Research Article

A Method for Making Transparent Hard Rock-Like Material and Its Application

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At present, a similar material most commonly used in the similarity model experiment of rock blasting is cement mortar. However, it is not transparent, which leads to the problem that the cracks in the model made of cement mortar after the test cannot be observed directly. Therefore, a kind of transparent hard rock-like material that can replace the existing model material to solve the above problem was developed in this study. This transparent hard rock-like material is made of a mixture of rosin saturated solution (RSS), epoxy resin (ER), and curing agent (CA), and its physical and mechanical properties are similar to those of hard rock through relevant tests. In addition, it is found through the blasting model test that the model specimen made of transparent hard rock-like materials has the characteristic of “direct observation” after blasting test, which conforms to the rock blasting fracture mechanism. Hence, it can replace the existing nontransparent model materials to be applied in rock blasting similar model experiment. The results from this study are helpful to the further experimental study of blasting crack propagation in deep rock mass.

1. Introduction

Geomechanical model experiment is a research method of physical and mechanical properties of rock mass media that has been developed earlier, widely used, and visualized. It has been an important means to solve complex engineering problems for a long time [1]. In the geomechanical model experiment, the selection of model material and the mechanical similarity between the selected model material and the prototype material are two key factors for the success of the model experiment. Therefore, researchers have been focusing on the study and development of model materials [2–5]. At present, the model similar materials commonly used in the model test are pure gypsum materials, gypsum mixtures, similar materials with paraffin as binder, similar materials with engine oil as binder, and similar materials with rosin or rosin alcohol solution as binder. Overall, the physical and mechanical properties of these similar materials have been proved to be relatively stable by long-term practical application, and its strength, modulus of elasticity,

and related mechanical parameters will vary greatly with the content of cementing materials. Therefore, they can be used to simulate most rock mass materials from soft rock to hard rock, meeting the experimental requirements under different conditions.

However, because of the opaque materials used in current physical models, the occurrence, expansion, and evolution of cracks in the model body cannot be fully and meticulously observed, and only technologies such as acoustic emission, CT scanning, and borehole photography can be adopted to observe it [6–11]. For example, the three-dimensional image in the model can be obtained by using the computerized tomography (CT) based on X-ray or nuclear magnetic resonance (NMR), so the deformation of the model can be measured. But technologies like CT scanning need very expensive equipment and are limited by many experimental conditions such as the size of the model, which cannot meet all the requirements for the model test. In addition, most of these methods belong to contact, indirect, and local internal observation methods, and the amount of

data obtained from these methods is also very limited, which are not enough to comprehensively and thoroughly analyze some engineering and technical problems under complex conditions.

In order to observe the deformation and fracture of the surface and inside of the model clearly, it is obviously the most effective method to use transparent similar materials instead of opaque similar materials to make the model specimen. Some studies [12–17] have shown that the fracture behavior of transparent materials such as PMMA (poly(methyl methacrylate)) and brittle resin under load are similar to that of hard rock, and they are often used as substitutes for hard rock in the field of research on rock mechanics. But, at present, only the similarity of fracture between transparent materials used to simulate rock with the real rock mass was considered, and the similarity of strength for model experiment was not considered. So, they cannot be directly applied to the similar model experiment to quantitatively analyze the cracks on the surface and damage inside of the model but can be as useful references for the further study of transparent rock-like materials. Therefore, a kind of transparent hard rock-like material was developed in this study based on the previous experimental methods for developing transparent material; meanwhile, it met the requirements for similar model test.

2. Requirements for Making Transparent Hard Rock-Like Material

In this study, the purpose of developing similar material is to make the cracks inside of the model specimen visible after blasting. Therefore, the developed materials must have characteristics of transparency, same or similar mechanical properties with rock, satisfying the similar conditions.

2.1. Transparent. Four phenomena occur: transmission, refraction, absorption, and scattering, when natural light propagates through a medium. According to the four phenomena, substances can be divided into three categories: opaque, translucent, and transparent.

There are some substances like sugar in nature, which their individual crystal itself has transparent nature, but due to the massive aggregation of particles and influence of other impurities, they become opaque. Sometimes natural light passing from a material into another material will also cause the phenomenon of refraction because of the different density of the material.

Therefore, to make the synthetic transparent materials obtain good transparency, it should be ensured that the selected materials must have high transparency and their refractive index should match each other.

2.2. Rock-Like Materials. Rock-like materials means that the mechanical characteristics of materials should be similar to or consistent with those of rock, which mainly include the similarity of stress-strain curves and failure modes of the specimens under uniaxial compression. In addition, similar materials should be brittle in nature, which is the most

typical characteristic of rock materials. Only when these requirements are satisfied, compared with the test results of real rock, can the test results of the model made of similar materials have high reliability, portability, and substitutability.

2.3. Adjustable Strength. In similar systems, the ratio of the same physical quantities is called similarity ratio (or called similarity constant and similarity coefficient), that is, “prototype physical quantity (P)/model physical quantity (M) = similarity ratio (α).” According to the balance equation, geometry equation, physical equation, stress boundary condition, and displacement boundary condition of the prototype and model (process omitted), the similarity relation between various physical quantities of the model test can be obtained as

$$\begin{cases} \alpha_\mu = 1, \\ \alpha_\varepsilon = 1, \\ \alpha_\varphi = 1, \\ \alpha_\delta = \alpha_L, \\ \alpha_X = \alpha_Y = \alpha_Z = \alpha_\gamma, \\ \alpha_\sigma = \alpha_L \cdot \alpha_\gamma, \\ \alpha_{\sigma_c} = \alpha_{\sigma_t} = \alpha_E = \alpha_C = \alpha_\sigma, \\ \alpha_T = \sqrt{\alpha_L}. \end{cases} \quad (1)$$

It can be concluded from the third above formula that the value of stress similarity ratio depends on the geometric similarity ratio and bulk density similarity ratio. Therefore, the stress similarity ratio will change with the change of the geometric similarity ratio and bulk density similarity ratio when the engineering background is changed. The change of the stress similarity ratio will lead to the corresponding change of strength from model materials, in order to make the uniaxial compressive strength (UCS) of model materials conform to the similarity criterion, which requires that the UCS of model materials can be adjusted according to the actual demand.

The subscript p of each physical and mechanical parameter represents the prototype, and the subscript m represents the model.

3. Development Process of Transparent Rock-Like Materials

3.1. Selection of Raw Materials. There are several types of transparent similar materials commonly used by researchers to simulate rocks, including ice [18], PMMA [19–22], and resin materials [23–26], and among which PMMA and resin materials are the most widely used. However, resin materials compared with PMMA have become a hotspot in the development of transparent rock-like materials due to their strong plasticity. Especially in recent years, 3D printing technology has been applied to the research field of rock mechanics, and more and more researchers have developed transparent resin 3D printing materials similar to rocks.

Ju et al. [27] developed a transparent resin material used in 3D printing of real rock to accurately characterize and visualize the complex internal structure and stress distribution of rock. The material is made of photopolymer material Vero Clear as matrix and loose material Fullcure705 as filling crack. The test proved that mechanical properties of the printed model, such as uniaxial compressive strength, elastic modulus, and Poisson's ratio, are close to those of the prototype rock.

Jiang and Zhao [28] used polylactic acid (PLA) as the printing material, and the specimens were constructed with a 3D Touch printer that employs fused deposition modelling (FDM) technology. Unfortunately, their study has demonstrated that the FDM 3D printing with PLA is unsuitable for the direct simulation of rock. It is also suggested that additional studies should focus on the development of an appropriate substitution for the printing material (brittle and stiff).

Zhou and Zhu [29] identified the most suitable 3DP material from five targeted available 3DP materials, i.e., ceramics, gypsum, PMMA, SR20 (acrylic copolymer), and resin (Accura® 60), to simulate brittle and hard rocks. Experimental results indicate that among current 3DP techniques, the resin produced via stereolithography (SLA) is the most suitable 3DP material for mimicking brittle and hard rocks, although its brittleness needs to be improved.

Inspired by previous studies, the transparent hard rock-like materials in this study are still based on resin materials. Considering the requirements of model test, RSS (rosin saturated solution) is added to adjust the strength.

3.2. Introduction to Raw Materials

3.2.1. Epoxy Resin. The appearance of epoxy resin is colorless and highly transparent, which mainly has the following characteristics:

- (1) Excellent mechanical properties: epoxy resin has strong cohesion and dense molecular structure, so its mechanical properties are better than phenolic resin and unsaturated polyester and other general thermosetting resin.
- (2) Easy curing: by choosing a variety of different curing agents, epoxy resin system can almost be cured at 0~180°C temperature range.
- (3) Small curing shrinkage: the reaction of epoxy resin with the curing agent used is carried out by direct addition reaction or ring-opening polymerization of epoxy groups in the resin molecules without water or other volatile by-products being released. Compared with unsaturated polyester resin and phenolic resin, they show low shrinkage during curing, generally 1%~2%.
- (4) Good manufacturability: Epoxy resin curing hardly produces low molecular volatiles, so it can be formed under low pressure or contact.

3.2.2. Curing Agent. Epoxy resin itself is a thermoplastic macromolecule prepolymer, showing viscous liquid or brittle solid. Pure resins are of little use value. Only after the

addition of substances called curing agents for curing reaction to generate three-dimensional crosslinked network structure, insoluble polymer, can it present a series of excellent performance and become useful.

3.2.3. Rosin Saturated Solution. Rosin is a nonvolatile natural resin. The rosin made from turpentine is a transparent and hard brittle solid material, has broken surface like shells, and has glass luster. Rosin has a dense ring structure, which can be added to the epoxy resin system to improve the rigidity of the solidified material and further reduce its bending strength. Since rosin blocks or rosin powders are solid materials that cannot be added directly to the epoxy resin system, they need to be dissolved into a liquid state before the test.

Since the mechanical properties of epoxy resin after curing are greatly affected by the curing agent, colorless transparent epoxy resin #618 and colorless transparent modified curing agent are selected as the basic raw materials according to the requirements of developing transparent hard rock-like similar materials. Meanwhile, the RSS was made of optimal rosin. Figure 1 shows the physical pictures of three raw materials.

3.3. Making Method. Taking the plate model specimen as an example, the detailed making steps are as follows.

3.3.1. Premade Solution. Unlike epoxy resins and curing agents, RSS cannot be purchased directly and need to be made. Firstly, the optimal rosin blocks were broken into powders, which were screened through a 100-mesh screen. Then, 100 mesh of rosin powder was melted into an appropriate amount of anhydrous alcohol solution until the solution reached a saturated state.

3.3.2. Sticking Film in Mold. According to the exploratory test, it was found that pouring the mixed solution directly into the mold would make it difficult to disassemble the mold, so it was necessary to pretreat the mold before pouring. Firstly, a thin layer of Vaseline was applied to the surface of the mold, and then an antistick film was applied to the surface.

3.3.3. Pouring Specimen. Firstly, epoxy resin, curing agent, and RSS were weighed according to the designed experimental proportion and placed in beaker. Then, epoxy resin and curing agent were heated in an oven at 50°C, and RSS was heated in a water bath at 50°C. When all the bubbles in epoxy resin and curing agent were removed, they were mixed and stirred evenly. At this time, the bubbles inevitably appeared again in the mixed solution, and they were still heated in the oven at 50°C until the bubbles were removed. Finally, the RSS from the water bath was taken out and poured into the epoxy resin system. After the mixture was stirred evenly, it was poured into the mold. It is concluded by many experiments that no bubbles will occur as long as the

FIGURE 1: Raw materials for making transparent hard rock-like materials. From left to right: modified curing agent, epoxy resin #618, and RSS.

mixture of three solutions is stirred slowly and uniformly, when the preheated RSS is mixed with the nonbubbled thermal epoxy resin system.

3.3.4. Maintenance and Polishing of Specimen. The mold filled with resin mixture solution was smoothly placed at a constant room temperature for maintenance. After the specimen was fully cured, the mold was removed and the uneven places of the specimen were polished with sandpaper or a small grinder.

4. Physical and Mechanical Properties of Transparent Hard Rock-Like Materials

4.1. Characterization for Transparency. When a substance is irradiated by light, it will produce absorption effect, and at the same time, it has selectivity to absorb light. Different substances have different absorption spectra. When a monochromatic light passes through the solution, its energy will be weakened by absorption, and the degree of the energy weakening is proportional to the concentration of the substance. Based on this principle, a spectrophotometer can be used to measure the transmittance of solutions with different ratios.

Three mixed solutions with different mass ratios (Figure 2) were made for the photometric test. The ratio of them, respectively, is ER:CA:RSS = 1:1:0, ER:CA:RSS = 25:25:1, and ER:CA:RSS = 5:5:1 (epoxy resin: ER; curing agent: CA), i.e., the ratio of RSS mass to total solution mass was 0%, 2%, and 10%.

Assuming that the transmittance of colorless and transparent water is 100%, using this as a reference, the transmittance of mixed solution in Figure 2(a) is 99.9%, and the transmittance of mixed solution in Figure 2(b) is 98.5%, and the transmittance of mixed solution in Figure 2(c) is 97.2%. It can be found that the transmittance of the mixed solution decreases with the increase in the ratio of RSS (the ratio of the mass of RSS to the total mass of the mixed solution). But what is interesting is that we cannot tell with the naked eye if the transmittance of the mixed solution goes down. In fact, the words “0% RSS,” “2% RSS,” and “10% RSS” in Figure 2 were not added to the picture through PS but were printed on the white paper at the bottom of the beaker in the picture. Looking at these words in a mixed solution, it is still clear, which means that

the increase in the ratio of RSS (0–10%) does not affect the transparency of mixed solution much. Thus, it can be concluded that the addition of the colored rosin in the transparent resin system conforms to requirements of development of transparent hard rock-like material for transmittance.

4.2. Testing for Uniaxial Compressive Strength

4.2.1. Experimental Design. According to the preliminary exploratory test, the factors affecting the strength of transparent hard rock-like materials include curing temperature, curing time, and ratio of RSS (the ratio of the mass of RSS to the total mass of the mixed solution). Due to limited space, this study mainly focused on the influence of ratio of RSS on its uniaxial compressive strength (UCS). The mass ratio of ER and CA was kept unchanged, the amount of RSS was changed, and six mixtures with different proportions were designed. In view of the fact that the curing period and production difficulty of the cylindrical specimen are much higher than that of the cube specimen, in order to improve the test efficiency, the preliminary exploratory test is conducted and this test adopted the small cube mold with the size of $20 \times 20 \times 20 \text{ mm}^3$ to make the transparent specimens (as shown in Figure 3).

According to the exploratory test, it is also found that the excessive temperature difference and the constraint of the mold may cause the initial stress in the specimen, thus resulting in the increased dispersion of the strength of the specimen. When the curing time is relatively short, the reaction of solution will be insufficient, which will affect the brittleness of the transparent rock specimen. In this case, the curing temperature of the specimen is set to be $10^\circ\text{C} (\pm 2)$, the reasonable curing time of the transparent rock specimen is 28 days at this temperature, and the demolding time is shortened (demolding immediately after once cured). Detailed test plans are shown in Table 1.

4.2.2. Results and Analysis. Taking the ratio of RSS as the abscissa and UCS of transparent rock specimens as the ordinate, UCS test results of transparent hard rock-like materials with different proportions are shown in Figure 4.

Figure 4 shows that the static UCS of the transparent rock specimens without RSS is much greater than that of the transparent rock specimens with RSS. With the increase of the RSS ratio, the UCS of transparent rock specimens decreases gradually and tends to be stable.

For epoxy resin [30], its strength is related to the cross-linking density formed after curing. The closer the cross-linking network is, the higher the strength of the material is. Conversely, the sparser the cross-linking network is, the lower the strength of the material is. Therefore, the addition of RSS in transparent rock-like materials is likely to reduce the cross-linking density of the epoxy resin system, resulting in the reduction in its strength, that is, the UCS of the material decreases. To verify the above inference, the fracture surfaces of transparent rock specimens containing 0%, 6%,

FIGURE 2: Mixed solutions with different mass ratios: (a) ER:CA:RSS = 1:1:0; (b) ER:CA:RSS = 25:25:1; (c) ER:CA:RSS = 5:5:1.

FIGURE 3: Specimens of transparent rock-like materials with different mass ratios.

TABLE 1: The design for the USC test.

ER:CA:RSS	Ratio of RSS (%)	Curing time (day)	Curing temperature (°C)	The number of specimens
1:1:0	0	28	10 ± 2	6
25:25:1	2	28	10 ± 2	6
25:25:2	4	28	10 ± 2	6
25:25:3	6	28	10 ± 2	6
25:25:4	8	28	10 ± 2	6
5:5:1	10	28	10 ± 2	6

FIGURE 4: UCS of transparent hard rock-like materials with different mass ratios.

and 10% RSS were selected for the scanning electron microscopy (SEM) test, and the photographs were taken as shown in Figure 5.

By analyzing the fracture morphology in Figure 5, it is found that with the increase of RSS content, the fracture surfaces of transparent rock specimens tend to be flat and smooth, the crack trend develops along a straight line, and the stress dispersion phenomenon disappears gradually, showing typical brittle fracture stripes.

Without the addition of RSS (Figure 5(a)), the fracture surface of the transparent rock specimen was very rough and uneven, the failure of which was not carried out in a plane, and obvious faults and gully occurred. Obvious dimple and tear morphology can be observed near the crack line, where a lot of tiny root-like branches are generated. It can be concluded that, when subjected to external forces, these cracks bifurcate to effectively disperse the external stress, thus making the material to absorb more energy in the process of failure.

After the addition of RSS, the fracture surfaces of transparent rock specimens show different degrees of brittleness. When 6% RSS was added (Figure 5(b)), the fracture surface of the transparent rock specimen began to change, which the fracture occurred in the same plane. The fracture surface was relatively rough compared with that of

FIGURE 5: Microscopic fracture morphology of transparent hard rock-like materials. (a) Without RSS. (b) With 6% RSS. (c) With 10% RSS.

transparent rock specimens added 0% RSS, the crack of which became sparse and rough, and the number of stress stripes decreased. When 10% RSS was added (Figure 5(c)), the fracture surface of the transparent rock specimen changed greatly. Except that the fracture still occurred in the same plane, the fracture surface became very smooth, and the stress streaks were sparse and straight without obvious stress dispersion.

According to the analysis of the fracture morphology of transparent rock specimens, it is shown that RSS affects the crosslinking density of the epoxy resin system, thus changing the strength and brittleness of transparent hard rock-like materials. Therefore, by increasing or decreasing the proportion of RSS in the epoxy resin system, the UCS of transparent hard rock-like material can be adjusted, which proves that the developed transparent rock-like materials conform to the requirements of adjustable strength of model similar materials in Section 2.3.

4.3. Testing for Uniaxial Tensile Strength. The uniaxial tensile strength (UTS) of rock is one of the physical and mechanical properties of rocks. It refers to the average tensile stress on the section perpendicular to the tensile force when the rock

specimen is damaged under the action of tensile stress. Due to the difficulties in specimen production and uniaxial tensile loading, the direct tensile test is rarely used, and the indirect tensile test-splitting method is commonly used to determine the tensile strength of rock. Unfortunately, because of the friction caused by the closure of microcracks in rock under pressure, the tensile strength measured by the splitting method is slightly higher than that measured by the direct tensile test.

The Brazilian disc splitting test method, also known as splitting tensile test method, was also used to test UTS of transparent hard rock-like materials in this study. The operation process of the Brazilian disc splitting test is simple and easy: firstly, the disc specimen is transversely placed between the upper and lower indenters of the testing machine, and then the direct loading mode is used to carry out the loading along the radial direction of the specimen. The tensile stress can be calculated according to formula as follows [31]:

$$\sigma_t = -\frac{2P_t}{\pi DL}, \quad (2)$$

where P_t is the failure load, L is the length (thickness) of the specimen, and D is the diameter of the specimen.

The UTS of transparent rock specimens with 0% RSS, 6% RSS, and 10% RSS (ER : CA : RSS = 1 : 1 : 0/25 : 25 : 3/5 : 5 : 1) was tested. Three parallel specimens made by a custom-made mold (Figure 6) were used in each group test, and the size of the specimens was $\phi 50 \text{ mm} \times 25 \text{ mm}$ (Figure 7).

The typical tensile stress-strain curves of transparent rock specimens are obtained by the Brazilian disc splitting test, as shown in Figure 8.

As can be seen from Figure 8, the tensile stress-strain curve of transparent rock specimens can be divided into three stages, namely, OA, AB, and AC. Wherein, the OA stage is caused by the stress concentration produced at the contact site between the upper and lower indenters and the specimen; the AB stage showing better linear characteristics is similar to the straight stage of the uniaxial compression test curve, which is caused by the stress transfer within the specimens; the BC stage, the curve drops sharply without obvious yield stage after reaching the extreme value, and at the same time, the specimen shows obvious splitting cracks that is basically completely connected, which is basically the same as the splitting tensile failure process of rock materials [32].

The tensile mechanical parameters of transparent rock specimens were obtained according to its tensile stress-strain curve, as shown in Table 2.

It can be seen from Table 2 that both UTS and axial strain of transparent rock specimens decrease with the increase of the RSS ratio, the variation law of which is the same as it is of UCS. In addition, the axial strain is all less than 0.02, which means that the compression amount of transparent rock specimens when they reach fracture or failure is less than 1 mm in the splitting tensile test, which is similar to that of the common brittle hard rock (such as sandstone), but it does not match with that of the high-strength hard brittle rock (such as granite) [33]. The average ratio of UTS to UCS of three kinds of transparent rock specimens is 1/13.2, which is obviously within the range of that of rock materials (1/10~1/20). So, it can be concluded that the transparent hard rock-like materials in this study have similar tensile deformation properties with common hard rock materials.

5. Analysing Similarity for Transparent Rock-Like Materials

In order to verify the similarity between transparent hard rock-like material of this study and real rock, the basic mechanical properties and uniaxial compression failure patterns of three kinds of transparent rock specimens with different proportions (ratio of RSS = 0%, 2%, and 10%) were compared and analyzed with the sandstone in the rock roadway at 965 m of Zhujidong Coal Mine in Huainan City (the specimen size is $50 \times 50 \times 50 \text{ mm}^3$).

5.1. Comparison of Basic Mechanical Properties. The stress-strain curves of the sandstone specimen and transparent rock specimens tested by the UCS test are shown in Figure 9.

Generally, the more brittle the material is, the smaller the postpeak strain is for its stress-strain curve. That is to say, the

FIGURE 6: Custom-made mold for making specimens.

FIGURE 7: Transparent rock specimens with 6% RSS.

stress decreases rapidly after the peak value. The stronger the brittleness, the greater the strain ratio before and after the peak value of the stress-strain curve. The material with excellent brittleness even has no strain after the peak value.

It is generally believed that most of the natural rocks are extremely highly brittle and are prone to brittle failure under load, that is, under the condition of no obvious permanent deformation or very small strain deformation, the nature of failure pattern will be generated. For rock materials with a certain degree of elastic strain in the loading process, failure can also be considered as brittle if the inelastic strain is relatively small. In engineering, brittle rock is defined as rock whose total strain does not exceed 5% before failure is considered as brittle rock; otherwise, it is considered as plastic rock. Heard (1963) divided rocks into three categories: brittle rocks with a total strain less than 3%, semi-brittle or brittle plastic rocks with a total strain between 3% and 5%, and plastic rocks with a total strain greater than 5%.

5.1.1. Comparison and Analysis of Stress-Strain Curves. It can be seen from Figure 9(a) that the total strain is less than 2%, and the postpeak strain is small; in other words, the stress decreases quickly after the peak value. In addition, it can be found from Figures 9(b)–9(d) that the total strain is less than 2.25%, which conforms to the classification standard of brittle rock (total strain is less than 3%) by Heard (1963). Moreover, with the increase of ratio of RSS, the postpeak strain decreases and tends to zero, indicating that the larger the ratio of RSS is, the stronger the material brittleness characteristic is.

FIGURE 8: Tensile stress-strain curves of transparent rock specimens. (a) Without RSS. (b) With 6% RSS. (c) With 10% RSS.

TABLE 2: Tensile mechanical parameters of transparent rock specimens.

Ratio of RSS (%)	P_t	σ_t	ε_t	σ_t/σ_c
0	14176	7.22	0.01485	1/13.3
6	733.08	0.373	0.008436	1/14.2
10	508.72	0.259	0.008052	1/12.7

P_t : failure load; σ_t : uniaxial tensile strength (UTS); ε_t : axial strain; σ_t/σ_c : ratio of UTS to UCS.

FIGURE 9: Stress-strain curves of sandstone and transparent rock specimens in the UCS test. (a) Sandstone specimen. (b) Transparent rock specimen without RSS. (c) Transparent rock specimen with 2% RSS. (d) Transparent rock specimen with 10% RSS.

Therefore, the stress-strain variation law of the transparent rock specimen is very similar to that of the sandstone specimen by comparison, which conforms to the characteristics of brittle rock materials that stress decreases rapidly after the peak of the stress-strain curve, and postpeak strain is small.

5.1.2. Comparison and Analysis of Elastic Modulus. Since the stress-strain curves of transparent rock specimens are nonlinear, the elastic modulus depends on the selected reference point in stress-strain curves. The methods for calculating the modulus of elasticity include initial modulus E_I , secant modulus E_s , tangent modulus E_t , and mixed modulus E . The method of the mixed modulus was adopted to calculate in this study, i.e., the slope of the two-point connection in the ascending section of the curve, and UCS corresponding to these two points is 20% and 80% of the peak strength, respectively.

As shown in Table 3, the elastic modulus (mixed modulus) of transparent rock specimens is much smaller than that of sandstone and decreases with the increase of RSS addition. The elastic modulus similarity constant of the model depends on the product of its bulk density similarity constant and geometric similarity constants, which can be obtained from the relationship between elastic modulus similarity constants, stress similarity constants, bulk density similarity constants, and geometric similarity constants ($\alpha_E = \alpha_\sigma = \alpha_L \alpha_v$). Therefore, the elastic modulus of the model material should be adjusted flexibly. In addition, in the similar model test, in order to make the similar model more widely simulate the prototype rock mass on the geometric scale, the similar material is required to have the characteristics of high bulk density, low elastic modulus, and low strength [34]. However, it was proved by the data in Table 3 that the similar materials developed in this study had low elastic modulus, the elastic modulus of which could be adjusted according to the ratio of RSS. Hence, it can meet the requirements of the model test for the elastic modulus when transparent hard rock-like materials were used in the model test.

5.1.3. Comparison and Analysis of Stress-Strain Curves. According to the stress-strain curves of sandstone and transparent rock specimens under uniaxial compression, the process of its deformation and failure can be divided into four stages: microcrack closure or tension crack stage (OA), elastic deformation stage (AB/AB⁰), plastic strengthening stage (B⁰B), and failure stage (BC). Based on the stress-strain curves, the uniaxial compression deformation and failure of sandstone and transparent rock specimens are described in stages:

- (1) Microcrack closure or tension crack stage OA: the curve of this stage is slightly bent upward and nearly elastic, with a slight elastic aftereffect. For the sandstone specimen, this is the result of compaction of rock microcracks; while for transparent rock specimens, this is due to internal tension cracks.

TABLE 3: Elastic modulus for sandstone and transparent rock specimens in the UCS test.

Name	Sandstone	TRS (0% RSS)	TRS (2% RSS)	TRS (10% RSS)
E (MPa)	12740	1802	1176	384

TRS: transparent rock specimen.

- (2) Elastic deformation stage AB/AB⁰: the curve in this stage is very similar to a straight line, and the deformation is almost linear with the load, in line with Hooke's law. The slope of the curve is a constant. For the transparent rock specimen without RSS (0% RSS), some small cracks can be observed on the surface of the specimen at this stage, and a slight crackling sound can be heard. At the same time, a small amount of clastic resin can be seen flying out on the surface of the specimen. In the case of transparent rock specimens with RSS, only a slight crack development sound can be observed at this stage.
- (3) Plastic strengthening stage (growth and confluence of subsequent cracks) B⁰B: this stage only occurs in the transparent rock specimen without RSS (0% RSS). The slope of the curve in this stage decreases gradually to zero with the increase of stress. Point B⁰ is the yield point, which occurs at two-thirds of the peak stress (stress of point B), and its corresponding stress value is the yield limit. In this stage, the microcrack in the resin specimen continued to expand and the length and width of cracks gradually increased, which were integrated with each other to form large cracks. Meanwhile, the morphology of cracks also changed, starting to deviate from the initial direction of crack initiation.
- (4) Failure stage BC: in this stage, the whole specimen became unstable, the stress of which dropped rapidly, and the specimen formed a macroscopic fracture surface. For the sandstone specimen, with the continuous increase of the load, the internal microcracks continued to expand and connect and finally converge to form a macroscopic fracture surface, resulting in the typical splitting failure of the specimen; for transparent rock specimens, with the gradual increase of the load, the specimens emitted a dense crackling sound, and the cracks grew rapidly in the vertical direction until the end face of the specimens, forming a through crack.

In conclusion, the stress-strain curves of transparent rock specimens are similar to that of sandstone under uniaxial compression. However, it should be pointed out that only transparent rock specimens with RSS have the same deformation and failure process as the sandstone specimen under uniaxial compression, while the transparent rock specimen without RSS has plastic strengthening stages (B⁰B). Therefore, it is proved that adding RSS into the epoxy resin system is an effective method to develop materials similar to real rocks.

FIGURE 10: Failure pattern of transparent rock specimens in the UCS test. (a) Without RSS. (b) With 2% RSS. (c) With 10% RSS.

5.2. Comparison and Analysis for Failure Patterns. The failure pattern of uniaxial compression is a necessary factor to test whether the transparent hard rock-like material was developed successfully in this study. Generally, there are three failure patterns of rock specimens under uniaxial compressive load: (a) X-shaped conjugate inclined shear failure, (b) single inclined shear failure, and (c) tensile failure [35].

The failure of transparent rock specimens under uniaxial compression is shown in Figure 10.

From Figure 10, it can be seen that the macroscopic fracture surfaces of transparent rock specimens with different proportions are all in the form of direct splitting from top to bottom, which can be judged as tensile failure. This means that the transverse tensile stress generated in the transparent rock specimen under the action of axial compressive stress exceeds the tensile limit of the specimen. Tensile failure belongs to brittle fracture of rock. Therefore, it can be considered that the transparent rock-like materials

developed in this study have the similar crushing failure pattern to the real rock.

6. Application of Transparent Hard Rock-Like Materials

6.1. Test Design. In order to test the application effect of transparent hard rock-like material in the blasting model test, according to the specimen production method in Section 3.3, a flat specimen with a ratio of ER : CA : RSS = 1 : 1 : 0 was made in the laboratory, the size of which is $300 \times 300 \times 20 \text{ mm}^3$. The basic physical parameters are shown in Table 4. In view of the small amount of explosives used in the model test, a relatively safe and stable small detonator was selected as the explosive in this test, and its main component was DDNP (Table 5). The charge hole was located in the center of the specimen with a radius of 5 mm, the two ends of which were bonded with 1 mm thick plastic

TABLE 4: Physical and mechanical parameters of transparent hard rock-like material.

Density ($\text{kg}\cdot\text{m}^{-3}$)	Compressional wave velocity (m/s)	Modulus of elasticity (MPa)	Poisson's ratio	Compressive strength (MPa)	Tensile strength (MPa)
1200	2423	1802	0.29	96	7.22

TABLE 5: Explosive physical parameters of the special small detonator.

Geometric dimension (mm)		Main ingredients	Explosive charge (g)	Density ($\text{kg}\cdot\text{m}^{-3}$)	Detonation velocity (m/s)
Length	Diameter				
30	6	DDNP	0.3	1500	6600

DDNP: dinitrodiazophenol, molecular formula: $\text{C}_6\text{H}_2\text{N}_4\text{O}_5$.

discs for fixing the special small detonator. The detailed charging structure is shown in Figure 11:

6.2. Results and Analysis. The effect of the model specimen made of transparent hard rock-like materials after blasting is shown in Figure 12.

According to the existing explosion theory [36, 37], after explosion of explosives embedded in infinite rocks, different damage zones from near to far with charge as the center will be formed in rocks, which are called crushing zone, fissure zone, and elastic vibration zone in turn (Figure 13).

As can be seen from Figure 13, the characteristics of blasting fracture observed directly after blasting of transparent model specimens were very similar to those observed in real rocks, which can be divided into crushing zone (R_1), fissure zone (R_2), and elastic vibration zone (beyond R_2). Therefore, according to the mechanism of rock blasting fracture, the failure process of transparent model specimens under blasting load can be inferred as follows: firstly, the detonation waves acted on the transparent rock wall around the detonator, which generated the shock wave in the specimen and quickly attenuated to stress waves. Shock waves caused “crushing” in the transparent rock near the detonator, and stress waves caused radial fractures in the transparent rock outside the crushed zone. Subsequently, the detonation gas products continue to compress the transparent rock crushed by the shock wave, and the detonation gas “wedges” into the cracks generated by the stress wave so that it continues to extend and further open.

Since the cracks formed by the explosion in the transparent model specimen are directly visible, the model specimen was divided into eight equal parts on average, and the diameters of the crushing circle and fissure circle in each part were measured, respectively, with a ruler. The results were summarized in Table 6.

On the contrary, the theoretical values of crushing circle and fissure circle radius in the model test can be calculated according to the formula derived by Dai [38, 39]. The physical parameters of explosive explosion and transparent rock-like materials (as shown in Table 7) were plugged into this formula for calculating the radius of the crushing circle and fissure circle, and the results were as follows:

FIGURE 11: Charging structure diagram of the transparent model specimen.

FIGURE 12: Transparent model specimen after explosion.

$$R_1 = \left(\frac{\rho_0 D^2 n k^{-2\gamma} l_e B}{8\sqrt{2} \sigma_{cd}} \right)^{1/a} r_b. \quad (3)$$

Then, $R_1 = 8.35$ mm.

$$R_2 = \left(\frac{\sigma_R B}{\sqrt{2} \sigma_{td}} \right)^{1/\beta} \left(\frac{\rho_0 D^2 n k^{-2\gamma} l_e B}{8\sqrt{2} \sigma_{cd}} \right)^{1/a} r_b. \quad (4)$$

Then, $R_2 = 52.55$ mm.

It is found that the theoretical value is very close to the experimental value by comparison with each other, but there is still error between them. This may be due to the poor plugging on the hole of the test, which leads to the leakage of explosive gas, so the fracture area is smaller than that of calculated. According to Hanukayev's research [37], the radius of the crushing circle formed after explosion of

FIGURE 13: The schematic of rock blasting. O: charge; d_0 : charging diameter; r_1 : crushing zone; r_2 : fissure zone.

TABLE 6: The radius of the crushing zone and fissure zone measured in the transparent model specimen.

Name\measuring point (mm)	1	2	3	4	5	6	7	8	Average
R_1	10	9.5	8.9	8.2	8.8	10	9.5	9.2	9.3
R_2	43.5	42.1	47.5	52	51	49	46.8	42	46.7

TABLE 7: The values of parameters plugged into the formula.

ρ_O (kg/m ³)	D (m/s)	n	k	γ	l_e	B
1500	6600	10	1.67	3	1	1.616509
σ_{cd} (MPa)	α	r_b (mm)	σ_R	σ_{th} (MPa)	β	μ_d
164.16	2.302083	4.8	160.6573	7.22	1.697917	0.232

explosive embedded in rock is 2~3 times of the radius of charge and 5~10 times of the radius of the fissure circle. Therefore, it is considered that the theoretical values are basically in agreement with the test results, and it is feasible for the transparent rock-like material to be used as model material for the blasting test.

7. Conclusions

In this study, transparent hard rock-like material was developed by using rosin saturated solution (RSS), epoxy resin (ER), and curing agent (CA) as raw materials. Its basic physical and mechanical parameters were tested, and its applicability in blasting model test was verified. The transparent rock similar material made according to the mass ratio and method described in this study has the advantages of simple operation, abundant material sources, and low cost and will not produce toxic and harmful gases in the process of production, which can be used in general laboratories.

The experimental results showed that the transmittance of this similar material was greater than 95%; its UCS, UTS, and elastic modulus could be adjusted according to the proportion of RSS (saturated rosin solution); and its static uniaxial compression stress-strain curve and macroscopic fracture model were similar to those of real rock. It was also concluded from the model test results that the model specimen after detonation had better effect for “direct

observation”; the length of the crack measured by a ruler directly on the model after detonation was in agreement with the results calculated by using the formulas.

Compared with nontransparent hard rock-like materials, the transparent hard rock-like material had great advantages and could replace the existing nontransparent hard rock-like materials for the model test. However, the materials in this study do not have the characteristics of discontinuity and anisotropy of the natural rock, which would have a significant impact on failure behavior of rock mass under pressure. Therefore, additional studies should focus on the development of an anisotropic transparent hard rock-like material by combining with 3D printing technology.

Nomenclature

α :	Similarity ratio
L :	Length
μ :	Poisson's ratio
γ :	Bulk density
σ_t :	Tensile strength
ε :	Strain
φ :	Angle of internal friction
δ :	Displacement
E :	Modulus of elasticity
σ :	Stress
σ_c :	Compressive strength

X, Y	Volume forces
Z	
C	Cohesion
T	Time
ρ_O	Density of explosive (kg/m^3)
D	Detonation velocity of explosive (m/s)
γ	Expansion adiabatic index of detonation products, generally $\gamma = 3$
μ_d	Dynamic Poisson's ratio of rocks, $\mu_d = 0.8\mu$; μ is static Poisson's ratio of rocks
σ_R	Radial stress on the interface between crushing circle and fissure circle (MPa); $\sigma_R = \sigma_r _{r=R_1} = \sqrt{2}\sigma_{cd}/B$
k	K is the radial uncoupling coefficient of charge, $K = d_b/d_c$; d_b and d_c are the radius of borehole and charge, respectively (mm)
B	$B = [(1+b)^2 + (1+b^2) - 2\mu_d(1-\mu_d)(1-b)^2]^{1/2}$; b is the lateral stress coefficient, $b = \mu_d/1 - \mu_d$
r_b	Blasthole radius (mm)
l_e	Axial coefficient of charge; $l_e = 1$ represents axial air-free column
β	Stress wave attenuation index, $\beta = 2 - \mu_d/1 - \mu_d$
n	Coefficient of pressure increase when explosive product expands and collides with the borehole wall, generally $n = 10$
σ_{td}	Uniaxial dynamic tensile strength of rock (MPa), $\sigma_{td} = \sigma_t$; σ_t is the uniaxial static tensile strength of rock (MPa)
α	Load propagation attenuation index, $\alpha = 2 \pm \mu_d/1 - \mu_d$; signs of positive and negative correspond to the shock wave zone and stress wave zone, respectively
σ_{cd}	Uniaxial dynamic compressive strength of rock (MPa), $\sigma_{cd} = \sigma_c \dot{\epsilon}^{1/3}$; σ_c is the uniaxial static compressive strength of rock (MPa); $\dot{\epsilon}$ is the loading strain rate (s^{-1}). In engineering blasting, $\dot{\epsilon}$ of rock is between 100 and 104 s^{-1} [40]; in this study, $\dot{\epsilon}$ is 7 s^{-1} .

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

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

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