The study underscores the influential roles of barite content, quartz sand-to-gypsum ratio, and cement-to-gypsum ratio on the density and compressive strength of similar materials. This research contributes essential data for the application of high-strength gypsum in geotechnical model testing, particularly in replicating the mechanical behavior of quartzite.

Keywords: High-Strength Gypsum; Similar Materials; Geomechanical Model Tests; Quartzite; Mechanical parameters.

1. Introduction

Quartzite, a metamorphic rock predominantly comprised of quartz (with a quartz content exceeding 85%), results from the metamorphism of quartz sandstone and siliceous rock. With a compressive strength of up to 400 MPa, it holds paramount significance in construction and mining projects, posing substantial engineering implications. The core of geomechanical model testing involves constructing models that generalize geological prototypes based on similarity theory. These models aim to conduct targeted research reflecting analogous physical and mechanical properties of prototype materials.

Currently, the prevailing choice for model tests involves traditional gypsum-based materials [1]. Different proportions of gypsum, cement, quartz sand, river sand, and additional materials such as paraffin and talc are amalgamated for model composition. This approach offers advantages such as readily available raw materials, operational ease, and a broad range of adjustable strength. Scholars have extensively investigated this methodology. Wu [2] and Shi [3] determined gypsum material ratios meeting diverse mechanical criteria through numerous physical tests, revealing that the quartz sand-to-gypsum ratio and water-cement ratio exerted the most significant influence on uniaxial compressive strength and elastic modulus. Yang, et al. [5] employed gypsum as the primary binder, supplemented with fine sand and cement as modifiers in a large-scale deep mine model test. Ning, et al. [4] utilized iron powder, barite powder, gypsum, and other materials to fabricate rock analogs, conducting relevant bottom friction model tests, demonstrating the efficacy of experiments based on analogous materials. Ren, et al. [6], Huang et al. [7], Ren, et al. [8], among others, conducted model tests for slope engineering using gypsum with different proportions.

A prevalent limitation in the aforementioned studies is the narrow range of similar mechanical parameters of gypsum and its relatively low strength. To replicate hard rocks like quartzite, materials with higher strength and performance are imperative.

Addressing the fundamental requisites for geotechnical model tests on hard rocks (quartzite), this study investigates the mechanical properties of quartzite-like materials using high-strength gypsum materials, aiming to achieve a uniaxial compressive strength of 10~20 MPa. The experimental design employs an orthogonal experimental design method, facilitating multi-factor experiments to seek optimal combinations, thereby reducing workload and testing cycles efficiently. Through indoor experiments with various ratios of similar materials, this paper obtained the physical and mechanical parameters of the analogous materials. Concurrently, mechanical tests were conducted on natural rock samples from the study area to acquire the mechanical properties of quartzite. Based on the measured mechanical parameters of quartzite, the suitability of high-strength gypsum material ratios was discussed. The experimental results provide valuable data references for similar model tests on hard rocks.

2. Similar Materials Raw Materials and Proportions

2.1. Selection of Similar Materials

For this study, high-strength gypsum (GRG) were chosen as the primary simulation materials. These were combined with 160-mesh barite powder, 160-mesh quartz sand, cement, and water. To ensure the similar materials were formed before the initial setting of the gypsum and could be quickly demolded, a retarding agent was added to control the setting time. Drawing from previous experiences, 1% borax was added to water, forming a 1% borax solution [9].

2.2. Experimental Design

If the mixing amount exceeds the water required for the hydration of gypsum, the formed specimens may exhibit a porous structure, leading to a decrease in compactness and a corresponding reduction in various strength indicators. To determine the suitable water-to-gypsum ratio for gypsum in this study, preliminary tests were conducted with pure high-strength gypsum and water. Five sets of preliminary tests were performed with a gradient of 0.25, with water-to-gypsum ratios of 1:2, 1:2.25, 1:2.5, 1:2.75, and 1:3. Following this, with a fixed water content (water-to-gypsum ratio = 1:2.5), quartz sand-to-gypsum ratio (mass of quartz sand / mass of high-strength gypsum), cement-to-gypsum ratio (mass of cement/mass of gypsum), and barite content (mass of barite/mass of aggregate) were set as basic control variables. A three-factor orthogonal experiment was designed with three levels, using the L9 (3) ^{3} orthogonal table for the relevant experiments. The proportion table for the orthogonal experiment is shown in Table 1.

Table 1. Orthogonal design levels of similar materials

Factor		Q:G	C:G	Q:B	The concentration of borax in water is 1%
Level.	1	1:1	0:1	1:1	
	2	1.25:1	0.05:1	1:1.25	
	3	1.5:1	0.1:1	1:1.5	

In the table: W-Water, Q-Quartz sand, G-Gypsum, C-Cement, B-Barite powder

2.3. Preparation of Specimens and Strength Testing

In accordance with the mechanical testing requirements, cylindrical specimens of φ50mm×100mm cylinders were prepared for uniaxial compression tests. The standard specimen preparation process is illustrated in Figure 1:

(1) Raw Material Preparation: Calculate and weigh the quantities of similar materials for each test based on the determined ratios.

(2) Specimen Preparation: Add water to the mixing bucket, then add aggregates and binders in proportion. Mix rapidly until the mixture is uniform. Pour the well-mixed slurry slowly into molds coated with Vaseline on the inner walls. Compact the slurry manually or using a vibrating table when the slurry is about to overflow the mold. Once the mold is filled and compacted, during the initial setting of the specimen, smooth the upper surface of the mold with a steel ruler to ensure a clean and even surface.

(3) Numbering and Curing: After the specimens have hardened to a basic level, demold them and assign identification numbers. Place the prepared specimens in a 40°C high-low-temperature test chamber for curing for 48 hours.

(4) Indoor Testing: After weighing and measuring the prepared specimens, conduct uniaxial compressive strength tests.

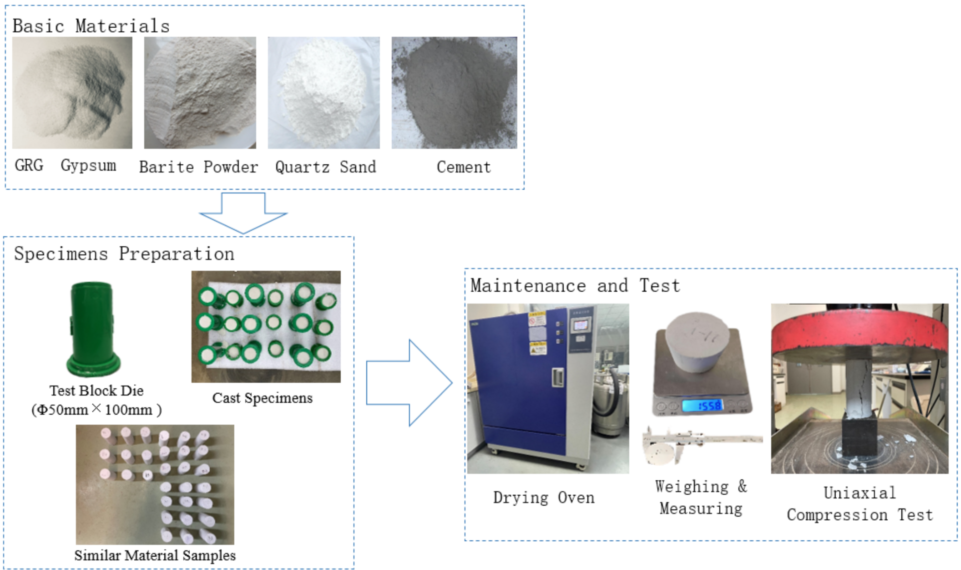


Figure 1. Samples preparation and testing process

3. Analysis of Mechanical Testing on Standard Specimens

Mechanical performance tests were conducted using a computer-controlled pressure testing machine. Before testing, the specimen surface was sanded with sandpaper, and dimensions were measured with precision to 0.01 mm. The specimens were placed in the center of the testing machine's loading seat, aligning the center with the center of the upper and lower pressure plates to ensure uniform loading. The tests were displacement-controlled, pre-loaded with 0.5 kN stress, stabilized, and then loaded at a rate of 0.1 mm/min until failure. Based on the real-time recording of the test status by the testing machine, stress-strain curves were plotted to calculate the uniaxial compressive strength of the specimens.

Extensive ratio tests were conducted, and the results of similar material ratio tests are presented in Table 2. The table includes only the specimens used for result analysis, with backup specimens for each test scheme.

Table 2. Experimental ratio results of similar materials of high-strength gypsum

No	W:G	Q:G	C:G	Q:B	Density g/cm^3	Compressive Strength /MPa
1	1:2				1.82	10.51
2	1:2.25				1.90	15.29
3	1:2. 5				1.99	17.08
4	1:2.75				2.06	25.44
5	1:3				2.17	22.38
6	1:2.5	1:1	0:1	1:1	2.55	17.77
7	1:2.5	1:1	0.05:1	1:1.25	2.60	16.26
8	1:2.5	1:1	0.1:1	1:1.5	2.63	15.98
9	1:2. 5	1.25:1	0:1	1:1.25	2.62	14.52
10	1:2. 5	1.25:1	0.05:1	1:1.5	2.65	13.60
11	1:2. 5	1.25:1	0.1:1	1:1	2.57	12.97
12	1:2.5	1.5:1	0:1	1:1.5	2.74	13.21
13	1:2.5	1.5:1	0.05:1	1:1	2.67	12.94
14	1:2.5	1.5:1	0.1:1	1:1.25	2.70	11.28

(1) By examining the graph depicting the relationship between specimen strength and mixing water amount (Figure 2), it is evident that within the range satisfying the requirements for specimen formation, material strength can be adjusted by varying the mixing water amount. The specimen strength increases with the water-to-gypsum ratio, reaching its peak at 1:2.75, after which it decreases. Simultaneously, during the experimental process, it was observed that excessive mixing water can lead to overflow of the mixed slurry during the forming process, rendering the model material unable to meet design requirements. Conversely, insufficient mixing water prevents the slurry from flowing, resulting in unsuccessful specimen formation. Hence, a water-to-gypsum ratio in the range of 1:2 to 1:2.75 is deemed appropriate during the specific specimen preparation process.

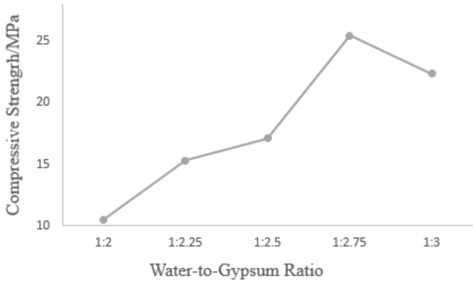


Figure 2. Effect of water-to-gypsum ratio on uniaxial compressive strength

(2) The range and influence patterns of various factors on specimen density are illustrated in table 3 and figure 3. The density of similar materials increases with the increase in barite content, and there is a certain increasing trend with the increase in the cement-to-gypsum ratio.

Table 3. Extremum difference analysis of density (unit: g/cm^3)

No.	Q:G	C:G	Q:B
6	2.58	2.44	2.62
7	2.6	2.45	2.74
8	2.58	2.45	2.86
9	2.56	2.52	2.78
10	2.57	2.51	2.88
11	2.56	2.51	2.65
12	2.67	2.65	2.89
13	2.69	2.66	2.65
14	2.69	2.65	2.76
Range	0.13	0.22	0.27

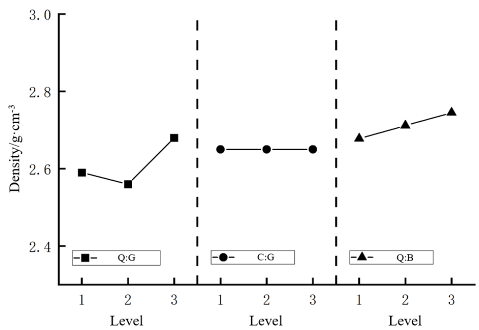


Figure 3. Influence rule of impact factors on density of materials

(3) The range and influence patterns of various factors on specimen compressive strength are presented in Table 4 and Figure 4. The compressive strength of similar materials increases with the increase in the cement-to-gypsum ratio. It decreases with the increase in the quartz sand-to-gypsum ratio, while the relationship with barite content is not pronounced.

Table 4. Extremum difference analysis of compressive strength (unit: MPa)

No.	Q:G	C:G	Q:B
6	22.95	13.65	16.71
7	18.85	14.74	15.2
8	17.84	15.36	14.75
9	14.69	15.14	13.74
10	13.78	14.35	12.68
11	12.87	14.37	11.67
12	13.04	14.04	12.54
13	12.79	14.35	11.68
14	9.86	14.23	9.75
Range	13.087	1.71	6.96

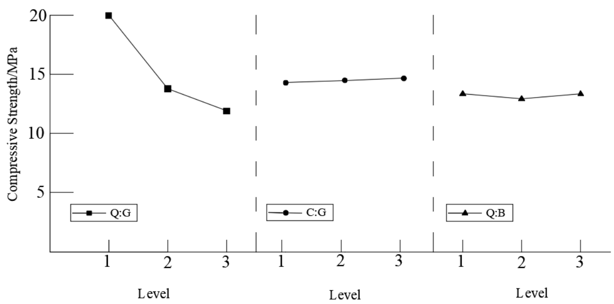
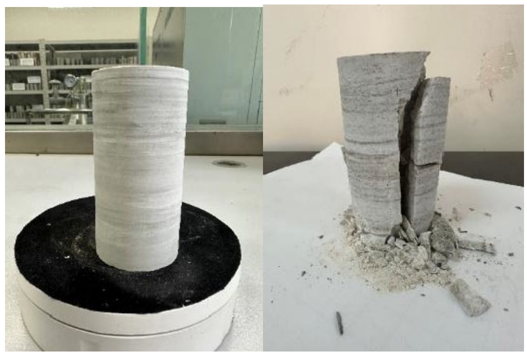


Figure 4. Influence rule of impact factors on compressive strength of materials

(4) Under the same water-to-gypsum ratio, the addition of quartz sand and barite in high-strength gypsum materials reduces specimen strength. This is attributed to the fact that the inclusion of aggregates in the mixed material results in a corresponding decrease in gypsum content, weakening the bonding strength of the mixed material. Therefore, in practical experiments, a singular increase in aggregate content is not advisable. Instead, aggregates should be added in suitable proportions to achieve the goal of enhancing specimen strength.

4. Selection of Quartzite-Like Materials

To provide insights into the application of high-strength gypsum-based similar materials in geomechanical model tests simulating quartzite, typical quartzite specimens from the study area were selected for mechanical testing. The sampling location was a high slope in the southwest, characterized by predominant lithologies such as quartzite and mica quartz schist. Indoor rock mechanics tests were conducted on the obtained rock samples, obtaining physical and mechanical parameters such as density and uniaxial compressive strength for quartzite and mica quartzite. Photographs of the rock samples before and after testing are shown in Figures 5 and 6, and the measured data is presented in Table 5.



(a) Before (b) After

Figure 5. Photographs of the quartzite sample before and after testing

(a) Before (b) After

Figure 6. Photographs of the quartz schist sample before and after testing

Table 5. Rock Mechanical Parameters

No	1-1	1-2	1-3	Average	2-1	2-2	2-3	Average
Rock Type		Quartzite				Quartz schist		
Density g/cm^3	2.613	2.613	2.614	2.613	2.643	2.643	2.644	2.643
Compressive Strength /MPa	184.43	173.51	159.77	172.57	116.81	115.83	117.12	116.58

Using quartzite in the study area as an example: if the similarity ratio is set at 10, then the mix corresponding to specimen number 6 would be deemed appropriate. Using Quartz schist in the study area as an example: if the similarity ratio is set at 10, then the mix corresponding to specimen number 12 would be considered suitable.

Quartzite exhibits significant variations in mechanical strength, with a maximum reaching 400 MPa, while common strengths for quartzite are typically around 160 MPa. Overall, the mechanical strength parameters under the current experimental ratio can meet the requirements for modeling common quartzite. However, to ensure appropriate density, the addition of barite powder is necessary in the mix.

5. Conclusions

In this study on quartzite-like materials, various experimental designs with different ratios of similar materials were conducted, and indoor tests were performed to derive the following conclusions:

(1) Utilizing an orthogonal experimental design method with basic control variables such as quartz sand-to-gypsum ratio (mass of aggregate/binder mass), cement-to-gypsum ratio (mass of cement/mass of gypsum), and barite content (mass of barite/mass of aggregate), a three-factor orthogonal experiment with three levels was executed. Batch weighing and uniaxial compression tests were carried out for each material combination, yielding physical and mechanical performance parameters such as density and compressive strength for different ratios of similar materials.

(2) The experimental results indicate that the physical and mechanical indicators of similar materials exhibit a broad range, capable of meeting the requirements of model tests at different similarity ratios. A high-strength gypsum material ratio, achieving a uniaxial compressive strength within the range of 10~20 MPa, was obtained. This information serves as a valuable reference for research on hard rock model tests using high-strength gypsum materials.

(3) The density of similar materials increases with an increase in barite content. The compressive strength of similar materials decreases with an increase in quartz sand-to-gypsum ratio and increases with an increase in the cement-to-gypsum ratio.

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