An Experimental Study on Preparation of Reconstituted Tectonic Coal Samples: Optimization of Preparation Conditions

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Abstract: The uniquely soft and fragile nature of tectonic coal makes it difficult to obtain core samples suitable for laboratory experimentation. Preparation of reconstituted tectonic coal (RTC) samples generally adopts the secondary forming method. Reliable coal samples are needed to obtain credible permeability and mechanical parameters that can guide Coalbed Methane (CBM) extraction and improve mining safety. In this study, the compaction mechanism of coal particles is analyzed based on the Kawakita model, and optimal sample preparation conditions are systematically investigated, particularly particle size and particle size distribution, forming pressure, and moisture content. The density and P-wave velocity of coal samples were used to test whether the RTC samples were realistic. Finally, the mechanical properties and deformation characteristics of the RTC samples were determined. The results indicate that RTC samples prepared for laboratory testing of mechanical properties require (1) the original particle size of the tectonic coal to be retained as much as possible; (2) a forming pressure that compacts the sample similar to the original tectonic coal; and (3) an optimum moisture content.

Keywords: tectonic coal particles; reconstituted coal; compaction mechanism; mechanical properties; effectiveness evaluation

1. Introduction

As like most coal seams in China, coal seams could have experienced numerous tectonic events, including folding, faulting and slipping over a long geological history [1–3]. As a result, the original structure of intact coal has suffered various degrees of deformation, forming tectonic coal of different kinds, such as cataclastic coal, fractionation coal, scaly coal and mylonite coal [4,5]. Tectonic coal exhibits a low-strength, weakly cohesive morphology compared to intact coal, and is prone to coal and gas outburst accidents, causing casualties and economic losses, and the exploitation and utilization rate of coexisting Coalbed Methane (CBM) is low [6,7]. In recent years, many researchers have paid increasing attention to the study of tectonic coal reservoir properties, mainly regarding pore characteristics, gas adsorption and desorption, and gas diffusion [8–11]. However, the less involved study of the mechanical properties of tectonic coal body is also of great significance to mining safety and CBM resource development.

The most important mechanical properties of coal include its deformation and strength characteristics, which can change gradually during underground engineering activities such as mining, roadway excavation and gas drainage drilling. The mechanical and damage deformation characteristics of coal can be systematically understood by laboratory testing of standard coal samples [12,13]. Intact coal can be drilled, cut and polished into cuboid or cylindrical samples of a certain size to meet the requirements of mechanical and permeability experiments; however, tectonic coal is soft and easily crushed or pulverized, making it difficult to obtain original coal samples that meet testing requirements.
Some researchers have studied the mechanical properties of tectonic coal using coal particles [14,15], but the relationship between particle strength and coal body strength has not been rigorously studied. The mechanical properties of coal particles cannot really represent the constitutive relationship between coal strength and the deformation properties of a tectonic coal body. Additionally, the particle size and particle size distribution of coal have obvious influences on the strength of a tectonic coal body. Meanwhile, when considering gas drainage borehole drilling and CBM utilization, the research object is the tectonic coal body rather than coal particles, such that the properties of coal particles are of little use [7].

For a long time, researchers have carried out systematic research on CO₂ sequestration, mechanisms of coal and gas outbursts, permeability evolution characteristics of coal containing gas under loading, and damage evolution in unloaded coal bodies using reconstituted coal samples or briquettes [16–19]. Reconstituted coal preparation methods have been extensive researched, and can be divided into the following categories:

(1) Dry coal particles that are directly pressed into standard coal samples without any additives; however, the strength and success rate of coal samples prepared by this method are very low [20–22].

(2) Pulverized coal that is pressed into standard coal samples with liquid or solid cementitious materials (such as kerosene, asphalt, cement, gypsum, fly ash, sodium humate, activated carbon, etc.). Thus, the adsorption and desorption characteristics of coal samples prepared by this method are very different from those of raw coal [23–25].

(3) Coal that is collected from a mine working face with a special sampling tool and then processed into coal samples meeting the size requirements. The method of preparing such coal samples generally involves multistep procedures that have a low success rate and high costs [18,26,27].

Among the above methods, the most common one is to perform secondary forming of coal particles with water as an additive. Table 1 illustrates the detailed preparation information for reconstituted tectonic coal (RTC) in China, which shows that there can be a wide range forming pressures. Furthermore, the particle sizes vary from 0–1 mm, which may be different from the actual particle size distribution of tectonic coal.

| Sampling Site | Sample Size (mm) | Particle Size (mm) | Forming Pressure | Pressure Time | Reference |
|---------------|------------------|--------------------|------------------|--------------|-----------|
| No. 13-1 coal seam in Zhangji coal mine | Φ50 × 100 | 0.18–0.425 | 100 MPa | – | Xu et al. [28] |
| No. 8 coal mine in Pingdingshan | Φ50 × 100 | 0.18–0.38 | 200 kN | 30 min | Liu [29] |
| No. 1 coal seam of a coal mine in Guizhou | Φ50 × 100 | 0.18–0.25 | 200 kN | 30 min | Wang [25] |
| No. 8 coal mine in Pingmei Sijiazhuang coal mine in Jincheng | Φ25× 50 | <1, 1–2 | 200 kN | 20 min | Guo et al. [6] |
| No. 1 coal seam of Hebi coal mine in Guizhou | Φ50 × 100 | 0.25–0.425 | 100 MPa | – | Zhang [30] |
| No.1 coal seam of Yuses coal mine in Guizhou Qinan coal mine | Φ50 × 100 | <0.5 | 135 kN | 30 min | Wang [31] |
| Nantong coal mine | Φ50 × 100 | 0.15–0.2, 0.3–0.45 | 100 MPa | 20 min | Yuan et al. [32] |
| Outburst coal seam | Φ50 × 100 | 0.2–0.25 | 200 kN | 30 min | Chen [19] |
| | Φ50 × 100 | 0.1–0.2 | 100 MPa | – | Hu et al. [33] |
| | Φ50 × 100 | 0.25–0.425 | 100 MPa | – | Wang et al. [34] |

Tectonic coal particles are similar to metal powder, sandy soil, coal gangue and other granular materials and they show a complex structure with high degrees of anisotropy and heterogeneity. The compaction and mechanical characteristics of RTC samples made form compressed coal particles are closely related to the material properties and forming conditions. Therefore, it is necessary to systematically analyze the compaction mechanism of tectonic coal particles and prepare more reliable standard samples to make the testing
of the mechanical properties and permeability of tectonic coal more accurate. This study aimed to investigate the compaction mechanism of RTC and the problems that should be considered in the preparation of coal samples, thereby putting forward a more reasonable sample preparation method. To achieve this aim, the following experimental strategy was adopted:

(1) Collection of tectonic coal from a working face in Zhangji coal mine and determination of its basic physical and mechanical properties.
(2) Preparation of RTC samples under various conditions.
(3) Analysis of the compaction mechanism of coal particles, and determination of suitable conditions for coal sample preparation.
(4) Investigation of the effectiveness of the obtained reconstituted coal samples through conventional mechanical testing.

2. Tectonic Coal and Sample Preparation

2.1. Tectonic Coal

Tectonic coal was collected from the No. 11–2 coal seam at a depth of approximately 550 m in Zhangji coal mine, Huainan coalfield, China. This seam contains coal with the semidark and semibright macrolithotypes. Tectonic coal exhibits a duller color, lower strength and weaker cohesiveness than intact coal (Figure 1). X-ray diffraction (XRD) analysis indicated that the main mineral components of the obtained tectonic coal are kaolinite, quartz, calcite, and pyrite (Figure 2). The initial moisture content of the tectonic coal is in the range of 1.8–2.3%. A proximate analysis showed a volatile matter content Vdaf = 38.32%, ash yield Ad = 43.09% and moisture yield Mad = 2.13%. Due to the stress-relieving effect of coal or CBM exploitation, tectonic coal that was originally in a tightly-compressed state becomes broken and loose. The collected tectonic coal had >80% of particles with a size <5 mm, and there were a few coal blocks that could be broken between the fingers. The wax sealing method was used to determine the density of the coal blocks used as the actual tectonic coal in this study, following the standard Methods for Determining the Block Density of Coal and Rock (China National Code GB/T 23561.3-2009). For the determination of the P-wave velocity, relatively dense and complete coal blocks were selected. The opposite sides of each block were carefully smoothed and then measured by an acoustic detector. We used 25 coal blocks to measure the density and P-wave velocity. The density of actual tectonic coal was 1.34 ± 0.02 g/cm³. The P-wave velocity showed a large range of fluctuation (0.51–1.20 km/s) due to the coal’s uniform structure but mainly ranged within 0.80–1.00 km/s.

![Stratification and morphology of intact coal and tectonic coal at No. 1216(1) working face in Zhangji coal mine.](image_url)
To investigate the influence of preparation conditions on the compactness and physico-mechanical properties of the reconstituted coal, three types of samples were prepared. The first used coarse (5–20 mm), medium (0.2–5 mm) and fine particles (<0.2 mm) of various proportions. The second type was coal samples prepared at forming pressures of 5–70 MPa, with a pressure gradient of 5 MPa. The third type was prepared with moisture contents of 6–12%.

**Figure 2.** XRD pattern of the tectonic coal.

**2.2. Sample Preparation**

The currently recognized method for preparing reconstituted coal samples is the secondary forming method. Its main steps are as follows: The qualified pulverized coal is dried and sieved first, and then a certain mass of coal particles is put into a steel mold, and pressure is applied by an electric-hydraulic serving compression machine to form the RTC sample. To reduce the influence of friction force on the internal structure of the sample, a layer of petroleum jelly was evenly applied on the inner wall of the mold. The coal sample was pressed at a certain pressure for 1 h and then demolded. The RTC sample preparation process is shown in Figure 3. The prepared coal samples were put in an oven until dry. Finally, both ends of the coal samples were polished to make cylinders of 50 mm diameter and 100 mm height.

**Figure 3.** Preparation of RTC samples.
3. Coal Particle Compaction Mechanism

According to the mechanical mechanism of powder formation, the compaction of coal particles is a process of reducing the void volume and increasing the solid density. Two classical theoretical models, the Heckel model [35] and Kawakita model [36], are commonly used to describe the compression characteristics of granular materials. There is a general acceptance that the Heckel model is mainly suitable for high pressures and hard powders with low porosity, such as metal powders, while the Kawakita model is suitable for low pressures and porous soft materials, such as pharmaceutical powders and coal powders [13,36–38]. Therefore, in this study, the Kawakita model is used to analyze the compaction characteristics of tectonic coal samples.

The relationship between volume shrinkage and forming pressure during the compression process is as follows:

\[
C = \frac{V_0 - V_P}{V_0} = \frac{abP}{1 + bP} \tag{1}
\]

After the formal transformation of Equation (1), the Kawakita equation can be obtained as:

\[
\frac{P}{C} = \frac{1}{a} + \frac{1}{ab}
\]

where \(C\) is the volume compressibility; \(V_0\) is the initial volume; \(V_P\) is the volume at forming pressure \(P\); \(a\) is a constant related to the initial porosity; and \(b\) is a constant with its reciprocal \(1/b\) defined as the Kawakita parameter.

With the increase of forming pressure, the volume compression ratio of the agglomerate increases gradually. Assuming the \(P_\infty\) is the ultimate forming pressure, the volume of the agglomerate at this time is \(V_\infty\), then:

\[
C_\infty = \frac{V_0 - V_\infty}{V_0} = \frac{abP_\infty}{1 + bP_\infty} \approx a \tag{3}
\]

It can be seen from Equation (3) that \(a\) represents the ultimate compression ratio, which reflects the compression performance of the powder. Under a certain forming pressure \(P_f\) and ultimate forming pressure \(P_\infty\), the porosity \(n\) of tectonic coal agglomerate is:

\[
n_i = 1 - \frac{\rho_0}{\rho_i}; \quad n_\infty = 1 - \frac{\rho_0}{\rho_\infty} \tag{4}
\]

According to Equations (2)–(4), the Kawakita equation can be transformed into a relationship between density and pressure:

\[
\frac{\rho_i}{\rho_\infty} = 1 - \frac{a}{1 + bP_f - abP_f} \tag{5}
\]

where \(\rho_i\) and \(\rho_\infty\) are the densities at forming pressures \(P_f\) and \(P_\infty\); and \(\rho_i/\rho_\infty\) is the relative density of tectonic coal.

To explore the compaction characteristics of tectonic coal, the relationship between the volume compression ratio of pulverized coal and forming pressures in the range of 0–100 MPa was analyzed, as shown in Figure 4. The \(P/C\) increases linearly with forming pressure, and the ultimate compression ratio \(a\) and parameter \(b\) are 0.309 and 0.075, respectively (Figure 4a). Therefore, the relative density of the tectonic coal agglomerate can be calculated using with the Equation (5). It increases rapidly with forming pressure and then levels out (Figure 4b). The relative density increases from 0.75 when no pressure is applied to 0.9 at 40M Pa and 0.95 at 100 MPa, increases of 20% and 26%, respectively. This indicates that pressure has a significant influence on the compactness of RTC and, thus, the compaction mechanism can be described as follows.
The arrangement of coal particles is very loose and there are many voids in the initial state. When there is a small external pressure, the original stress balance of the coal particles is broken. The smaller particles overcome friction resistance and slip and roll to fill in the voids between large particles until the particles contact each other. This forms a more compact arrangement, which reduces the voids and increases the compactness. With increases in pressure, the voids and fissure spaces are further eliminated and the coal agglomerate gradually becomes denser. As pressure increases further, the stresses at the contact points between coal particles exceed their own strength, or the stress tips of the tiny cavities and cracks inside the particles exceed their tensile strength, such that the particles are destroyed and the stress balance of the agglomerate is broken again. The crushed fine particles again slip and roll and fill into the voids, which further increases the compactness. As the pressure increases to a certain point, it becomes extremely difficult for particles to move and fill, so the density remains almost unchanged. Higher forming pressures can then only cause small deformations in the particle structure.

However, in addition to the forming pressure, the maceral composition, particle size distribution, plasticity, hardness and moisture content of coal are important parameters in the process of coal reorganization. Moreover, the relationships between other properties of coal samples (such as density, wave velocity and permeability) and actual tectonic coal should be considered comprehensively.

4. Considerations in RTC Sample Preparation

The effects of particle size, particle size distribution, forming pressure, and moisture content were investigated in order to determine more reliable RTC preparation conditions.

4.1. Particle Size and Particle Size Distribution

Figure 5 represents the variation in coal particle strength with particle size based on compression testing of single coal particles. The compressive strength of coal particles decreases with increasing of particle size following an approximate power function (Figure 5a). At particle sizes >3 mm, the compressive strength reaches a constant value of about 2 MPa. Meanwhile, Figure 5b shows that whether it is intact coal or tectonic coal, the tensile strength of the coal particles decreases with increases in particle size. The significant effect of size on coal particle strength can be explained by the pre-existing defects and discontinuities in the particles themselves. For larger particles, the probability of there being macropores and minor cracks is high, which leads to more pronounced internal discontinuities. Therefore, larger particles crush more easily under an applied force and exhibit lower mechanical strength than small particles [14,15].

Figure 4. Kawakita curve and relative density change during compression. (a) $P/C$; (b) $\rho_i/\rho_\infty$
The relationship between mechanical strength and particle size of coal particles. (c) Scheme 3; (b) tensile strength.

The morphologies of reconstituted coal formed by particles with different size distributions are shown in Figure 6. The surfaces of coal samples formed by coarse particles are rough and the particles are not tightly combined (Figure 6a). Meanwhile, the surfaces of samples formed by medium (Figure 6b) and fine particles (Figure 6c) are smoother. The coal samples with more coarse particles have rougher surfaces, while those with more fine particles have smoother surfaces (Figure 6d–h).

![Graphs showing compressive and tensile strength vs. particle diameter.](image)

**Figure 5.** The relationship between mechanical strength and particle size of coal particles. (a) Compressive strength; (b) tensile strength.

**Figure 6.** Surface morphology of reconstituted coal formed with different particle content. (a) Scheme 1; (b) Scheme 2; (c) Scheme 3; (d) Scheme 4; (e) Scheme 5; (f) Scheme 6; (g) Scheme 7; (h) Scheme 8.

It can be seen from Table 2 that with the increase of particle size, the P-wave velocity and uniaxial compressive strength of coal samples decrease, and the larger the particle size,
the more obvious the strength reduction. This implies that fine coal particles have a high total specific surface area and interparticle contact adhesion area. Moreover, fine particles have good regularity and uniformity, so they more easily arrange into a compact form with higher strength. On the contrary, coarse coal particles are irregular and inhomogeneity, and the samples made from them contain more pores and cracks. A low forming pressure does not make the coal particles contact closely and the voids between particles cannot be filled effectively, so they have poor cohesion and deformation resistance. A high forming pressure damages the structure of coarse coal particles and forms a failure surface, which also affects the strength of the samples. Therefore, at a given forming pressure, samples made from fine coal particles have a better structure and higher strength than coarse samples. This is consistent with the results of Xu et al. [39,40].

Table 2. The physico-mechanical parameters of reconstituted coal sample with various particle size distribution.

| Scheme | Particle Size Ratio (%) | Physical and Mechanical Parameters |
|--------|-------------------------|-----------------------------------|
|        | 5–20 (mm) | 0.2–5 (mm) | <0.2 (mm) | Density (g/cm³) | P-Wave Velocity (km/s) | Compression Strength (MPa) | Elastic Modulus (MPa) |
| 1      | 100 0 0  | 1.35 0.41  | 0.102 4.77 |
| 2      | 0 100 0  | 1.31 0.49  | 0.219 10.13 |
| 3      | 0 0 100  | 1.27 0.94  | 0.849 38.49 |
| 4      | 20 80 0  | 1.29 0.47  | 0.168 7.73  |
| 5      | 80 20 0  | 1.30 0.43  | 0.104 5.59  |
| 6      | 0 20 80  | 1.34 0.96  | 0.869 43.61 |
| 7      | 33.3 33.3 33.3  | 1.33 0.51  | 0.221 14.98 |
| 8      | 20 60 20 | 1.32 0.57  | 0.254 12.15 |

4.2. Forming Pressure

The compaction mechanism (Section 2) suggests that the compactness of reconstituted coal samples increases with forming pressure; however, the forming pressure of reconstituted coal samples prepared from original coal particles with particle sizes <5 mm requires further study. Figure 7 illustrates the density-forming pressure curve of coal samples after drying. It can be seen that at forming pressures of 5–25 MPa, the density increases rapidly due to voids becoming filled by particles. At pressures >25 MPa, the density increases slowly, which continues until at least 70 MPa, indicating that the coal particles continue to fill voids.

![Figure 7. Relationship between density and forming pressure of RTC.](image-url)
An excessive forming pressure will crush the coal particles, resulting in a large number of microporous cracks. The elastic wave velocity is widely used in the fields of coal and rock mass evaluation and classification, rock damage and fracture analysis, and determination of the loose zone range. Generally, low P-wave velocity means that there are more microcracks and voids in rock materials [41]. Figure 8 shows that the variation in the P-wave velocity of RTC samples prepared under different forming pressures. The P-wave velocity varies in two stages: an increasing stage (5–25 MPa) and a decreasing stage (25–70 MPa) (Figure 8a). In the increasing stage, the RTC is gradually compacted and the spaces between coal particles are filled continuously, which makes the wave propagation shorter as the waves conduct more easily through the particle skeleton. In the decreasing stage, the spaces between particles continue to be compacted; meanwhile, some particles that are subjected to strong forces or contain microdefects begin to be crushed, resulting in a large number of microporous cracks in the reconstituted samples. Therefore, the density continues to increase while the P-wave velocity gradually decreases, which is similar to the results of Wang et al. [42] (Figure 8b).

![Figure 8](image_url). Relationship between P-wave velocity and forming pressure of RTC. (a) P-wave velocity vs. forming pressure; (b) P-wave velocity vs. density.

The uniaxial compressive strength and elastic modulus will not increase continuously with forming pressure (Figure 9). This is mainly controlled by two reasons: (1) gradual fragmentation of coal particles results in tensile microcracks; and (2) a high forming pressure increases the lateral force of the sidewall of the mold on the coal sample, which increases the side friction resistance of the sample during demolding, resulting in obvious cracks on the surface of the sample. The reason for the fragmentation of tectonic coal particles is that extremely uneven forces are distributed in the RTC samples under loading (Figure 10). It can be seen that the internal contact forces in reconstituted coal are mainly transmitted in the form of force chains. The thickness of a force chain represents the magnitude of the contact force. A strong force chain bears a large external force, and the particles in the chain also bear a large force; therefore, these particles are the first to be crushed. Once the particles are damaged, the force chain will be altered and more particles will be broken, resulting in an increase in microcracks. In addition, Xiao et al. [43] pointed out that the fragmentation of coal particles is closely related to the coordination number. Under the same stress conditions, particles with a higher coordination number transfer higher stresses to adjacent particles, while particles with lower coordination numbers bear greater stresses due to the smaller number of adjacent particles and so are more prone to damage. Therefore, for a reconstituted sample with a certain density and particle size, when the forming pressure is appropriate, the particles are well bonded to each other and
the coordination number is high, so the force on a single particle is smaller and it does not easily break. If the pressure is too high, greater pressure is exerted on the particles and may break them, resulting in reconstituted coal with a loose structure.

![Figure 9](image1.png)

**Figure 9.** Relationship between mechanical parameters and forming pressure of RTC. (a) Uniaxial compressive strength; (b) elastic modulus.

![Figure 10](image2.png)

**Figure 10.** Distribution diagram of contact force between particles under vertical loading.

4.3. **Moisture Content**

Figure 11 illustrates the variation in the compressive strength of reconstituted coal samples with moisture content. It can be seen that there is an optimum moisture content, which was 8% for the tectonic coal used in this study. Reconstituted coal with the optimum moisture content has the maximum compressive strength. Further increases or decreases in moisture content decrease the compressive strength of samples. The optimal moisture content may vary according to the coal’s properties, particle size distribution and sample preparation methods. This trend is in agreement with those reported in the literature [44–46].
moisture content) should be comprehensively analyzed. Also, RTC needs to be compared to a certain type of coal. The reconstituted samples prepared from different types of tectonic coal may have different mechanical strengths at a given particle size distribution and moisture content. Before preparing reliable RTC samples, the relationships between its physico-mechanical properties, sample preparation methods should be specific to a certain type of coal. Therefore, the RTC samples prepared at this forming pressure can be considered suitable for determining the mechanical parameters and deformation characteristics of actual tectonic coal.

Since tectonic coal from different sources may have quite different stress environments and physico-mechanical properties, sample preparation methods should be specific to a certain type of coal. The reconstituted samples prepared from different types of tectonic coal may have different mechanical strengths at a given particle size distribution and moisture content. Before preparing reliable RTC samples, the relationships between its structure, density and preparation conditions (particle size distribution, forming pressure, moisture content) should be comprehensively analyzed. Also, RTC needs to be compared with the conditions of the original tectonic coal to determine the most suitable sample preparation method.

Although the sample preparation methods for different tectonic coals vary, RTC samples should ideally have similar characteristics; that is, a skeleton of large coal particles surrounded by fine particle aggregations that form a relatively dense sample. The stress-

![Figure 11. Effect of moisture content on uniaxial compressive strength of reconstitute coal.](image)

The change of compressive strength due to moisture content can be attributed to change in the distance between particles, which affects the bonding force between particles. The appropriate moisture content can lubricate coal particles, reduce interparticle friction in the compaction process, and promote the movement of small particles into voids. Furthermore, it can promote the hydration of functional groups on the surface of coal particles, which is conducive to adhesion among coal particles. Moreover, the clay minerals (particularly kaolinite) in the coal can bind the coal particles under the action of water infiltration and pressure. When the moisture content is too high, a thicker water film will be formed on the surface of coal particles, which reduces the interparticle compactness, resulting in a decrease in strength [47]. On the contrary, when the moisture content is too low, the friction between particles is relatively high, so more energy is needed to overcome it. The RTC samples pressed at the same forming pressure have a loose internal structure.

**4.4. Characteristics of Reliable RTC**

To make RTC samples more closely resemble actual tectonic coal, certain parameters of the latter need to be considered, such as density, P-wave velocity and in situ stress environment. It can be seen from Figures 7 and 8 that at a forming pressure of 25 MPa, the structure of RTC samples is the most compact and their average density and P-wave velocity are 1.35 g/cm³ and 0.95 km/s, respectively, which are close to those of actual tectonic coal. Therefore, the RTC samples prepared at this forming pressure can be considered suitable for determining the mechanical parameters and deformation characteristics of actual tectonic coal.

![Graph](image)
strain relationship of ideal RTC is shown Figure 12. It can be seen that the reconstituted sample takes a long strain/stress path (solid lines) to fully compress the void space and reach the linear elastic stage (dotted lines). A relatively short strain/stress path is required for reliable RTC compression, as shown by the red curve in Figure 12. In addition, the deformation of RTC samples under loading is much larger than that of intact coal, which indicates that reconstituted samples have better plastic fluidity and similar deformation characteristics to those of ideal plastic materials.

![Figure 12. The stress-strain comparison diagram of RTC.](image)

**5. Discussion of the Effectiveness of RTC**

Mechanical properties and deformation characteristics are important indexes of the effectiveness of RTC. Conventional uniaxial and triaxial compressive tests of reconstituted samples were carried out to determine their mechanical strength and elastic modulus under different stress environments. In addition, electrical resistivity and acoustic emissions (AE) were measured, which can indirectly reflect the deformation and failure characteristics of coal during loading.

Figure 13 shows that there was an obvious postpeak stress drop in the reconstituted coal samples under uniaxial conditions, which was weaker under triaxial test conditions. As the confining pressure increased, the postpeak stress-axial strain curve and stress-lateral strain curve became less steep. The deformation of coal samples gradually developed into ductility and, finally, showed the characteristics of plastic failure. On the contrary, intact coal was suddenly damaged after the peak strength pointed and showed an obvious postpeak stress drop, indicative of brittle failure characteristics (Figure 13b). In addition, the peak stress and corresponding elastic modulus increased significantly with confining pressure. The peak strength and elastic modulus of tectonic coal increased from 1.34 MPa and 0.179 GPa under uniaxial stress to 19.52 MPa and 0.53 GPa at a confining pressure of 6 MPa, respectively. The peak strength and elastic modulus of intact coal were significantly higher than those of tectonic coal. Under uniaxial stress, the peak strength and elastic modulus of intact coal were 11.6 MPa and 3.805 GPa, respectively, which are about 9 and 22 times that of tectonic coal. This trend is in agreement with previous studies, as shown in Figure 14.
Figure 13. The deviator stress–strain curves of different coal under triaxial condition. (a) RTC; (b) intact coal.

Figure 14. The difference of mechanical properties between RTC and intact coal. (a) Compressive strength of RTC [18,48–50]; (b) compressive strength of intact coal; [51–54]; (c) elastic modulus of RTC [18,48–50]; (d) elastic modulus of intact coal [51,53,55,56].
Figure 15 shows the variations in axial stress, electrical resistivity, AE energy, and cumulative AE energy of RTC during loading. The tectonic coal had the characteristics of much lower compressive strength and higher deformation than intact coal. The tectonic coal showed elastic-plastic deformation under low load, and the strength decreased rapidly after the peak value and almost had no bearing capacity, which is different from intact coal. Loading will lead to the initial compaction of micropores/cracks and the final penetration of macroscopic cracks in the coal samples, which can be indirectly reflected by electrical resistivity [57,58]. The electrical resistivity of both types of coal decreased gradually at first and then increased rapidly at the moment of sample failure. The initial electrical resistivity for tectonic coal was 20 kΩ·m due to its loose structure, which was about four times lower than that of intact coal. Meanwhile, the electrical resistivity of tectonic coal decreased rapidly at the initial loading stage and then more slowly, while the electrical resistivity of intact coal decreased gradually before being damaged. The AE of tectonic coal remained at a relatively stable level during the deformation and failure process, and there was no significant increase in acoustic emissions when approaching the peak stress (Figure 15a). However, the AE of intact coal increased sharply when it was damaged, as shown in Figure 15b. The generation of AE signals is mainly due to the ductile damage caused by friction and dislocation between coal particles, rather than brittle fracture of the intact coal. This means that AE is unsuitable for use as a precursor criterion of coal failure in the stability monitoring of tectonic coal. This phenomenon is in agreement with Shu et al. [59].

![Figure 15. Relationship between stress and AE energy of coal samples under uniaxial compressive loading. (a) RTC; (b) Intact coal.](image)

The physical and mechanical parameters of the RTC prepared in this study are in good agreement with previous research results. Therefore, it can be concluded that the method of reconstituting tectonic coal samples by pressing tectonic coal particles with a realistic particle size distribution at a certain forming pressure and moisture content is effective.

6. Conclusions

In this paper, the compaction mechanism of RTC and considerations for the preparation of RTC sample were investigated in detail. A coal sample preparation method was proposed and the effectiveness of reconstituted coal samples was evaluated in terms of density and P-wave velocity. The mechanical properties and deformation characteristics of reconstituted coal samples were also determined. According to the results obtained in this study, the main conclusions are as follows.

The Kawakita model can describe the compressive process of tectonic coal particles well; that is, the compactness of reconstituted coal samples increases rapidly with forming pressure and levels out thereafter. The coal sample compaction process mainly involves
the compression of coal particles and the filling of voids between bigger particles by smaller particles.

The physicomechanical properties of RTC samples are significantly influenced by particle size distribution, forming pressure, and moisture content. When the particle size distribution is similar to that of the original tectonic coal, the forming pressure is close to the occurrence environment of tectonic coal, and the moisture content is at the optimal level, it is beneficial to prepare the reliable RTC samples.

The suitable preparation conditions for coal remodeling vary according to the reservoir conditions, lithotypes and mechanical properties of tectonic coal. Before preparing samples of reliable RTC, the relationship between its structure, density and preparation conditions should be comprehensively analyzed. Suitable conditions for preparing tectonic coal samples from No. 11-2 coal seam in Zhangji coal mine are: the density and P-wave velocity of the original tectonic coal, the original particle size distribution (<5 mm), a moulding pressure of 25 MPa and a moisture content of 8%.

The density and P-wave velocity of RTC samples prepared after optimizing preparation conditions are 1.35 g/cm$^3$ and 0.95 km/s, respectively, which are close to the values of the original tectonic coal. The compressive strength and elastic modulus of the RTC are 1.05 MPa and 0.179 GPa, and the RTC samples have obvious ductility characteristics under loading. The electrical resistivity and AE monitoring results show that the reconstituted coal samples has a soft and loose structure similar to that of the original tectonic coal.

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