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Preparation Method of Similar Materials for the Progressive Disintegration of Red-Bedded Soft Rock Based on Diagenesis Simulation

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Abstract: Solid waste formed during the excavation of soft red stratum rock is often encountered in engineering practice. However, its reuse has been limited because it often shows a gradual degradation mechanism during water–rock interactions. Similarity simulation experiments of geotechnical materials have been developed to be environmentally friendly; however, their application in soft rock mechanics is still limited. Based on these limitations, this study aims to prepare red-bedded soft rock-like materials by referring to the diagenetic process of sedimentary rocks using low-melting-point glass powder (STGP) and high-temperature and vertical stress to accurately simulate the progressive disintegration properties of red-bedded soft rock. For this purpose, a series of laboratory tests were conducted to verify the function of STGP in the embedment of skeleton particles of soft rock as a cement material for resisting the dry–wet cycle. Micro-scanning electron microscopy, disintegration experiments with dry–wet cycles, and basic physical and mechanical property tests were conducted for the synthetic red soft rock-like material. Finally, the synthetic and natural materials were compared based on their density, microstructure, disintegration breakage, and uniaxial compression mechanical properties. The results showed that adding STGP promoted embedded solidification between aggregate particles. The simulated material exhibited the same characteristics of gradual disintegration breakage as natural red-bedded soft rock. Meanwhile, the basic physical and mechanical properties were in substantial agreement when the STGP content was 0.5~2%.

Keywords: solid waste; red-bedded soft rock; disintegrate; similar materials preparation

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1. Introduction

Red beds are widely distributed across China and tend to exhibit progressive disintegration [1–3], i.e., the disintegration of a rock mass in contact with water does not occur immediately but rather gradually over time through cycles of wet and dry conditions until it reaches its smallest particle size. Such gradual disintegration indicates long-term variability, which is challenging in stabilizing in aqueous environments. Consequently, red-bedded soft rocks are not easily utilized as foundations, fill materials, or raw materials for building material manufacturing. As a result, engineering construction in red-bedded areas can be expensive, and waste reuse is difficult, necessitating further research [4–6].

Similar materials are often employed in indoor experiments to facilitate research in rock science and engineering. Developing similar materials that can simulate the progressive disintegration characteristics of red-bedded soft rocks advances the study of the interaction between rocks and water with sensitive hydrological properties and promotes the use of soft rocks in the red layer.

The majority of current studies focusing on rock-like materials employ barite powder [7–9], sand [9–12], and iron powder [9,11] as primary aggregates. Gypsum [9–12], clay minerals [7,10], cement [10,11], and rosin alcohol solution [9,12] are commonly utilized as binding materials, with aggregates and binders combined to prepare rock-like materials. Alterations in the type, gradation, and strength of these aggregates and binding materials facilitate the preparation of materials with diverse analogous ratios to natural rocks, as determined through physical and mechanical parameters, such as the strength, elastic modulus, and density. To address the issue of producing materials with analogous hydrological characteristics, X.D. et al. [13] used bentonite, quartz sand, barite powder, rosin alcohol solution, and gypsum as source materials to prepare similar materials for swelling rocks. They then analyzed the disintegration behavior of these materials with varying ratios as they absorbed water and swelled. C.Z. et al. [14] created a material to imitate the eventual disintegration of soft rock, achieved by employing natural red-bed soft rock powder as the aggregate, sodium silicate as the cementing agent, and sodium dihydrogen phosphate as the curing agent. To date, none of the aforementioned studies have successfully prepared similar materials that can realistically replicate the gradual disintegration behavior exhibited by soft rocks because the strength and hydrological properties of these materials are entirely dependent on the cementing material. When the cementing material is insoluble in water, the resulting material exhibits no disintegration characteristics when immersed. Conversely, when the cementing material is soluble in water, similar materials disintegrate immediately upon immersion and cannot replicate the gradual disintegration behaviors observed in red-bedded soft rocks within a water environment, thus highlighting the significant challenge in generating comparable materials with progressive disintegration characteristics solely using binder materials and underscoring the need for new and innovative approaches.

Red-bedded soft rock is a type of sedimentary rock that forms gradually over an extended period of geological history. While the temperature and pressure conditions during their formation are not sufficiently high to cause metamorphism, the sediment particles are subjected to geological processes such as edge-breaking and recrystallization under prolonged stratigraphic pressure. As a result, sediment particles undergo tightly embedded solidification [15–17]. Therefore, the strength of natural soft rocks is not solely derived from the binding action of the cementing material but also from the embedded solidification between the particles themselves. This embedded solidification does not disintegrate immediately upon contact with water during soft rock immersion but instead requires several dry–wet cycles before it gradually loosens and eventually disintegrates. To prepare similar materials with progressive disintegration, it may be possible to simulate the partial diagenesis of soft rocks during their geological history and promote particle embedding within comparable materials.

This study aims to explore a technical approach for preparing similar materials with progressive disintegration characteristics that mimic red-bedded soft rock by analyzing their disintegration mechanisms. To achieve this goal, first, the mechanism of progressive disintegration and cementation formation in red-bedded soft rock is investigated. Subsequently, a suitable method is explored to hasten the development of embedded solidification between aggregates and develop corresponding sample preparation devices to prepare specimens under temperature and pressure conditions that simulate sedimentary rock aggregates without significant metamorphism and prepare similar materials with strong embedded solidification to simulate the progressive disintegration behavior of red-bedded soft rocks. The production of such materials and devices will provide valuable technical support for developing indoor model experiments to study the progressive disintegration characteristics of red-bedded soft rock.

2. Mechanisms of the Progressive Disintegration of Red-Bedded Soft Rock

In this study, the microstructural electron microscopy (SEM) results of a natural red-bedded soft rock sample (muddy siltstone) from Guang'an, Sichuan are shown in Figure 1, the basic physical and mechanical properties of the rock sample are shown in Table 1, the mineralogical composition of the XRD test is shown in Table 2, and the results of the particle size analysis are shown in Table 3.

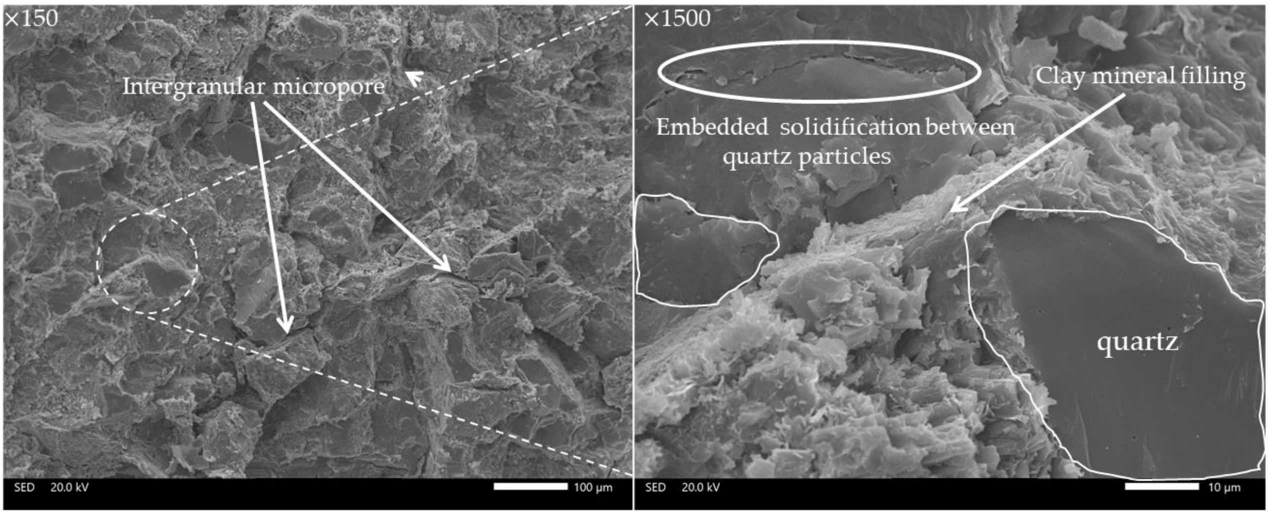


Figure 1. Natural red-bedded soft rock photos from SEM.

Table 1. Physical and mechanical parameters of natural red-bedded soft rock.

$\rho/(g \cdot cm^{-3})$	$\omega/(\%)$	$\sigma_c/(MPa)$	E/(MPa)
2.14	16.2	10.41	372.51

Table 2. XRD analysis results of natural red-bedded soft rock.

Mineral Composition	Quartz	Feldspar	Mica	Hematite	Montmorillonite	Chlorite
Mass ratio/(%)	29.5	9.6	9.1	2.7	42.7	6.4

Table 3. Results of particle size analysis of natural red-bedded soft rock.

Grain size/(μm)	~15.63	~74.33	~148.7	~210.2	~353.6
Cumulative Percentage/(%)	51.42	69.32	81.18	89.29	100

As shown in Figure 1: the primary mineral quartz sand particles in the rock are closely arranged, form an embedded solidification between the particles, and are closely wrapped by clay minerals. A large amount of microporosity is also visible in the natural rock samples, and the microporosity can absorb water after drying. The compositional analysis in Table 2 shows that the cement in the rocks is mainly muddy cement, which absorbs water, swells, and loses strength easily.

Previous studies have identified three principal causes of red-bedded soft rock disintegration [18–21]:

1. Cement dissolution resulting in the detachment of solid particles.
2. Non-uniform solid particle expansion due to water absorption after immersion.
3. Pneumatic cracking of soft rocks occurs as water enters the pores of the rock and compresses the air in the sealed pores after immersion.

The mechanisms and processes of these three modes of disintegration are not identical:

4. Cement dissolution, which undermines the mineral cementation of the rock, progresses more rapidly, and remains dissolved as long as the solution does not reach the saturation state of the corresponding ion. Thus, adequate water immersion does not lead to progressive disintegration via cement dissolution.
5. Non-uniform swelling of particles by immersion in water disrupts cementation and mineral particle bonding; however, a single non-uniform swelling event only slightly

opens the cementation; therefore, multiple iterations of non-uniform swelling are required for cracking to occur, necessitating repeated dry soaking to break tightly cemented bonds.

6. Gas-induced collapse, illustrated in Figure 2, is the primary contributor to red-bedded soft rock disintegration.

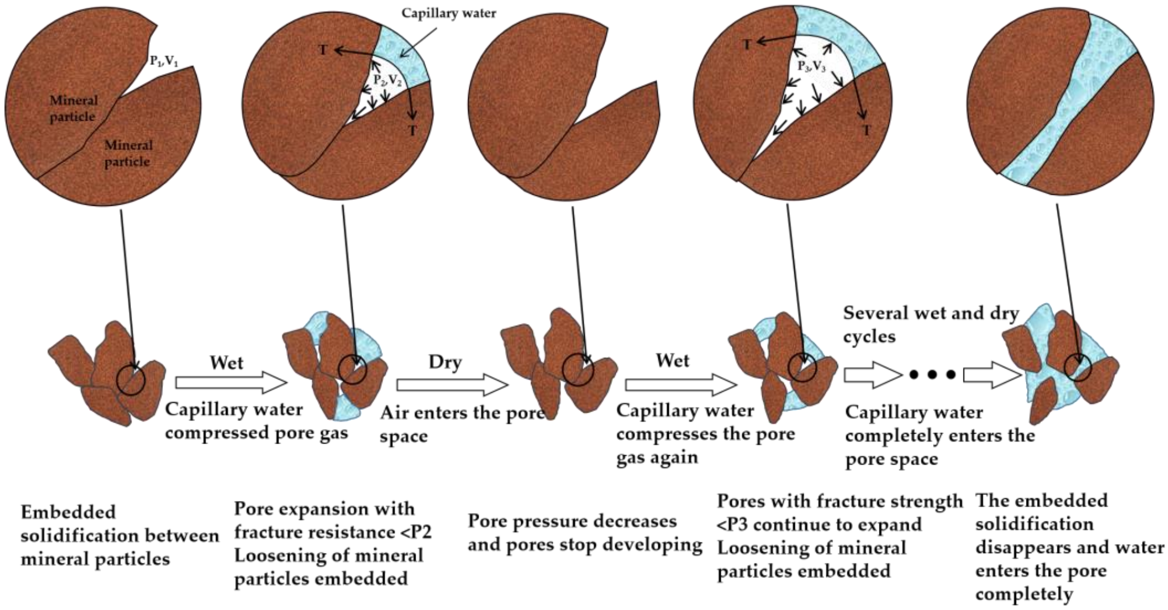


Figure 2. Air pressure fracturing of red-bedded soft rock with dry–wet cycles.

The disintegration process of soft rock, as depicted in Figure 2, can be described as follows. After a soft rock containing micropores is dried and immersed in water, the pore water penetrates deep into the pores of the rock under capillary forces (surface tension). The original air in the pores is compressed, resulting in a decrease in volume from V_1 to V_2 and an increase in pore pressure from P_1 to P_2, causing pores with a crack strength less than P_2 to expand and mineral particles to loosen. As the pores continue to expand, the volume of available air increases, leading to a decrease in the air pressure and ultimately stopping the expansion process. This cycle is repeated in the subsequent drying and leaching stages, resulting in the progressive disintegration of the rock from particle loosening to unraveling.

The strength of red-bedded soft rock arises from two primary factors:

7. Cementation between mineral grains.
8. Embedded solidification. The disintegration of clay cement is the primary cause of soft rock disintegration. However, the disintegration of many red-bed soft rocks does not occur instantaneously; instead, it occurs progressively with dry–wet cycles, resulting in progressive disintegration.

Therefore, embedded solidification in red-bedded soft rock is the primary reason for progressive disintegration upon water immersion. Previous studies used different cements to prepare similar materials, which can only impart cementing strength but not embedded strength. Consequently, the resulting materials either disintegrate immediately or do not disintegrate, failing to reflect the progressive nature of disintegration.

The primary challenge is the inability to simulate long geological time scales under laboratory conditions. Therefore, it is necessary to accelerate the rheology and recrystallization of similar particles to mimic the pressure-soluble and growing effects of the particle edges in natural rocks. Through extensive exploratory experiments, ultra-low-temperature silica–titanium transparent glass powder (STGP) was identified as an effective material. STGP is an inorganic, fixed, hard particle composed of SiO_2, TiO_2, and other materials that melts and crystallizes at high temperatures. STGP is chemically stable and begins to melt at 450 °C. In this study, STGP was mixed with quartz sand aggregate (with a melting point of 1000 °C). Upon heating above 450 °C, STGP gradually fuses and attaches to the surface of the quartz sand aggregate, increasing its volume and allowing the angles of the particles to grow into the pores, prompting the formation of an embedded solidification between the aggregate particles.

3. Sample Preparation

3.1. Sample Materials and Sample Preparation Systems

The careful selection of materials is necessary to ensure similarity between similar specimens and natural rock samples in terms of basic physical and mechanical properties as well as disintegration properties. When considering the three mechanisms of disintegration and the destruction of red-bedded soft rocks, the materials chosen must adhere to the following principles: first, they should possess the fundamental characteristics of soft rocks; second, they should partially dissolve in water; third, they should exhibit a certain degree of water absorption and swelling characteristics; fourth, they should be capable of resisting water inlay and gradually deteriorate under multiple dry–wet cycles.

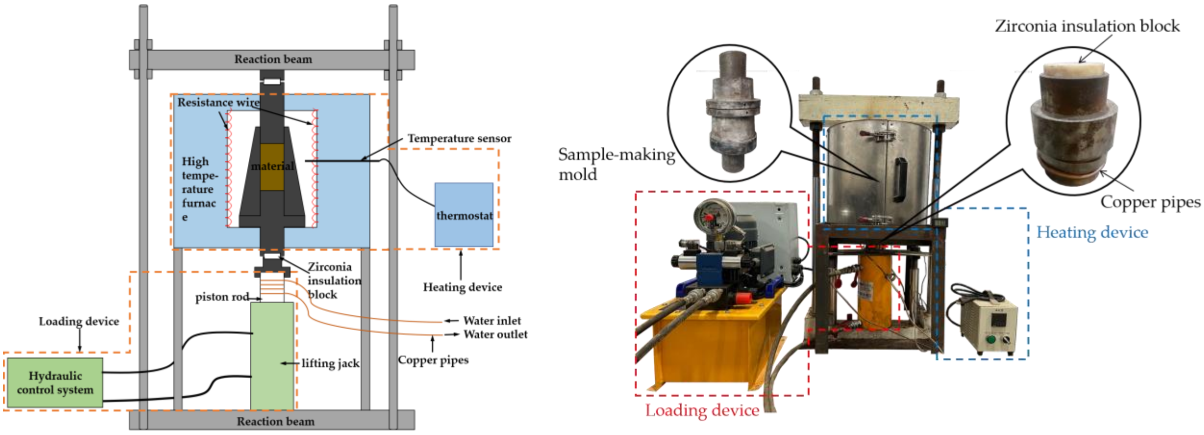
Considering the relatively stable physicochemical properties of quartz sand, it was selected as the aggregate particle to satisfy the aforementioned requirements. The influence of montmorillonite on the disintegration of the clay mineral composition of the natural red-bedded soft rock to be modeled is critical, and montmorillonite was chosen as the clay mineral. The materials used to create similar specimens are as follows:

- Sodium chloride
- Montmorillonite particles (800 mesh)
- STGP (with a melting point of 450 °C and a particle size of 800 mesh)
- Quartz sand (a mixture of various particle sizes, including 40–70 mesh (35%), 70–110 mesh (10%), 110–200 mesh (20%), and 200–300 mesh (35%)).

The roles of each material are as follows: quartz sand acts as the aggregate; sodium chloride is used to create a saturated solution that acts as a cementing agent, which, under 105 °C conditions, crystallizes and causes a cementing effect with the surrounding particles. Sodium chloride dissolves when encountering water, whereas montmorillonite swells when absorbing water, resulting in uneven internal stress within the specimen. STGP melts at temperatures above its melting point and attaches to the surface of particles, promoting the movement and densification of the particles. After cooling and solidification, the surrounding particles are embedded and solidified.

As previously discussed, interparticle entrenchment is crucial for the gradual disintegration of similar materials, achieved by STGP forming entrenchments with the surrounding particles, which can only be accomplished by maintaining high-temperature and -pressure conditions for an extended period of time during the pressing and forming of the specimens. Therefore, to address this issue, a specimen preparation system that can create the necessary temperature and pressure conditions for the STGP to melt and form the required entrenchments was developed.

The system used for preparing the samples comprised a loading device, heating device, and sample-making mold, as illustrated in Figure 3. The loading device incorporates an electric jack controlled by an intelligent system, whereas the heating device employs a high-temperature furnace also controlled by an intelligent system, thereby enabling continuous pressurization and heating for extended periods. The sample-making mold was designed and processed in-house and features a semi-open conical shape that facilitates sample retrieval and ensures consistent force application.



(**a**) (**b**)

Figure 3. (**a**) Schematic diagram of the sample preparation system; (**b**) Physical view of the sample preparation system.

Zirconium oxide heat-insulation blocks with a low thermal conductivity of <2 were employed to isolate the mold barrel from the external environment and maintain a stable temperature inside the furnace. Copper pipes from an external water circulation circuit were wrapped around the jack piston rod to ensure its operation at a normal working temperature.

The parameters of the specimen preparation system are as follows:

- Loading device: jack loading range of 0–125 MPa, with a piston rod diameter of 50 mm;
- Heating device: high-temperature furnace with a heating range from room temperature to 800 °C and an accuracy of ±1 °C;
- Sample-making mold: inner diameter of 50 mm, accuracy of ±0.01 mm, and height of 160 mm.

3.2. Orthogonal Design Test Protocol

Metamorphism of aggregate particles can occur owing to excessive temperatures and pressures, rendering the resulting samples no longer classified as sedimentary rocks [22–24]. Previous literature [25,26] suggests that internal rock particles begin to metamorphose when temperatures exceed 600 °C, and mudstone and sandstone can reach near-metamorphic states at depths of burial greater than 1800 m (pressure > 35 MPa). Therefore, to prepare similar materials, it is important to ensure that the parameters satisfy certain conditions, such as pressure < 35 MPa and temperature < 600 °C.

Based on previous studies regarding the inversion of the sedimentary rock formation depth [27], the natural rock samples for this simulation were buried at depths of 1000~1500 m. A sample preparation pressure of 30 MPa was chosen to simulate the overburden pressure during the formation of natural rock samples and ensure that the sample particles did not undergo metamorphic effects. The components of the similar material were determined based on the mineral composition of the natural rock sample to be simulated, as detailed in Table 4.

Table 4. Proportioning of similar materials.

Material	STGP	Quartz	Montmorillonite	Sodium Chloride
Mass ratio/%	0.5~5	35~39.5	50	10

Using the orthogonal design test method, four levels were selected for the three influencing factors: STGP content, heating temperature, and pressing time. The resulting material preparation test is presented in Table 5.

Table 5. Orthogonal test table for similar materials.

Experiment No.	STGP Content/(%)	Temperature/(°C)	Pressing Duration/(h)
1	0.5	450	12
2	0.5	500	24
3	0.5	550	36
4	0.5	600	48
5	1	450	24
6	1	500	12
7	1	550	48
8	1	600	36
9	2	450	36
10	2	500	48
11	2	550	12
12	2	600	24
13	5	450	48
14	5	500	36
15	5	550	24
16	5	600	12

3.3. Specimen Preparation Procedure and Test Content

To prepare similar materials, the corresponding masses of STGP, quartz sand, and montmorillonite powder were weighed according to the ratio and mixed thoroughly. Next, sodium chloride was added to the powder mixture until the color was homogeneous and the particles were moistened. The mixed powder was placed in a mold cylinder coated with high-temperature-resistant grease and pre-pressed at a load of 10 MPa for 15 min using a universal testing machine.

The pre-pressed mixed powder and the mold cylinder were then placed in a specimen preparation system and pressed at a mild pressure of 30 MPa. After pressing, the mold barrel was cooled to room temperature, and the specimens were slowly removed using a stripping machine. To ensure smoothness, the specimens were polished at both ends using a grinding machine and then dried in an oven at 105 °C until a constant weight was achieved for subsequent testing.

The uniaxial compression tests were first carried out on the prepared specimens according to the standard for engineering rock test methods (GB/T 50266-2013) [28] to obtain the uniaxial compressive strength σ_c and elastic modulus E of the specimens; after the uniaxial compression tests were completed, the remaining parts of the specimens were taken for disintegration resistance tests and SEM observations. Figure 4 shows the details of these tests.

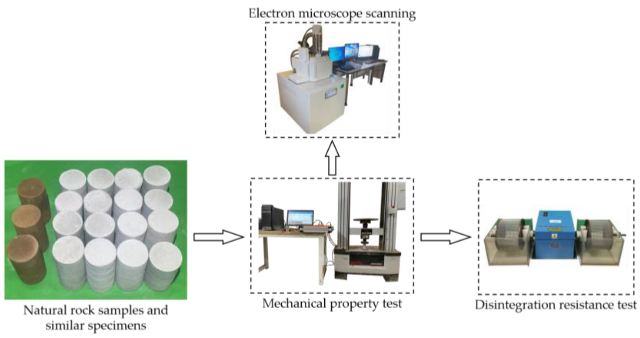


Figure 4. Test of basic physical and mechanical properties of rocks.

4. Test Results and Analysis

4.1. Progressive Disintegration Properties of Similar Materials

Experimental groups of similar materials—1# (rapid disintegration), 9# (normal disintegration), and 14# (slow disintegration)—were selected as representatives of the disintegration process to evaluate the similarity between similar materials and natural rock samples during the disintegration process and establish a general rule for the progressive disintegration of similar materials. The similarity of these materials to natural rock samples was examined by comparing their disintegration characteristics under static (using the immersion disintegration test) and dynamic conditions (using the disintegration resistance test). The results of this comparison are thoroughly analyzed and discussed.

4.1.1. Similar Material Disintegration Test by Immersion in Water

Photographs were captured for both the experimental group of similar materials and the natural red-bedded soft rock to document the visual changes in the specimens subjected to four dry–wet cycles of the immersion disintegration experiments. The cracks were traced using dotted lines to highlight the patterns and progression of crack formation on the specimen surfaces, with the resulting data presented in Figure 5.

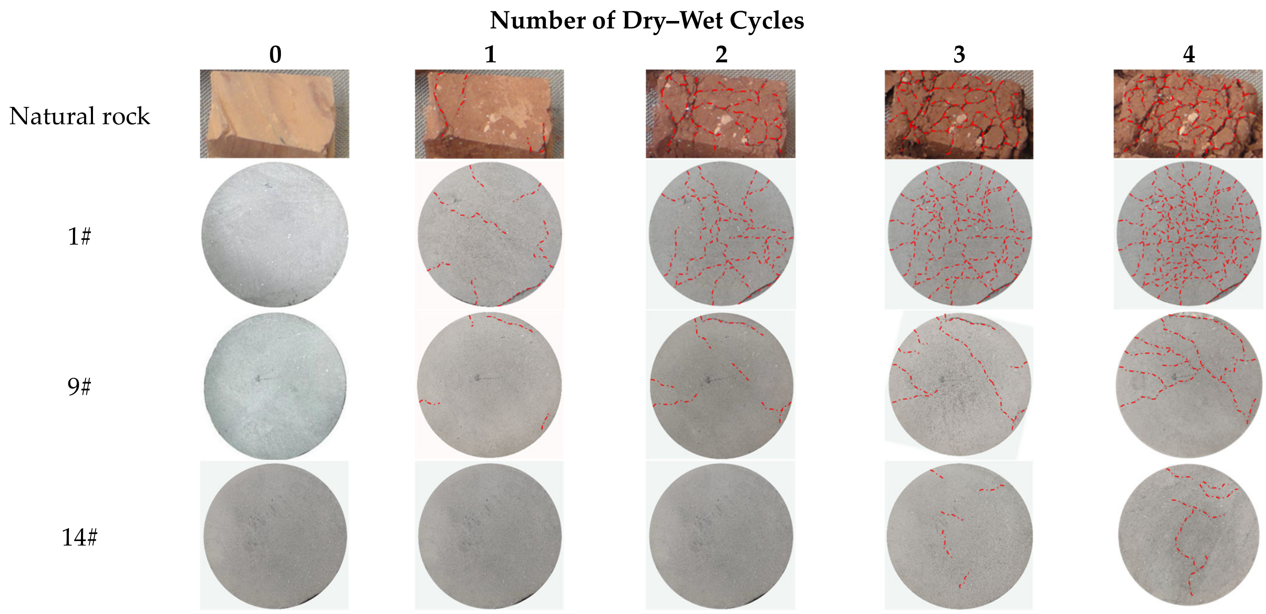


Figure 5. Development of cracks on the surface of similar material specimens by water immersion and disintegration.

The results depicted in Figure 5 demonstrate a clear relationship between the number of dry–wet cycles and the development of cracks on the surface of both the red-bedded soft rock and the comparable specimens. The observed cracks exhibited a gradual progression from small, localized, and short to wide, elongated, and through. Specimen 9# demonstrated the closest similarity to the progressive disintegration of natural red-bedded soft rock in terms of crack development.

4.1.2. Disintegration Resistance Test for Similar Materials

A disintegration resistance test was conducted to assess the disintegration resistance of the experimental specimens. After each dry–wet cycle, the morphology of the resulting disintegrated residue was meticulously captured and documented. Figure 6 shows a visual representation of the recorded images.

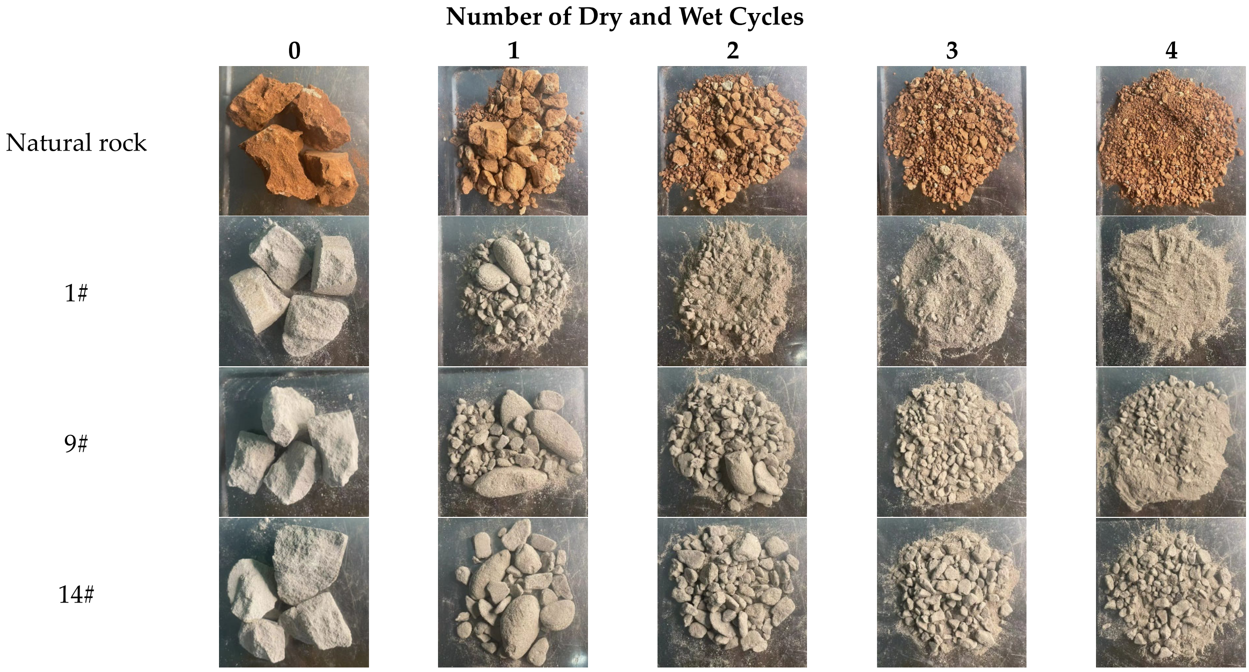


Figure 6. Disintegration resistance test performance of similar material specimens.

The trends observed in Figure 6 illustrate that, with an increasing number of dry–wet cycles, the disintegration of comparable specimens intensified, resulting in mixed disintegration residues of varying particle sizes as opposed to larger pieces. Notably, group 1# was slaking faster than other experimental groups, and the resulting disintegration residue of it was mainly composed of the smaller-sized particle.

4.2. Physical and Mechanical Properties of Similar Materials

The disintegration resistance index I_{dN} was plotted against the number of dry–wet cycles (N) for all experimental groups and natural red-bedded soft rock during dynamic disintegration to provide a quantitative analysis of the disintegration process of comparable materials. Figure 7 illustrates the findings. Additionally, we introduced a deviation factor ($\sigma_{I_{di}}$) utilizing Equation (1) to measure the degree of deviation between the experimental group curves and those of the natural red-bedded soft rock.

$$\sigma_{I_{di}} = \sqrt{\sum_{j=1}^{4}\left(I_{dj}^{i} - I_{dj}^{0}\right)^{2}} \tag{1}$$

$\sigma_{I_{di}}$—deviation factor of the curve for group i similar material specimens; I_{dj}^{i}—disintegration resistance index corresponding to the j-th dry–wet cycle of the i-th group of similar material specimens; I_{dj}^{0}—disintegration resistance index corresponding to the j-th dry–wet cycle of natural red-bedded soft rock.

The results of density (ρ), porosity (ω), uniaxial compressive strength (σ_c), modulus of elasticity (E), and $\sigma_{I_{di}}$ of similar materials are shown in Table 6. An analysis of variance (ANOVA) was performed on each parameter based on Table 6, with the contribution of each factor plotted (Figure 8).

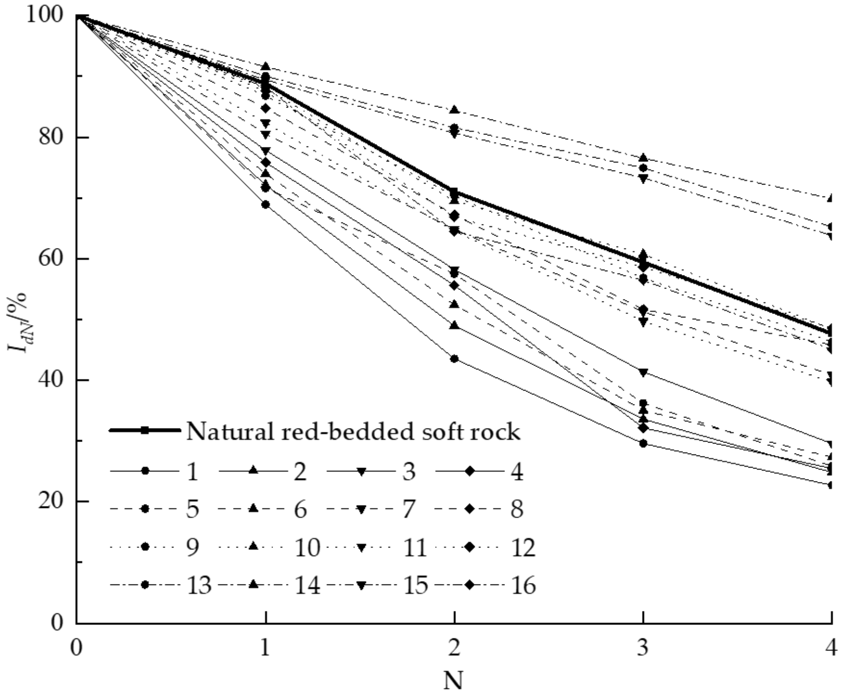


Figure 7. Relationship between disintegration resistance index and the number of dry–wet cycles for each specimen.

Table 6. Physical and mechanical properties of similar materials.

Experiment No.	$\rho/(g \cdot cm^{-3})$	ω/(%)	σ_c/(MPa)	E/(MPa)	$\sigma_{I_{di}}$
1	1.54	19.3	5.9	237.87	51.59
2	1.62	18.2	7.1	278.12	44.15
3	1.67	17.7	8.5	325.07	30.57
4	1.74	17.6	8.3	318.36	40.46
5	1.62	18.1	7.3	284.82	38.62
6	1.61	17.9	8	308.3	39.64
7	1.78	16.9	9.1	345.19	14.78
8	1.8	16.5	9.9	372.02	9.70
9	1.82	16.2	10.4	388.79	3.57
10	1.85	15	11.2	415.62	2.28
11	1.73	16.6	9.8	368.67	15.48
12	1.85	14.9	11.9	439.09	4.50
13	1.89	14.2	13.1	449.34	25.76
14	1.93	13.9	13.9	476.17	31.21
15	1.89	14.4	12.8	439.28	23.4
16	1.84	15.3	11.9	409.09	7.58

Figure 8 highlights the impact of the STGP content, heating temperature, and pressing time on the physical and mechanical properties and disintegration process of comparable materials; the STGP content had the most significant effect on the aforementioned properties. Test group parameters for comparable materials ranged from ρ = 1.54 to 1.93 g·cm^{-3}, ω = 13.9 to 19.3%, σ_c = 5.9 to 11.9 MPa, and E = 237.87 to 476.17 MPa. Notably, the physical and mechanical properties of similar materials were most similar to those of natural red-bedded soft rock with an STGP content in the 0.5–2% range. Heavier grains, such as barite powder, can be used as aggregates to increase specimen density. The $\sigma_{I_{di}}$ values ranged from 2.28 to 51.59, with smaller values observed for 8#–12#. Comparing the disintegration test performance of similar materials revealed that the disintegration process was most similar to that of natural red-bedded soft rock with an STGP content of 2%. Figure 9 shows that the mechanical behavior of similar materials is closer to that of natural red-bedded soft rocks, showing the classical four stages of the stress–strain curve, which proves that similar materials can simulate the mechanical properties of natural red-bedded soft rocks very well.

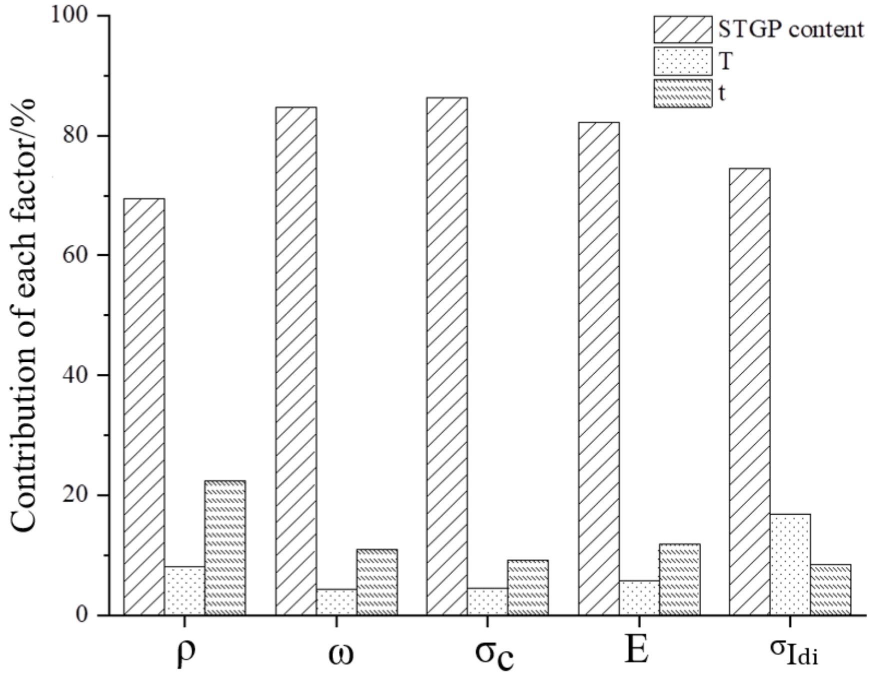


Figure 8. Contribution of each factor to the physical and mechanical properties of similar materials.

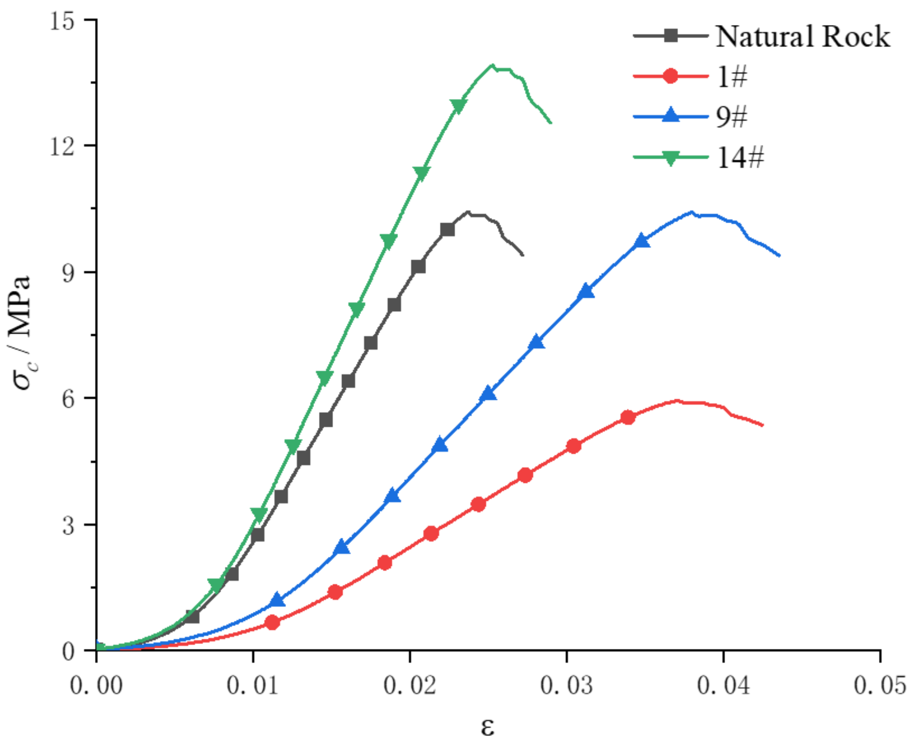


Figure 9. Stress–strain curves of similar specimens with representative disintegration processes and natural rock samples.

4.3. Microstructure of Similar Materials

As previously noted, controlling the disintegration process of similar materials is heavily dependent on the amount of STGP content. Three similar material specimens were produced at a pressure of 30 MPa, a temperature of 550 °C, and a pressing time of 24 h, with varying amounts of STGP content (0.5%, 2%, and 5%), to investigate the impact of STGP content on the microstructure of these specimens. Using a JSM-IT500LV scanning electron microscope to analyze fresh sections of the specimens, the particle chemical composition was identified, enabling the determination of component types. Additionally, the outer contours of the aggregate particles are circled to establish the particle spacing and degree of embeddedness. The findings of this analysis are shown in Figure 10.

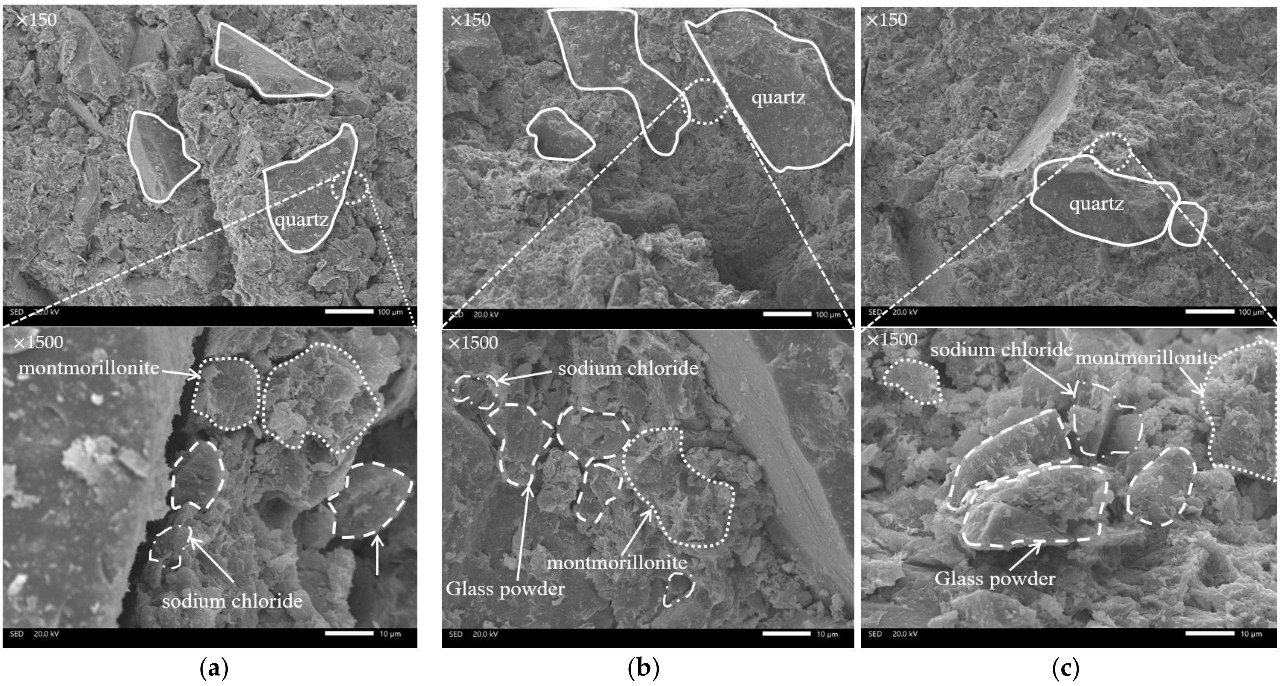


Figure 10. (**a**) 0.5% STGP content similar material microstructure; (**b**) 1% STGP content similar material microstructure; (**c**) 5% STGP content similar material microstructure.

Figure 10 indicates that STGP, sodium chloride crystals, and montmorillonite were present as mixed fillers between quartz sand particles. At an STGP content of 0.5% (Figure 10a), the filler was loosely cemented with the quartz sand particles, causing cracks at the edges of the quartz sand particles. At an STGP content of 2% (Figure 10b), the filler was tightly cemented with quartz sand particles, and the mixture adhered to the surface of the quartz sand particles. Additionally, microporosity was observed inside the specimen. At an STGP content of 5% (Figure 10c), a significant amount of filler was attached to the surface of the quartz sand particles, forming dense cementation and wrapping the particles. Owing to the dense wrapping of the filler, only a portion of the unwrapped quartz sand particle surface was observed. Moreover, no microporosity was detected in the specimen.

The observations mentioned above suggest that incorporating STGP into the production process facilitates the approach of large solid particles, which occurs when the STGP melts and fills the pores of the larger particles. After the STGP cools and solidifies, it wraps around and tightly cements with other fine particles present in the mixture, surrounding the larger particles. This process mimics the embedded cementation found between solid particles in natural rock samples and provides a necessary condition for the progressive disintegration of similar materials.

5. Conclusions

A technical approach for preparing similar materials that simulate the progressive disintegration of red-bedded soft rock was developed by simulating the rock-forming process and incorporating the STGP into the production process. A similar material was then pressed at a temperature and pressure that did not cause the aggregate to undergo metamorphic action and promoted the formation of similar material particles embedded during solidification. Subsequently, a corresponding sample preparation system was developed and experimentally verified, leading to the following conclusions:

9. The dynamic and static disintegration processes of similar material specimens indicate that incorporating STGP is feasible for preparing a similar material with a disintegration process similar to that of natural rock samples. A similar material can simulate the disintegration process of a natural red-bedded soft rock well.
10. Mixing STGP increased the density, compressive strength, and elastic modulus of similar material specimens while reducing the porosity ratio. The experiments demonstrated that similar materials made in the presented study have similar basic physical and mechanical properties compared with core red-bedded soft samples when the contents of STGP are 0.5–2%.
11. The STGP content was identified as the key factor affecting the physical and mechanical properties and disintegration process of similar materials, based on the analysis of the physical and mechanical test results of similar materials in the experimental group.
12. Scanning electron microscopic observations of specimens with different STGP content levels showed that the higher the STGP content, the smaller the particle spacing between the aggregates of similar material specimens, indicating that incorporating STGP can promote the formation of particles embedded in similar materials and result in the progressive disintegration of similar materials.

This study focused on the simulation of red-bedded soft rock formation and the preparation of a similar material that can progressively disintegrate by adding STGP to induce aggregate inlay formation. The results of this study provide valuable technical support for indoor model experiments on soft rocks with progressive disintegration characteristics.

Author Contributions: Conceptualization, methodology: X.L. and Q.J.; resources: T.W.; validation, formal analysis, data curation, writing—original draft preparation, writing—review and editing: D.J., Q.J. and H.X. All authors have read and agreed to the published version of the manuscript.

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