

Article

Experimental Study on Dynamic and Static Combined Dynamics of Temperature–Water-Coupled Sandstone and Energy Consumption Analysis

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Featured Application: This work has the potential to be applied to deep rock engineering under the coupling environment of groundwater, geothermal and in situ stress fields.

Abstract: In order to study the dynamic properties of temperature–water-coupled sandstone under axial pressure, impact compression tests were carried out on sandstone samples after temperature–water coupling under eight types of axial pressure (0.5–4.0 MPa) loading as well as no axial pressure loading by using the split-Hopkinson pressure bar (SHPB) test set. The results showed that the mass, volume, and density of the sandstone specimens increased by 0.57%, 0.37%, and 0.20%, respectively, after temperature–water coupling. With increasing axial pressure, the dynamic compressive strength of temperature–water-coupled sandstone samples decreased as a linear function, the dynamic strain increased as a quadratic function, the dynamic modulus of elasticity decreased as a quadratic function, and the average strain rate increased as an exponential function, indicating a strong strain rate effect. From the energy point of view, as the axial pressure increases, the absorption energy of the sample increases, the reflection energy gradually decreases, the crushing degree of the sample increases, and the size of the broken pieces decreases; the average particle size of the sandstone sample pieces decreases quadratically with the increase in the absorption energy and linearly with the increase in the axial pressure.

Keywords: rock dynamics; temperature–water coupling; dynamic and static combination; energy consumption analysis; SHPB test



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1. Introduction

The complex environments of deep rock masses are often subjected to temperature, ground stress, and groundwater coupling. This process introduces many new challenges to underground space development as well as safety issues. Engineered rock bodies are generally subject to strong dynamic disturbances, resulting in more complex and variable environments in which the rocks are located. Therefore, it is of great importance to study the changing laws underlying the dynamic characteristics of the coal mine roadways surrounding rocks under dynamic and static combined loads following temperature–water coupling.

To date, progress has been made in research on the influence of temperature and water on the mechanical properties of rocks. Zou et al. [1] conducted impact compression tests on deep sandstone under thermal–water–mechanical coupling conditions and found a

significant correlation between peak strain and axial stress, temperature, confining pressure, and water. Wang et al. [2] investigated the energy dissipation characteristics of fully saturated coal samples during the impact process and concluded that their energy density and incident energy were all positively correlated as a linear function. Ping et al. [3] studied the kinetic properties of annular sandstone samples after temperature–water coupling treatment and then analyzed their stress balance and energy change rules. Wang et al. [4] analyzed the tensile strength of rocks under different temperatures and water contents, concluding that the dynamic tensile strength of rocks changes in the opposite direction when the temperature and water content reach critical values. Roy et al. [5] investigated the mechanical properties of sandstone at different moisture contents, then concluded that the fracture stiffness of the specimens decreased with increasing saturation. Zhao et al. [6] explored the mechanical properties of borehole sandstone under water–force coupling conditions and concluded that the specimen showed similar uniaxial damage forms when the borehole pressure was close to the peripheral pressure. Jia et al. [7] conducted cyclic loading and unloading tests on different types of rocks after high-temperature water cooling and determined that as the number of cycles increased, the development of fracture surfaces in the rock specimens increased, and the rock samples fractured into smaller pieces. Yu et al. [8] analyzed the characteristic stresses of specimens with different water contents under uniaxial compression using the LSR method and the volumetric strain method. Wu et al. [9] investigated the deformation damage characteristics of high-temperature granite after hot–cold treatment. Feng et al. [10] established a crack propagation model for water-bearing sandstone specimens and concluded that the tensile failure of sandstone is mainly affected by the excavation unloading effect, water wedge effect, and intermediate principal stress effect. Li et al. [11] used the MTS815 test system to investigate the energy mechanism of rocks in five water-bearing states. The authors determined that the energy storage capacity of rocks is inversely proportional to the moisture content rate. Małkowski et al. [12] investigated the influence of water immersion time on the mechanical properties of carboniferous mudstone and found that the Young’s modulus and compressive strength increased to a certain extent with increasing water immersion time. Sakhno et al. [13,14] investigated the mechanism of bottom drumming of the water-bearing soft rock roadway and analyzed the evolution law of it using numerical simulation. Zhou et al. [15] analyzed the influence of water content on rock properties and concluded that the tensile strength and compressive strength of rocks with different saturations would be reduced under both static and dynamic conditions. It was concluded that the tensile strength and compressive strength of rocks with different degrees of saturation would be reduced under static and dynamic conditions.

Various studies have also explored the dynamic–static combined loading of rocks. Jin et al. [16] investigated the effects of static stress on the propagation of stress waves in red sandstone and found that the shapes of stress waves at the same measurement points varied considerably when axial compression was constant. However, the shapes of stress waves at different measurement points remained basically unchanged under the same axial compression. Xia et al. [17] used a dynamic–static combined SHPB device to explore the energy dissipation characteristics of rocks with various porosities during the impact process. The authors found that the energy dissipation caused by the critical failure of rocks gradually decreases with an increase in porosity. Zhang et al. [18] conducted SHPB tests on sandstone under a preloaded axial pressure of 25 MPa and obtained a positive correlation between the crack extension rate and impact pressure. Jin et al. [19] investigated the effects of high water pressure on the deformation characteristics of red sandstone based on a self-developed experimental device and found that the peak stress follows a logarithmic distribution with hydraulic pressure. Wang et al. [20] used an improved dynamic–static combined SHPB test device and concluded that the dynamic failure of coal samples is significantly influenced by water. Ye et al. [21], Li et al. [22], and Du et al. [23] thoroughly investigated the mechanical behavior and deformation characteristics of rocks under combined dynamic and static conditions. Liu et al. [24] conducted SHPB tests on

shale specimens with circular holes using a combined dynamic and static SHPB device and concluded that the main factor causing initial crack formation is the stress concentration caused by the circular holes. Liu et al. [25] analyzed the energy mechanism of postpeak fractured sandstone under axial compression and found that the energy absorption per unit volume of postpeak fractured sandstone follows a linear functional distribution with an increase in axial static load. Yu et al. [26] used a self-improved SHPB dynamic and static combined loading test apparatus to study the mechanical properties of limestone. The authors concluded that the damage patterns of the rock under different peripheral pressures mainly present tensile damage and compressive shear damage. Liu et al. [27,28] established a nonlinear dynamic model of combined coal rock under one-dimensional dynamic–static combined loading and investigated its energy dissipation characteristics as well as the stress-wave propagation mechanism.

The above scholars studied rocks primarily under conditions considering temperature, water, and kinetic–static combinations, loaded with one or both types of coupling. There is limited research, however, on the dynamic properties of rocks under the combined effects of dynamic and static loading after temperature–water coupling. Gao et al. [29] analyzed the mechanical properties of sandstone under the joint coupling of temperature, stress, and water but only performed static tests. Ping et al. [30] only studied the dynamic properties of sandstone under temperature–water coupling but did not perform relevant tests on the sandstone under a combination of dynamic and static loading.

Therefore, to prevent the occurrence of disasters and ensure the safe operation of underground space projects, it is necessary to carry out experimental research on the dynamic mechanics of temperature–water-coupled sandstone under dynamic and static combined loading. The sandstone used in this paper was obtained from the roadway of the Pan Er Coal Mine in Huainan City, Anhui Province, China, based on previous kinetic tests of local sandstone by Ping et al. It was found that the kinetic properties of sandstone change at 45 °C and that the strength of sandstone is weakest at 45 °C [31]. The dynamic and static combined SHPB device was used to carry out impact compression tests on sandstone with temperature–water-coupled effects at 45 °C under eight types of axial pressure (0.5~4.0 MPa) loading and without axial pressure loading. The loading rate was 13.9 m/s. In this way, the dynamic characteristics of sandstone specimens under different levels of axial compression were studied.

2. Materials and Methods

2.1. Preparation of Temperature–Water-Coupled Sandstone Specimens

In this paper, all specimens were taken from the same rock mass, and three wave-velocity-related specimens were selected from each group for the impact test; given that the dynamic test has a degree of dispersion, the value of the dispersion was chosen to be less than 30% for analysis.

Rock core samples were taken and cut according to the recommended testing methods of the International Society for Rock Mechanics and the “Rock Dynamics Test Code” of China [32,33]. Then, both ends were ground and polished to produce standard cylindrical samples with a diameter of $d = 50$ mm and a thickness of $h = 25$ mm. The prepared sandstone specimens were immersed in a constant-temperature water bath at a water temperature of 45 °C for 48 h to achieve saturation [34]. The samples before and after the temperature–water-coupled effects are shown in Figure 1.



Figure 1. Sandstone specimens before and after temperature–water coupling. (a) Before temperature–water coupling; (b) after temperature–water coupling.

Figure 1 shows that the samples after temperature–water coupling have a darker apparent color and enhanced grinding sensation after experiencing the temperature–water-coupled effect, preliminarily indicating that the temperature–water-coupled effect caused degradation damage to the sandstone specimens. The mass, volume, and density of the samples after experiencing the temperature–water-coupled effect increased by 0.57%, 0.37%, and 0.20%, respectively, compared with these values in the sandstone specimens before experiencing this effect. The reason for this result is that while experiencing the temperature–water-coupled effect, warm water infiltrated into the natural pores of the specimens, causing the mineral particles to expand. This process resulted in a slight increase in the mass and volume of the specimens. This increase in mass was greater than the expansion rate of volume, thereby resulting in increased density.

2.2. Dynamic and Static Combination SHPB Test Device

This experiment used a dynamic and static combined SHPB test device for deep coal mine mining response and disaster prevention from a national key laboratory, as shown in Figure 2.



Figure 2. Dynamic and static combination SHPB test device.

The device consists of five parts: impact loading system, data acquisition system, load transfer system, velocity measurement system, and preloading axial pressure system. The diameters of the impact rod, transmission rod, and absorbing rod are 50 mm, and their lengths are 2000 mm, 1500 mm, and 1000 mm, respectively. They were all machined from 40Cr alloy steel with a material elastic modulus of 210 GPa, a longitudinal wave velocity of 5190 m/s, and a Poisson's ratio of 0.28. The impact rod (impactor) was chosen to be a spindle shape to achieve a semisinusoidal wave loading. The power loading device (high pressure gas) provides the impact strength for the impact rod. When the impactor (bullet) in the chamber strikes the impact rod at a given velocity, an incident stress pulse is generated in the impact rod and transmitted through it to the specimen, which deforms under the action of the stress pulse. The transmitted and incident (reflected) wave signals in the rod can be picked up by the strain gauges on the transmitting and incident rods and displayed on the oscilloscope.

The schematic diagram of dynamic–static combined loading is shown in Figure 3, where P_s represents the dynamic impact load and P represents the axial preloading.

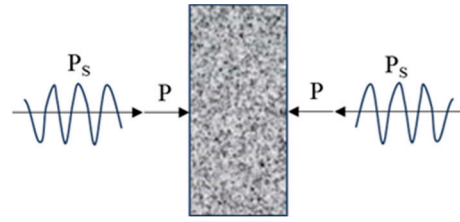


Figure 3. Schematic diagram of one-dimensional dynamic and static combined loading.

2.3. Analysis of Mineral Composition and Microstructure of Specimens

X-ray diffraction (XRD) and electron microscope (SEM) scanning tests were carried out on the crushed specimens after the impact test, and the test results were analyzed and processed to draw the XRD pattern shown in Figure 4 and the SEM image shown in Figure 5.

As shown in Figure 4, the mineral composition of the temperature–water-coupled sandstone was dominated by quartz (SiO_2), with small amounts of kaolinite [$\text{Al}_4(\text{OH})_8(\text{Si}_4\text{O}_{10})$] and illite [$\text{K}(\text{Al}_4\text{Si}_2\text{O}_9(\text{OH})_3)$]. As shown in Figure 5, microcracks and micropores were present in the sandstone when no axial pressure was applied. When axial pressure was applied, the number of cracks in the sandstone specimen increased, crack expansion occurred, and the fracture surface became rougher. As the axial pressure continued to increase, the number of cracks on the fracture surface significantly increased, and the length of the cracks continued to expand, penetrate, and gradually develop into longer cracks. The greater the axial pressure, the more obvious the cracks became.

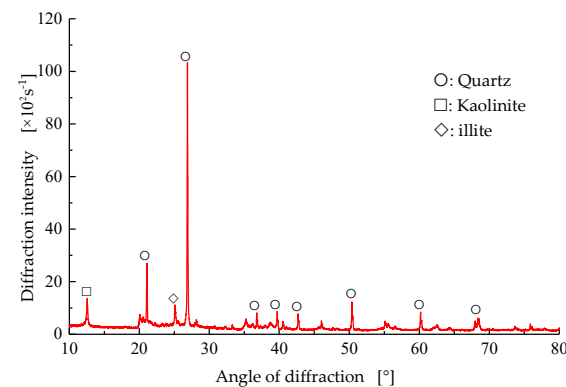
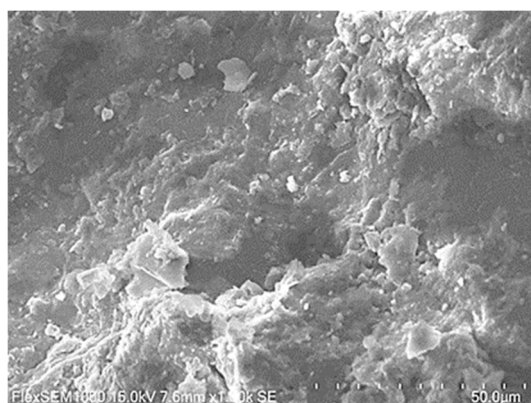
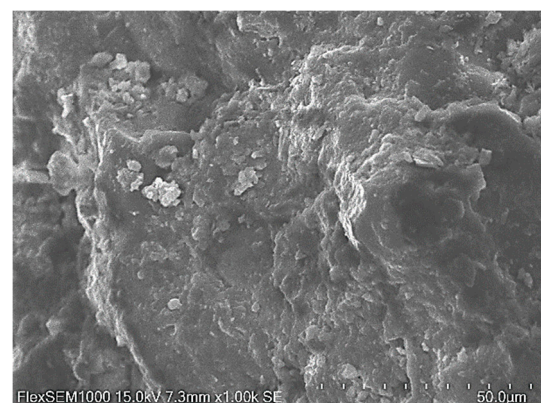


Figure 4. XRD diffraction pattern.

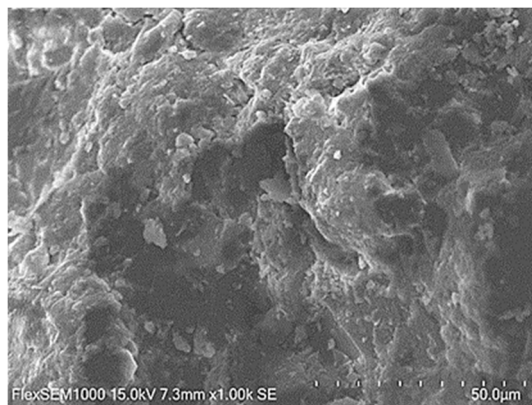


(a) No axial pressure.

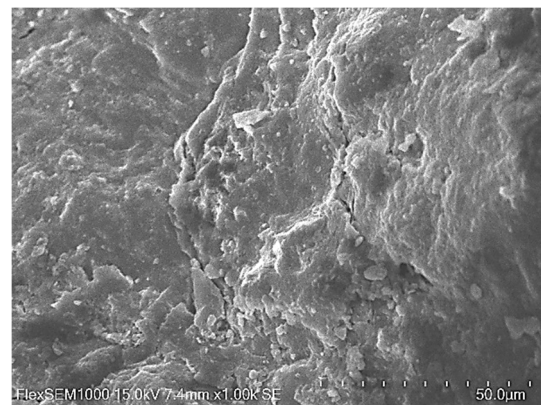


(b) 0.5 MPa.

Figure 5. Cont.



(c) 2.5 MPa.



(d) 3.5 MPa.

Figure 5. SEM images of sandstone under different axial pressures.

3. Experimental Results and Analysis

3.1. Dynamic and Static Combination SHPB Test Results

The dynamic and static combined SHPB dynamic compressive performance parameters of the temperature–water-coupled sandstone specimens are shown in Table 1.

Table 1. Temperature–water-coupled sandstone SHPB test results.

Axial Pressure (MPa)	Specimen Number	Dynamic Compressive Strength (MPa)	Peak Strain ($\times 10^{-3}$)	Dynamic Modulus of Elasticity (GPa)	Average Strain Rate (s^{-1})
0	PJ12-01	98.47	5.78	27.51	68
	PJ12-02	93.28	6.01	26.63	73
0.5	PJ12-03	91.30	5.96	28.46	66
	PJ12-04	91.37	6.03	25.51	88
1.0	PJ12-05	92.10	6.21	27.29	76
	PJ12-06	88.66	6.11	25.67	84
1.5	PJ12-07	84.08	6.32	22.40	85
	PJ12-08	77.48	6.23	27.75	89
2.0	PJ12-09	74.38	5.98	21.60	94
	PJ12-10	80.91	6.87	23.41	86
2.5	PJ12-11	76.83	6.44	17.92	104
	PJ12-12	76.49	6.73	18.90	106
3.0	PJ12-13	72.31	7.03	14.57	119
	PJ12-14	64.91	7.12	10.09	123
3.5	PJ12-15	60.50	7.09	12.06	124
	PJ12-16	73.23	7.56	10.34	136
4.0	PJ12-17	61.86	8.21	8.27	130
	PJ12-18	58.69	8.14	9.40	145

3.2. Dynamic Stress–Strain Curve

Figure 6 shows the dynamic stress–strain curves of the temperature–water-coupled sandstone specimens under eight axial pressure conditions and no axial pressure condition in the SHPB test.

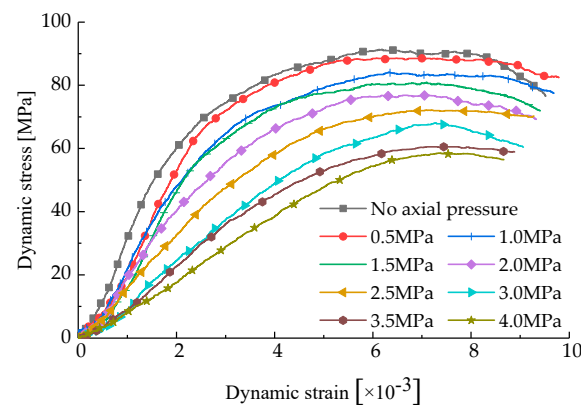


Figure 6. Dynamic stress–strain curve of sandstone specimens.

Figure 6 shows that under different axial pressures, the dynamic stress–strain curve of sandstone after experiencing the temperature–water-coupled effect exhibits strong regularity. As the axial pressure increases, the cluster of the dynamic stress–strain curve of sandstone samples gradually shifts to the lower right, indicating a decrease in the peak stress value and an increase in the strain.

3.3. The Change Law of Dynamic Compressive Strength

Figure 7 shows the variation in dynamic compressive strength with axial pressure for sandstone specimens with temperature–water coupling.

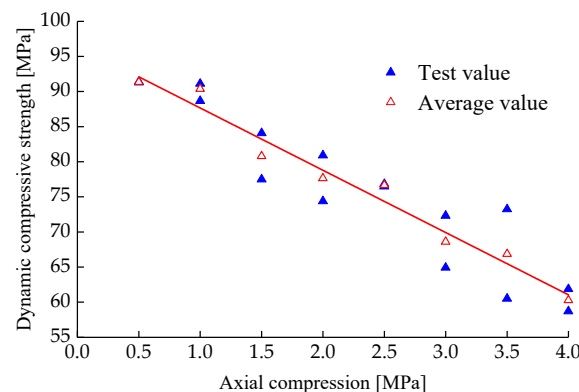


Figure 7. Dynamic compressive strength changes with axial pressure.

As shown in Figure 7, the dynamic compressive strength of sandstone samples increases as the axial pressure increases. The dynamic compressive strength of the temperature–water-coupled sandstone specimen is 96.28 MPa when there is no axial pressure, 91.89 MPa when the axial pressure is 0.5 MPa, and 61.15 MPa when the axial pressure is 4 MPa, which represents a decrease of 30.74 MPa. This phenomenon occurs because the internal structure of the sandstone sample is degraded by the action of the axial pressure, which weakens the load-bearing capacity of the specimen and thus reduces the dynamic compressive strength of the specimen. The dynamic compressive strength of the sample is thereby reduced. As the axial pressure increases, the internal structure of the sandstone sample is further degraded, internal defects are aggravated, and the bearing capacity of the sample is weakened, resulting in a decrease in the dynamic compressive strength of the sample. The dynamic compressive strength of the sandstone specimen decreases linearly with an increase in axial pressure. The fitted functional relationship is shown in Equation (1), with a correlation coefficient of 0.9709 and an obvious negative correlation:

$$\sigma(P) = 96.524 - 8.869P \quad (R^2 = 0.9709) \quad (1)$$

where $\sigma(P)$ represents the dynamic compressive strength of the sandstone sample, and P represents the axial pressure.

3.4. Analysis of Dynamic Peak Strain Law

Figure 8 shows the variation of the dynamic peak strain of sandstone specimens under different axial pressures due to the coupling effect of temperature–water coupling.

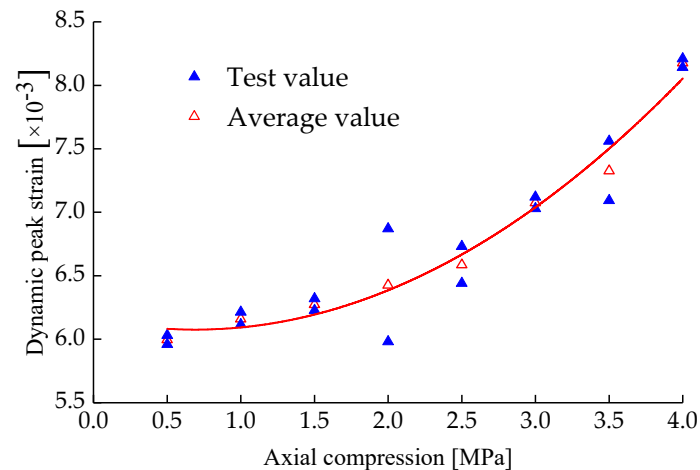


Figure 8. Dynamic peak strain and change with axial pressure.

Figure 8 shows that the dynamic peak strain of the sandstone sample increases with increasing axial pressure. The peak dynamic strain is 5.99×10^{-3} at no axial pressure, 5.98×10^{-3} at 0.5 MPa axial pressure, and 8.03×10^{-3} at 4 MPa axial pressure, which is an increase of 2.05×10^{-3} . This increase can be attributed to the internal structure of the sandstone sample being damaged when subjected to axial pressure, which reduces the dynamic compressive strength of the sandstone specimen and increases the dynamic peak strain. The dynamic compressive strength of the sandstone sample decreases and the dynamic peak strain increases. As the axial pressure increases, the internal damage to the sandstone specimen continues to accumulate, the dynamic compressive strength of the sample continues to decrease, and the dynamic peak strain continues to increase. As the axial pressure continues to increase, the internal structural damage of the sample is aggravated, and the internal cracks are interconnected, making it easier for the specimen to fracture, which is then manifested as a rapid decrease in dynamic compressive strength and a rapid increase in dynamic peak strain. The dynamic peak strain of the sandstone specimen with the increase in axial pressure of the temperature–water-coupled effect shows a quadratic growth trend. The fitting function for this trend is shown in Equation (2). Here, the correlation coefficient is 0.9804, which is obvious:

$$\varepsilon(P) = 6.161 - 0.249P + 0.181P^2 \quad (R^2 = 0.9804) \quad (2)$$

where $\varepsilon(P)$ is the dynamic strain of the sandstone sample.

3.5. Dynamic Elastic Modulus Variation

The dynamic elastic modulus of the temperature–water-coupled sandstone specimen with axial pressure is shown in Figure 9.

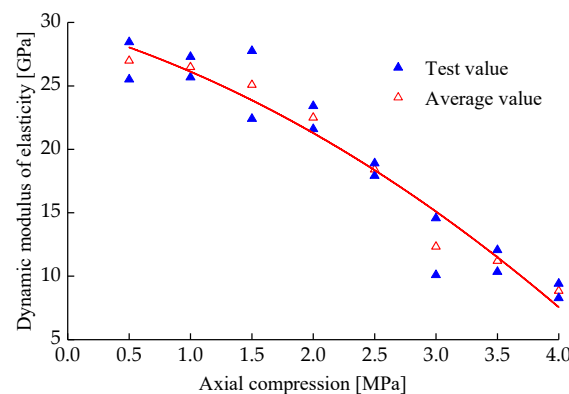


Figure 9. The elastic modulus of the sample changes with axial pressure.

Figure 9 shows that the elastic modulus of the sandstone sample decreases with increasing axial pressure. The dynamic the elastic modulus of the temperature–water-coupled sandstone specimen is 27.93 GPa when no axial pressure is applied, 26.44 GPa when the axial pressure is 0.5 MPa, and 7.23 GPa when the axial pressure is 4 MPa, with a decrease of 19.21 GPa. The decrease for this phenomenon occurs because of the action of axial pressure on the sandstone specimen, causing the internal structure of the specimen to be damaged, which decreases the dynamic compressive strength and increases the dynamic strain, leading to a decrease in the elastic modulus of the sample. The modulus of elasticity decreases. As the axial pressure increases, the internal cracks in the sandstone continue to nucleate and expand, accompanied by the formation of new cracks, making the specimen more susceptible to deformation and damage, resulting in a sharp decrease in the modulus of elasticity. The dynamic modulus of elasticity of the temperature–water-coupled sandstone specimen shows a decreasing trend with increasing axial pressure. The fitted functional relationship is shown in Equation (3), with a correlation coefficient of 0.9641, and the negative correlation of the quadratic function is obvious.

$$E(P) = 29.611 - 2.814P - 0.675P^2 \quad (R^2 = 0.9641) \quad (3)$$

where $E(P)$ represents the dynamic elastic modulus of the sandstone sample under the coupling effect of temperature and water.

3.6. Strain Rate Effect of the Specimen

The average strain rate of the sandstone sample under the coupling effect of temperature and water changes with axial pressure, as shown in Figure 10.

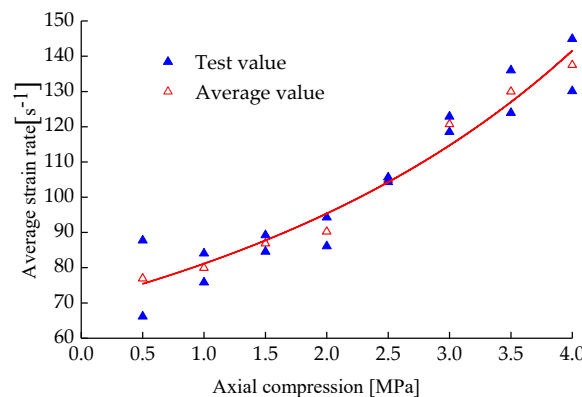


Figure 10. The average strain rate of the specimen changes with axial pressure.

Figure 10 illustrates that the average strain rate of the sandstone samples increases with an increase in axial pressure. The average strain rate of the sample without axial

pressure is 67.61 s^{-1} , the average strain rate of the sample with axial pressure of 0.5 MPa is 73.98 s^{-1} , and the average strain rate of the sample with axial pressure of 4 MPa is 138.90 s^{-1} , which reflects an increase of 64.92 s^{-1} . This phenomenon is due to the fact that the internal structure of the sandstone sample deteriorates when subjected to axial pressure, which causes the dynamic compressive strength of the sandstone sample to decrease and the average strain rate to increase. In this way, the dynamic compressive strength of the sandstone sample decreases, and the average strain rate increases. With an increase in axial pressure, new cracks are generated and gradually expand inside the specimen, making the deterioration damage to the internal structure more severe and more likely to occur, resulting in a rapid decrease in the dynamic compressive strength of the sandstone specimen and an exponential increase in the average strain rate. The average strain rate of the sandstone sample with an increase in axial pressure of the temperature–water coupling is an exponential function of growth, showing an obvious strain rate effect. The fitted functional relationship is shown in Equation (4), and the correlation coefficient is 0.9798, with an obvious positive correlation:

$$\dot{\varepsilon}(P) = 67.61e^{0.18p} \quad (R^2 = 0.9798) \quad (4)$$

where $\dot{\varepsilon}(P)$ represents the average strain rate of the sandstone sample under the coupling effect of temperature and water.

4. Analysis of the Crushing Morphology and Energy of the Sample

4.1. Failure Mode of Specimen Impact Compression

The dynamic compressive failure mode of the temperature–water-coupled sandstone sample is shown in Figure 11.

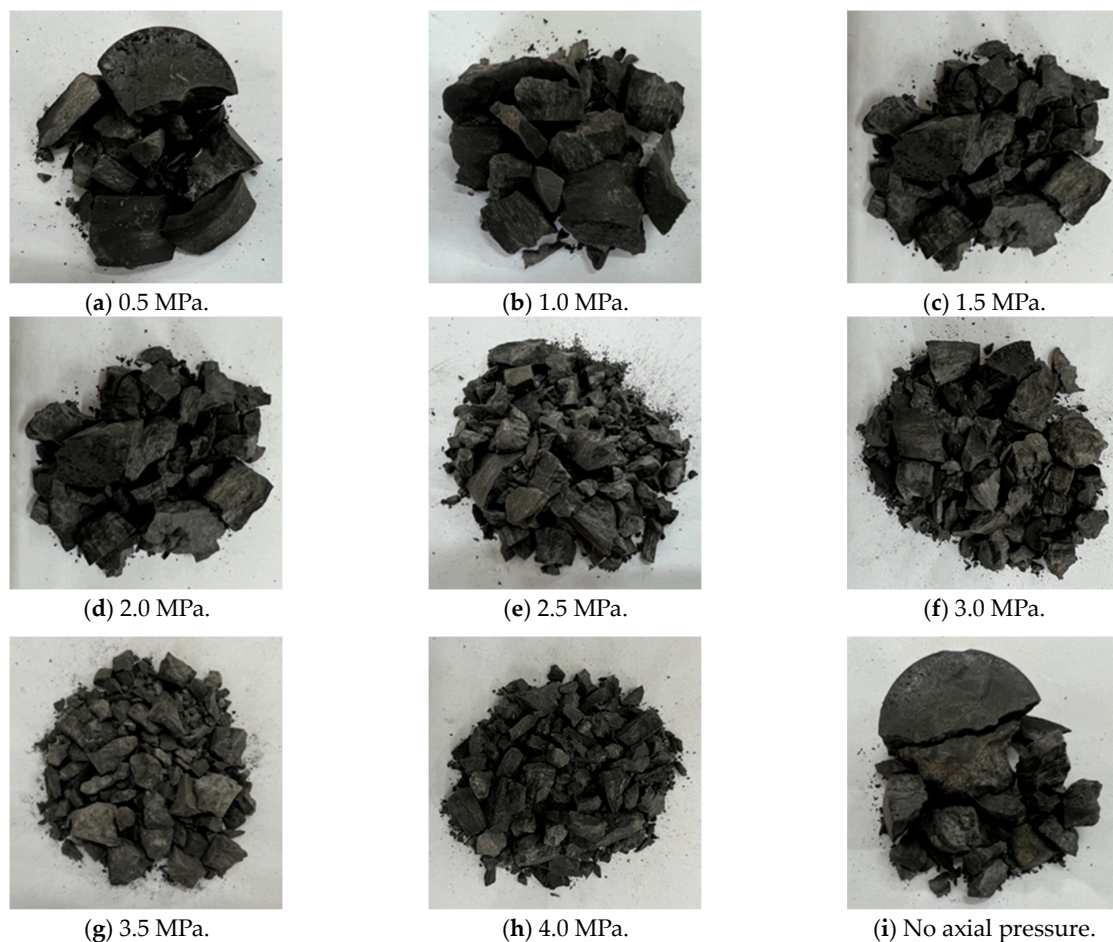


Figure 11. Crushing form of sandstone specimens under different axial pressures.

Figure 11 shows that as axial pressure increases, the degree of fragmentation and the fragment sizes of the temperature–water-coupled specimens intensify. A rise in axial pressure leads to the expansion and connection of microcracks and micropores within the sandstone, which weakens the specimen’s deformation resistance.

4.2. Fragment Screening Test Analysis

The average particle size of the fragmented pieces is used to analyze the degree of fragmentation under an impact load. This value is used to quantitatively describe the degree of fragmentation of the temperature–water-coupled sandstone specimens.

According to the relevant specifications, an STSJ-4 digital high-frequency vibration sieve is used to conduct sieve separation tests on the fragmented pieces, with the test data shown in Table 2.

Table 2. Results of SHPB impact failure fragmentation screening test of sandstone specimens.

Axial Pressure (MPa)	Specimen Number	Sieve Hole Size (mm)									Total Mass (g)	Average Particle Size (mm)
		0	0.15	0.3	0.6	1.18	2.36	4.75	9.5	13.2		
0	PJ12-01	0.14	0.07	0.21	0.4	0.94	2.04	12.13	9.96	107.05	132.94	11.821
0.5	PJ12-04	0.11	0.07	0.27	0.39	0.79	2.84	11.97	11.1	100.95	128.49	11.696
1.0	PJ12-05	0.29	0.14	0.51	0.87	1.82	5.89	14.38	22.58	80.13	126.61	10.72
1.5	PJ12-07	0.12	0.08	0.37	0.71	1.53	4.24	27.13	23	69.54	125.74	10.083
2.0	PJ12-10	0.26	0.15	0.69	1.18	2.64	7.8	23.55	16.49	72.98	126.72	9.975
2.5	PJ12-12	0.4	0.26	1.34	2.34	4.98	14.43	34.98	32.58	34.75	124.94	7.743
3.0	PJ12-13	0.76	0.47	1.75	2.55	4.85	15.85	40.26	17.64	40.81	126.06	7.546
3.5	PJ12-16	0.39	0.27	1.31	2.09	4.46	13.36	47.42	24.98	29.69	123.97	7.203
4.0	PJ12-18	0.36	0.24	1.45	2.48	5.08	16.61	61.45	24.56	12.55	124.78	5.915

Figure 12 shows the variation in the average particle sizes of the fragmented pieces of the temperature–water-coupled sandstone specimens under different axial pressures. Equation (5) presents the fitting function relationship with a correlation coefficient of 0.9594, demonstrating a significant negative correlation:

$$d_s = 12.242 - 1.526P \quad (R^2 = 0.9594) \quad (5)$$

where d_s is the average particle size of broken specimens.

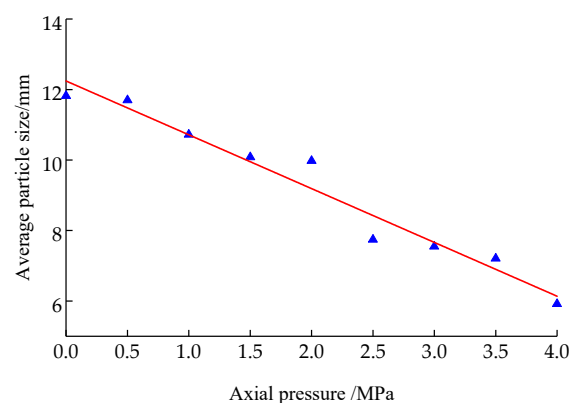


Figure 12. The average particle size varies with axial pressure.

Figure 12 shows that the average particle size of the fragmented pieces of the temperature–water-coupled sandstone specimens decreases linearly as the axial pressure increases. Therefore, the greater the axial pressure, the greater the degree of fragmentation of the sample.

4.3. Energy Analysis

According to the waveform signals collected in the SHPB dynamic–static combination tester, the incident energy, reflected energy, transmitted energy, and absorbed energy of the specimen under different axial pressures were calculated using Equation (6). The calculated energy data of the specimen are shown in Table 3:

$$\left. \begin{aligned} E_I(t) &= E_0 C_0 A_0 \int_0^t \varepsilon_I^2(t) dt \\ E_R(t) &= E_0 C_0 A_0 \int_0^t \varepsilon_R^2(t) dt \\ E_T(t) &= E_0 C_0 A_0 \int_0^t \varepsilon_T^2(t) dt \\ E_D(t) &= E_I(t) - E_R(t) - E_T(t) \end{aligned} \right\} \quad (6)$$

where $E_I(t)$, $E_R(t)$, $E_T(t)$, and $E_D(t)$ are the incident, reflected, transmitted, and absorbed energy of the sample.

Table 3. Energy data of sandstone specimens under different axial pressures.

Axial Pressure (MPa)	Specimen Number	Incident Energy (J)	Reflected Energy (J)	Transmission Energy (J)	Absorbed Energy (J)
0	PJ12-01	61.91	21.57	31.18	9.16
	PJ12-02	62.15	23.64	27.21	11.30
0.5	PJ12-03	64.32	24.85	29.24	10.24
	PJ12-04	62.41	22.43	27.88	12.09
1.0	PJ12-05	59.88	22.86	26.41	10.62
	PJ12-06	64.60	24.99	26.30	13.31
1.5	PJ12-07	65.95	25.18	27.62	13.15
	PJ12-08	60.93	25.73	22.67	12.52
2.0	PJ12-09	67.87	28.97	24.27	14.63
	PJ12-10	61.73	26.45	23.17	12.10
2.5	PJ12-11	64.36	25.65	22.78	15.93
	PJ12-12	70.81	30.50	25.11	15.20
3.0	PJ12-13	70.74	29.43	23.84	17.47
	PJ12-14	65.54	27.28	21.13	17.13
3.5	PJ12-15	73.21	32.02	22.53	18.67
	PJ12-16	65.09	27.29	20.51	17.29
4.0	PJ12-17	70.80	32.78	19.78	18.24
	PJ12-18	69.06	31.05	18.66	19.35

Table 3 shows that the incident energy remains within a certain range when the loading rate is constant. The variation in the reflected, transmitted, and absorbed energy of the sample with axial pressure in the SHPB test is shown in Figure 13.

Figure 13 shows that the absorbed energy of sandstone specimens increases with an increase in axial pressure. This result indicates that as axial pressure increases, the energy absorption in the sandstone specimens also increases, promoting the formation of more cracks and resulting in smaller fragments and greater fragmentation. The transmission energy of the sample decreases gradually with an increase in axial pressure, possibly because the increase in axial pressure makes the original cracks in the sample expand and extend, accompanied by the formation of new cracks, which reduces the effective area available for the transmission of the transmission wave. This phenomenon reduces the transmission wave through the specimen, decreasing the transmission energy.

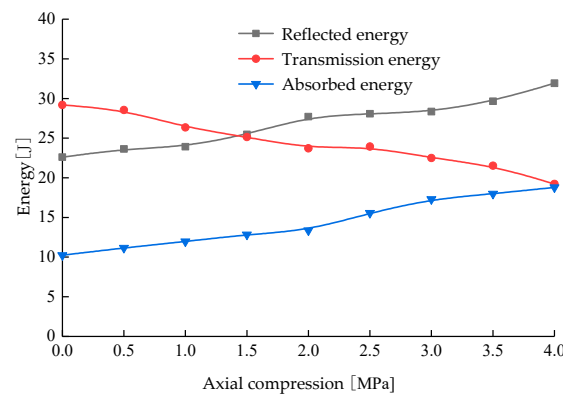


Figure 13. Variation of specimen energy with axial pressure.

4.4. The Relationship between the Absorbed Energy of the Sample and the Average Particle Size

The relationship between absorbed energy and mean grain size for sandstone samples is shown in Figure 14.

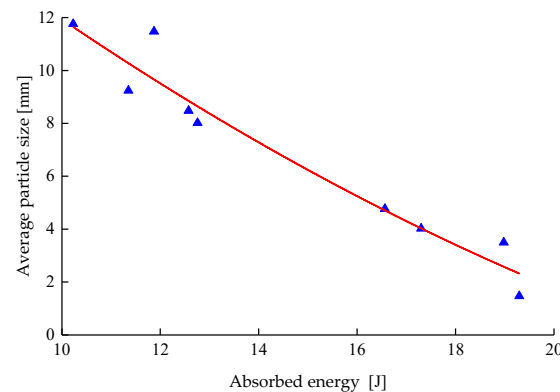


Figure 14. Relationship between absorbed energy ratio and average particle size.

Figure 14 illustrates that the average grain size of the broken pieces of the temperature–water-coupled sandstone gradually decreases after the energy impact as the absorbed energy increases. This result indicates that the higher the energy absorption of the temperature–water-coupled sandstone specimen, the higher the energy dissipation of the specimen in the process of deformation and crushing, resulting in an increase in the number of cracks in the specimen. Additionally, the cracks cross each other and expand. Thus, the temperature–water-coupled sandstone specimen’s crushing-block degree increases, the average particle size of the broken pieces decreases, and the degree of specimen crushing is intensified. The average particle size of the broken pieces of the temperature–water-coupled sandstone specimen shows a quadratic function relationship that decreases with an increase in absorption energy. The corresponding fitting function is shown in Equation (7), with a correlation coefficient of 0.9397 and an obvious negative correlation:

$$d_s = 26.989 - 1.749E_D + 0.024E_D^2 \quad (R^2 = 0.9397) \quad (7)$$

where E_D is the absorbed energy.

5. Conclusions

This paper provides a reference foundation for the safety production and disaster prevention of underground space engineering. If we can determine the axial stress of the rock surrounding the tunnels in environments of temperature and groundwater coupling, we can more quickly judge whether safety measures should be taken to ensure the safe operation of underground projects. However, because the rock samples used in these tests

were relatively limited, only the mechanical properties of local sandstone were studied. Moreover, the relevant test design was not perfect. As a result, the results obtained could characterize the properties of sandstone only under specific conditions, and the research results can be applied only under specific local geological conditions. In the future, when the experimental design is perfected, it will be possible to carry out tests on other rocks under the same conditions presented in this paper.

This paper presents the following main conclusions drawn from impact compression tests on temperature–water-coupled sandstones carried out under different axial pressure loadings using a dynamic–static combined SHPB test setup:

- (1) The mineral composition of the sandstone samples was mainly quartz, kaolinite, and illite. The mass, volume, and density of the sandstone samples increased by 0.57%, 0.37%, and 0.20%, respectively, after temperature–water coupling.
- (2) Axial pressure loading reduced the bearing capacity of temperature–water-coupled sandstone specimens. Additionally, the dynamic compressive strength of the specimens was distributed as a linear function showing a decrease with an increase in axial pressure and a quadratic positive correlation between the dynamic peak strains.
- (3) As the axial pressure increased, the internal structure of the temperature–water-coupled sandstone specimen became continuously damaged, resulting in the specimen's dynamic Young's modulus showing a quadratic downward trend. Moreover, the average strain rate showed an exponential increase, with a more pronounced strain rate effect.
- (4) The temperature–water-coupled sandstone specimen's absorption energy increased continuously with axial pressure. Additionally, the average particle size of the specimen is negatively correlated with the axial pressure as a linear function and quadratically decreases with the absorbed energy of the specimen.

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