Journal of Mines, Metals and Fuels, *73(2): 475-486; 2025. DOI: 10.18311/jmmf/2025/45560*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Research on Damage Mechanism and Dynamic Characteristics of Abandoned Basalt at Different Heating Conditions

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Abstract

Physical and mechanical tests are required to explore the reuse value of abandoned rock to recycle excavated rock resources in mountainous areas. After mining excavation from Qinling, Shaanxi, China, the abandoned basalt was processed into standard samples. After being treated with different heating temperatures and heating times, the surface temperature, ultrasonic wave velocity, open porosity, Scanning Electron Microscope (SEM), impact resistance and the degree of fragments after-impact failure of the basalt samples were tested. With the increase of heating temperature and heating time, the temperature rise rate of basalt samples first increases and then decreases, the attenuation rate of ultrasonic wave velocity continually increases, and the difference of open porosity also gradually increases. The difference in mineral heat absorption in basalt samples is the main cause of structural damage cracking. The cracks mainly develop along the interface of heat-absorbing and heat-insensitive minerals, forming a fracture grid in the basalt, and eventually leading to the failure of the sample. With the rise of heating temperature at different impact pressures, the impact peak stress and impact peak strain of the basalt sample gradually decrease, and the curvature of the stress-strain curve gradually weakens. With the rise of heating temperature at different impact pressures, the lumpiness of basalt samples increases gradually after crushing, and the proportion of large-size fragments becomes larger and larger. The conclusions of this paper can provide an experimental basis and guiding significance for the recycling of abandoned rock resources.

Keywords: *Abandoned Basalt, Mechanical Characteristic, SEM Test, Thermal Damage, Ultrasonic Wave Velocity*

1.0 Introduction

With the continuous excavation and construction of deep underground mining engineering and ultra-long deep-buried highway tunnels, the prospect of the secondary utilization of abandoned rock after excavation is facing more and more severe challenges. Before the secondary utilization, rocks usually experience high temperature, strong impact, high ground stress and high pore water pressure[1,2]. Before the secondary application, it is necessary to study the elasticity, deformation, stress characteristics and impact resistance characteristics of rocks, such as sudden settlement of rock-filled roadbeds, resistance to seasonal changes and long-term durability[3,4].

After experiencing high temperatures, the rock will undergo crystal changes and structural damage, which determine the physical and mechanical characteristics of the rock[5,6]. Qi Wenchao *et al.*, carried out high temperature

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and water cooling cycling to basalt at 100°C, 300°C and 450°C, and conducted microscopic tests with SEM to explore the static compressive mechanical characteristics and the law of macro and micro damage evolution of basalt[7]. Zhao Kui *et al.,* carried out uniaxial tests on granite after different temperatures to investigate the mechanical properties and energy evolution mechanism of granite at different temperatures and establish damage evolution models of granite with different temperatures[8]. Min Ming *et al.,* carried out triaxial compression tests using an MTS815 testing machine to explore the evolution law of physical parameters, mechanical parameters and failure characteristics of heat-damaged coarse-grained granite under different conditions[9]. According to the elastic modulus, compressive strength, shear strength and tensile strength of granite after thermal damage, Xi Baoping *et al.,* fitted the empirical formula of properties change with temperature and established the criterion of shear failure strength of granite under heat action[10].

The constitutive model of rock considering thermal damage can convey thermal and mechanical coupling characteristics[11,12]. Based on energy dissipation theory and Lemaitre's equivalent strain hypothesis, Xu Xiaoli *et al.,* established the constitutive model of rock considering thermal damage, which makes up for the deficiency of the traditional model, properly explains the nature of rock failure, and improves the theoretical system of damage constitutive model[13]. On the condition that the strength of the microelement follows the Hoek-brown criterion, Jia Baoxin *et al.,* improved the damage variable using the Weibull distribution function and built a statistical constitutive model considering the damage characteristics of the rock at high temperature[14]. Based on the effect of high temperature on rock mechanical parameters, Zhu Zhennan *et al.,* introduced the thermal damage variable and established the statistical thermal damage constitutive model of rocks after high temperature on the condition that the microelement failure met the Mohr-Coulomb criterion[15]. On account of the existing rock statistical damage constitutive model, Jiang Haopeng *et al.,* introduced the thermal damage variable and Weibull distribution function, established the statistical damage constitutive model of rocks after high temperature with the strength of the microelements obeyed the Mohr-Coulomb criterion, and determined the parameter expressions[16].

However, the thermal damage degree of rocks can be correlated with the ultrasonic wave properties. Wu Xinghui *et al.,* investigated the influence of temperature and cooling methods on the physical characteristics of high-temperature granite[17]. By testing physical characteristics and thermal conductivity characteristics such as density, mass, volume, and wave velocity by natural cooling and water cooling, the variation rules of parameters were compared and explained under the two cooling methods. Zhang Yuliang *et al.,* proposed a thermal damage evaluation method for rocks by using the acoustic emission test system and established a thermal damage evolution model considering both heating and cooling processes[18]. Zhang Yuliang *et al.,* also used the acoustic emission information during heating and cooling to reveal the microstructure characteristics of rocks before and after high temperatures and established the thermal damage evolution equation based on elastic modulus and acoustic emission energy[19]. Kong Biao *et al.,* used acoustic emission 3D positioning technology and analyzed acoustic emission signal time domain and thermal fracture development and evolution in rock[20]. Given the convenience and accuracy of rock wave characteristic testing, the damage equation of rock dynamic and static wave characteristic changes at high temperatures can be established to reflect the evolution process of rock dynamic and static damage at high temperatures[21].

Based on the basic theory of rock thermal damage, this paper selected the abandoned basalt of Qinling Tunnel in Shaanxi province of China as the test object, made standard samples for indoor heating tests with different temperature and time, conducted surface temperature, ultrasonic, open porosity, SEM and Split Hopkinson Pressure Bar (SHPB) tests on the basalt samples after heating, and analyzed the fragments characteristics of the sample after impact. The thermal damage mechanism and dynamic characteristics of basalt are studied. This paper can provide a theoretical basis and reference significance for the secondary utilization of abandoned basalt.

2. Methodology

2.1 Thermal Damage Theory of Rock

According to the research of relevant scholars, the thermal damage evolution equation of rock is based on the elastic

and brittle characteristics of rock, and the calculation formula is[22]:

$$\begin{cases} D(T)=1-E_T/E_0 \\ D(T)=b_0+b_1T+b_2T^2 \\ E_T=E_0\left[1-D(T)\right] \\ \sigma=E_0\left[1-D(T)\right]\left[1-D(\varepsilon)\right]\varepsilon \end{cases} \quad (1)$$

Where, $D(T)$ is the thermal damage variable; E_T and E_0 are the elastic modulus of rock sample at temperature T and room temperature, respectively; b_o, b_1 and b_2 are the parameters of rock materials; and are principal stress and rock deformation, respectively.

The relationship between force and temperature of rock materials was studied with the aid of ultrasonic waves, and the coupling equation was established[23]:

$$\begin{cases} \sigma=\mu E_0\varepsilon(1-D_T)(1-D_F) \\ D_T=1-V_T^2/V_0^2, D_F=\Omega/\Omega_M \end{cases} \quad (2)$$

$$\mu=\mu_0+A\exp\left[-2(\varepsilon-\varepsilon_c)^2/\omega^2\right]/\omega\sqrt{\pi/2} \quad (3)$$

Where, μ is the function of strain and temperature; D_T and D_F are the thermal damage variable and the force damage variable, respectively; Ω and Ω_M are the acoustic emission cumulative count of rock at the process and end of loading; V_T and V_0 are the longitudinal wave velocity of rock at temperature T and room temperature, respectively; ω and ε_c are the standard deviation of function and the peak strain, respectively.

The elastic modulus affects the deformation behaviour of rock under pressure and includes the static elastic modulus and the dynamic elastic modulus. The dynamic elastic modulus can be obtained by the longitudinal wave and shear wave velocity, and density:

$$E_d=\frac{\rho c_s^2\left(3c_p^2-4c_s^2\right)}{c_p^2-c_s^2} \quad (4)$$

Where, E_d is the dynamic elastic modulus; ρ is the rock density; c_p and c_s are the longitudinal wave and shear wave velocities, respectively.

Based on density and wave velocity, the dynamic bulk modulus of rock is:

$$K_d=\rho\left(c_p^2-\frac{4}{3}c_s^2\right) \quad (5)$$

And the dynamic shear modulus of rock can be calculated:

$$\mu_d=\rho c_s^2 \quad (6)$$

The dynamic-static ratio of elastic modulus is the most key index to characterize the relationship between the dynamic and static characteristics of rock, which can be calculated by:

$$k_{d/s}=\frac{E_d}{E_s}=\frac{E_d}{aE_d^b} \quad (7)$$

Where, E_s is the static elastic modulus; a and b are the parameters related to the rock stress state.

The theoretical longitudinal wave and shear wave velocities are obtained by:

$$\begin{cases} c_p=\sqrt{\dfrac{K_s+4\mu_s/3}{\rho}} \\ c_s=\sqrt{\dfrac{\mu_s}{\rho}} \end{cases} \quad (8)$$

Where, μ_s and K_s are the static shear modulus and the static bulk modulus, respectively.

The static elastic modulus used ultrasonic wave can characterize the change of thermal damage variable in rock. The calculation formula is as follows:

$$D\left(\hat{T}\right)=1-\frac{E_s^{UT}\left(\hat{T}\right)}{E_s^{UT}\Big|_{\hat{T}=25}} \quad (9)$$

Where, $D\left(\hat{T}\right)$ is the damage variable of the rock after a historical maximum temperature $\hat{T}$; $E_s^{UT}\Big|_{\hat{T}=25}$ and $E_s^{UT}\left(\hat{T}\right)$ are the static modulus of the rock before thermal damage and after the historical maximum temperature $\hat{T}$, respectively.

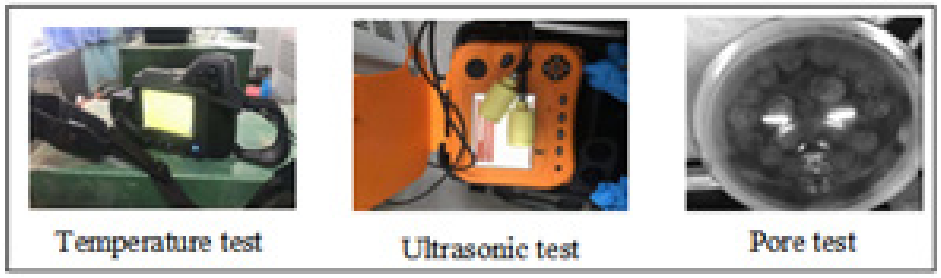
2.2 Experiment Method

The basalt used in the experiment is the abandoned rock after the excavation of Qinling Mountain tunnel in China with coordinates of 107°59.913′ and 33°48.602′. The blasting method is often used in tunnel excavation, and the basalt damage mechanism and dynamic characteristics were studied.

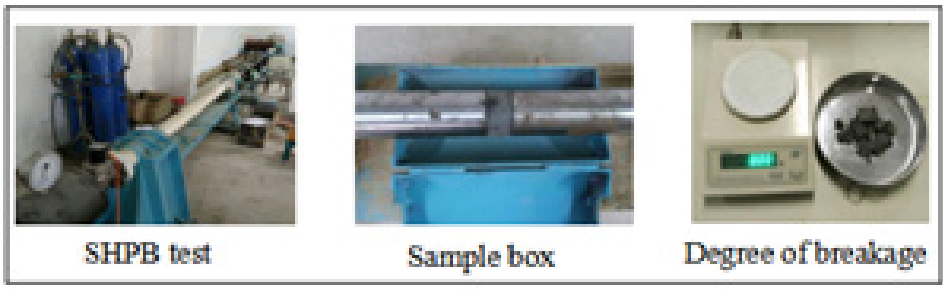
(1) According to thin slice examination, the basalt contains a certain amount of pyroxene minerals and a small number of metal minerals, which are mainly composed of plagioclase and in the shape of plate-column and can be named pyroxene basalt. Basalt is a porphyritic and inter-matrix particle structure; porphyry content is 3~5 %, and particle size is 0.5~1 mm. It is composed of disordered lath-shaped plagioclase and monoclinic pyroxene or orthopyroxene, and the pyroxene is filled in between plagioclase particles to form a local interfile structure. Under China's "Test Code for Dynamic Characteristics of Rocks" (T/CSRME 001-2019), the section size of the specimen should be consistent with that of the impact pressure rod, the ratio of height to diameter is 1/2, the abandoned basalt rock was selected, cored, polished and processed into cylindrical samples with sizes of Φ50×25 mm, as shown in Figure 1(a). The diameter error of the sample is not more than 2 mm, the height error is not more than 1mm, and the flatness error is less than 0.05 mm. The average dry density of the basalt sample is 2.89×10^3 kg/m^3, the average thermal conductivity is 1.827 m·K, the average thermal diffusion coefficient is 0.8083 mm^2/s, and the average specific heat capacity is 782 kg·K. The natural water content is 12.8%. The standard rock samples were dried naturally for 15d and then heat treated. An MXQ1700-20 box-type atmosphere furnace was used to heat the processed basalt



(a) Sample collection, preparation and heating.



(b) Sample damage test.



(c) Sample impact failure test.

Figure 1. Sample making and test scheme design.

sample, and the heating chamber size is 300×200×200 mm. Per China's "Regulation for testing the physical and mechanical properties of rock" (DZ/T 0276-2015), the designed heating temperatures were set to 0℃, 100℃, 200℃, 300℃, 400℃ and 500℃. The heating times after reaching the set temperature were controlled to 60min, 90min, 120min and 150 min, the heating rate was controlled to 10 ℃/min, and the temperature control accuracy was ±5℃[24]. Three samples per group, a total of 24 groups.

(2) After the heating is completed, the power supply is cut off, and the surface temperature of the sample is measured by the American Fillier T420 thermal imager. After the sample was naturally cooled to room temperature, the internal thermal damage of the sample was tested by a NN-4B non-metallic ultrasonic wave velocity tester. The thermal damage of the sample is the structural change caused by the matter and energy changes of the minerals inside the basalt. The thermal damage of the sample can be reflected by the change in the open porosity of the sample. The open porosity of the sample was measured by the water saturation method, as shown in Figure 1(b). After the sample is immersed in water 20mm above the surface for 48h, the saturated water content of the sample is measured, and the volume of water is the open pore volume. In addition, a digital scanning electron microscope equipment JSM-6460LV produced by Nippon Electronics Co., Ltd. was used to conduct an SEM test to observe the microstructure changes of thermal damage in basalt.

(3) The equipment used for the SHPB impact test on basalt was jointly designed by Northwest Institute of Nuclear Technology and Luoyang Tengyang Machinery Technology Co., LTD. of China, as shown in Figure 1(c). Per China's "Test Code for Dynamic Characteristics of Rocks" (T/CSRME 001-2019), to reduce friction, both ends of basalt samples were applied lubricating and placed in the test box with sizes of Φ100×200 mm. According to the impact velocity of the bullet, the strain rate of the shock wave in the entrance bar is controlled, and the air pressure of the test valve is set as 0.2MPa, 0.3MPa and 0.4MPa respectively. The compression axis of the specimen, the pressure bar and the bullet are in the same straight line.

Based on one-dimensional elastic stress wave theory and two-wave method formula, the dynamic properties of basalt materials are obtained:

$$\begin{cases} \sigma_s(t)=\dfrac{EA}{A_s}\left[\varepsilon_I\left(X_{G_1},t\right)+\varepsilon_R\left(X_{G_1},t\right)\right]=\dfrac{EA}{A_s}\varepsilon_T\left(X_{G_2},t\right) \\ \varepsilon_s(t)=-2\dfrac{C_0}{l_s}\int_0^t\left[\varepsilon_T\left(X_{G_2},t\right)-\varepsilon_I\left(X_{G_1},t\right)\right]=-2\dfrac{C_0}{l_s}\int_0^t\varepsilon_R\left(X_{G_1},t\right) \\ \dot{\varepsilon}_s(t)=-2\dfrac{C_0}{l_s}\left[\varepsilon_T\left(X_{G_2},t\right)-\varepsilon_I\left(X_{G_1},t\right)\right]=-2\dfrac{C_0}{l_s}\varepsilon_R\left(X_{G_1},t\right) \end{cases} \tag{10}$$

Where A and A_s are the cross-section area of the press bar and the sample respectively, mm^2; l_s is the sample length, mm; $\sigma_s(t)$ is the average stress in the sample at time t, MPa; $\varepsilon_s(t)$ is the average strain in the sample at time t; E is the elastic modulus of sample; ε_I, ε_R and ε_T are the incident, reflection and transmission wave deformation respectively; C_0 is the constant.

By means of sieve tests, the basalt fragments after the impact test were collected, the standard sieve was used for sieving, the sieve diameters are: 2.5mm, 5mm, 10mm, 15mm, 20mm, 25mm, 30mm and 35mm, respectively. The mass percentage of fragments passing through the sieves after heating at different temperatures was analyzed, as shown in Figure 1(c).

3. Results and Discussion

3.1 Thermal Damage Mechanism

The thermal damage mechanism of basalt is revealed through the temperature rise rate, ultrasonic attenuation rate, open porosity difference and microstructure change.

(1) The damage to the sample has an important relationship with the uneven change in temperature. On the one hand, the temperature causes the difference in the internal thermal stress of the sample, and on the other hand, it causes the difference in the thermal change of the mineral inside the sample, including the change of substance solid and liquid, the change of substance composition, the change of substance density and volume. It can be seen from Figure 2 that the higher the heating temperature and the longer the heating time, the higher the temperature rise rate of the basalt sample. After reaching the set heating temperature, the temperature rise rate of the sample showed a stable trend. With the further

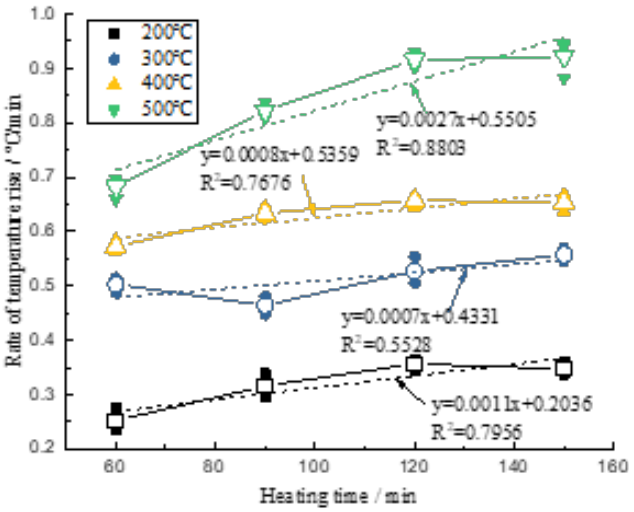


Figure 2. Variation trend of sample temperature rise rate.

progress of heating time, the temperature rise rate of the sample increases first and then decreases, and finally, the temperature of the sample is consistent with that of the heating chamber.

(2) The ultrasonic wave velocity is directly related to the rock density, reflecting the elastic modulus, and the change of ultrasonic wave velocity during heating can better reflect the defects and cracks in the basalt sample. As can be seen from Figure 3, with the increase of heating time at each heating temperature, the attenuation rate of ultrasonic wave velocity of basalt samples showed an obvious increasing trend. The higher the set heating temperature, the faster the attenuation rate of ultrasonic wave velocity. The shorter the heating time and the lower the set heating temperature, the greater the dispersion of the attenuation rate of ultrasonic wave velocity of each sample in each group, indicating the non-uniformity of the initial thermal damage inside the basalt sample and the difference between the thermal change of the internal mineral. With the increase of heating time and set heating temperature, the dispersion of attenuation rate of ultrasonic wave velocity of each sample in each group decreased, indicating that the damage degree internal the sample increased in the late heating period.

(3) Open porosity is a description of the percentage of water-saturated pore volume in the total volume of the rock, which can reflect the development and change of cracks in the sample to some extent. Figure 4 shows that with the increase of heating time and set heating temperature, the difference in opening porosity of the sample becomes larger. When the heating time increases, the larger the set heating temperature, the larger the difference of open porosity, and the greater the dispersion of each sample in each group, indicating that the greater the change of open porosity of the sample, the stronger the degree of thermal damage of the sample. However, it can be obtained from the changing trend of 200°C and 300°C with a heating time that the open porosity

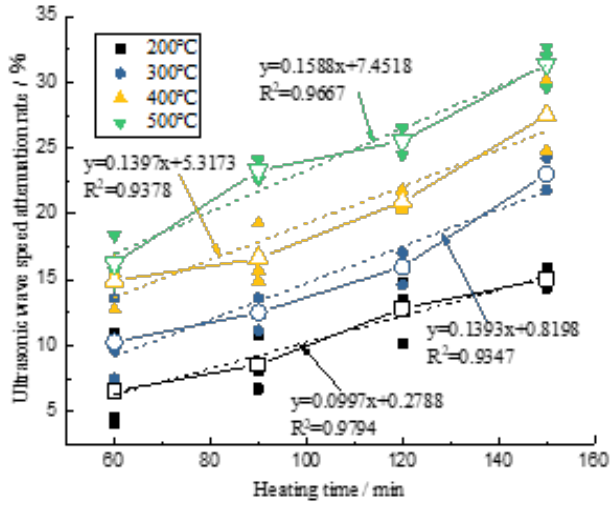


Figure 3. Variation trend of attenuation rate of ultrasonic wave velocity in sample.

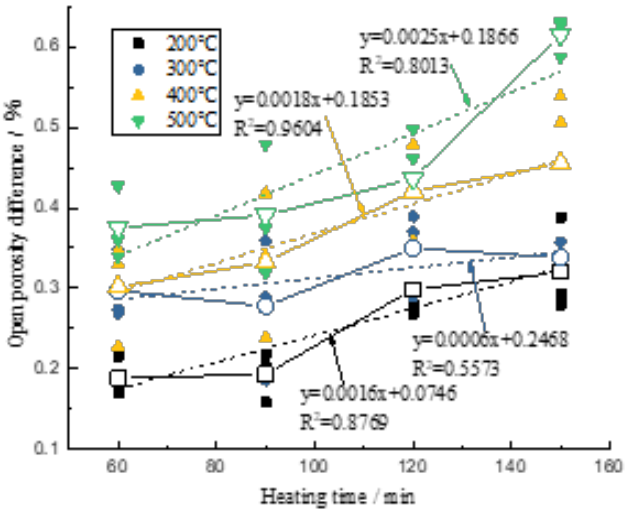
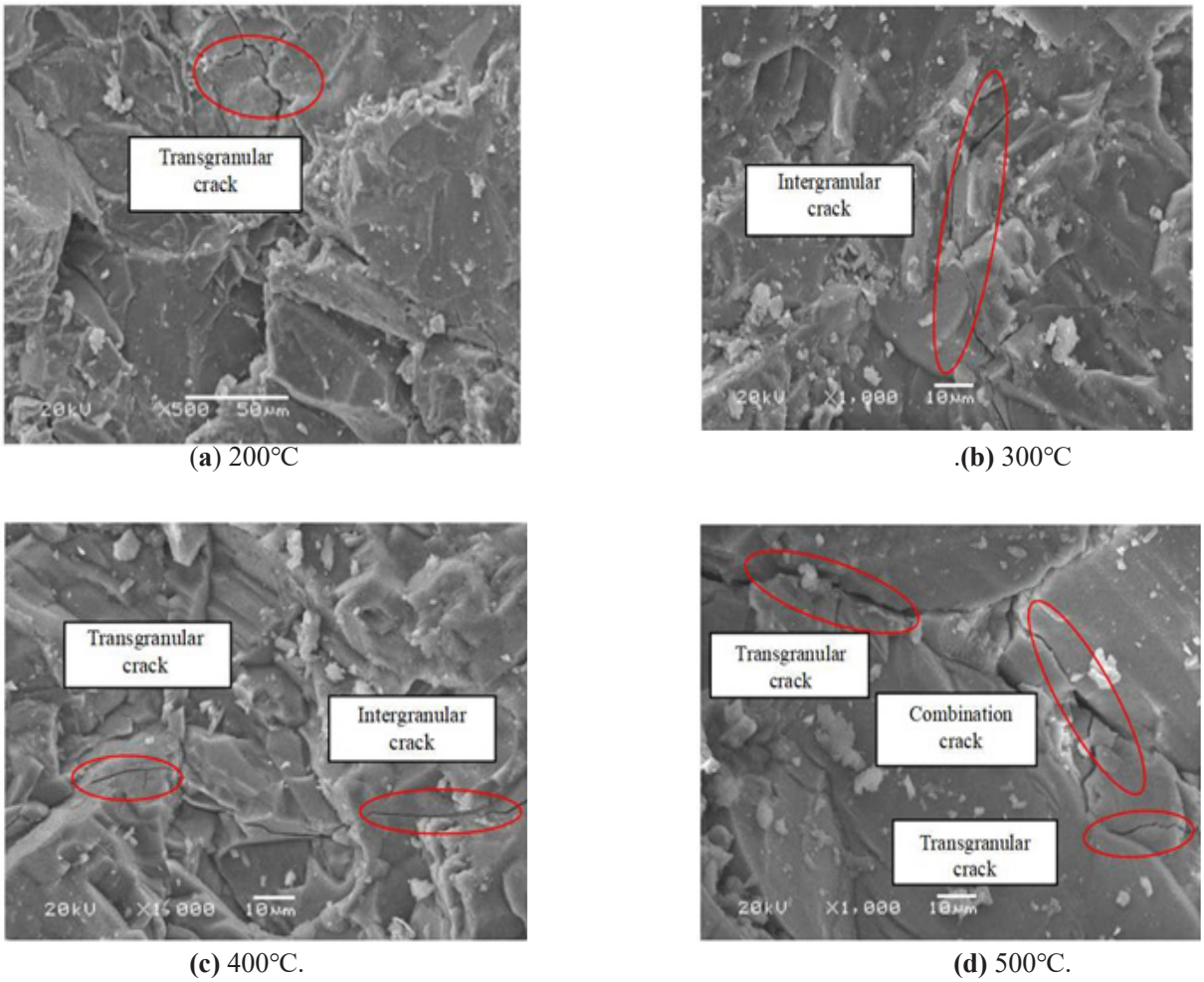


Figure 4. Variation trend of open porosity difference of sample.



(a) 200°C **.(b)** 300°C

(c) 400°C. **(d)** 500°C.

Figure 5. The microstructure of the basalt surface changes after different heating temperatures.

cannot reflect the thermal change of the mineral inside the sample, and the open porosity will close under the thermal deformation of the sample subjected to the action of extrusion. So the difference in the open porosity decreases with the increase of heating time.

(4) To further investigate the thermal damage properties of basalt, the SEM method was used to observe the generation and expansion of microscopic surface cracks before and after basalt heating, as shown in Figure 5.

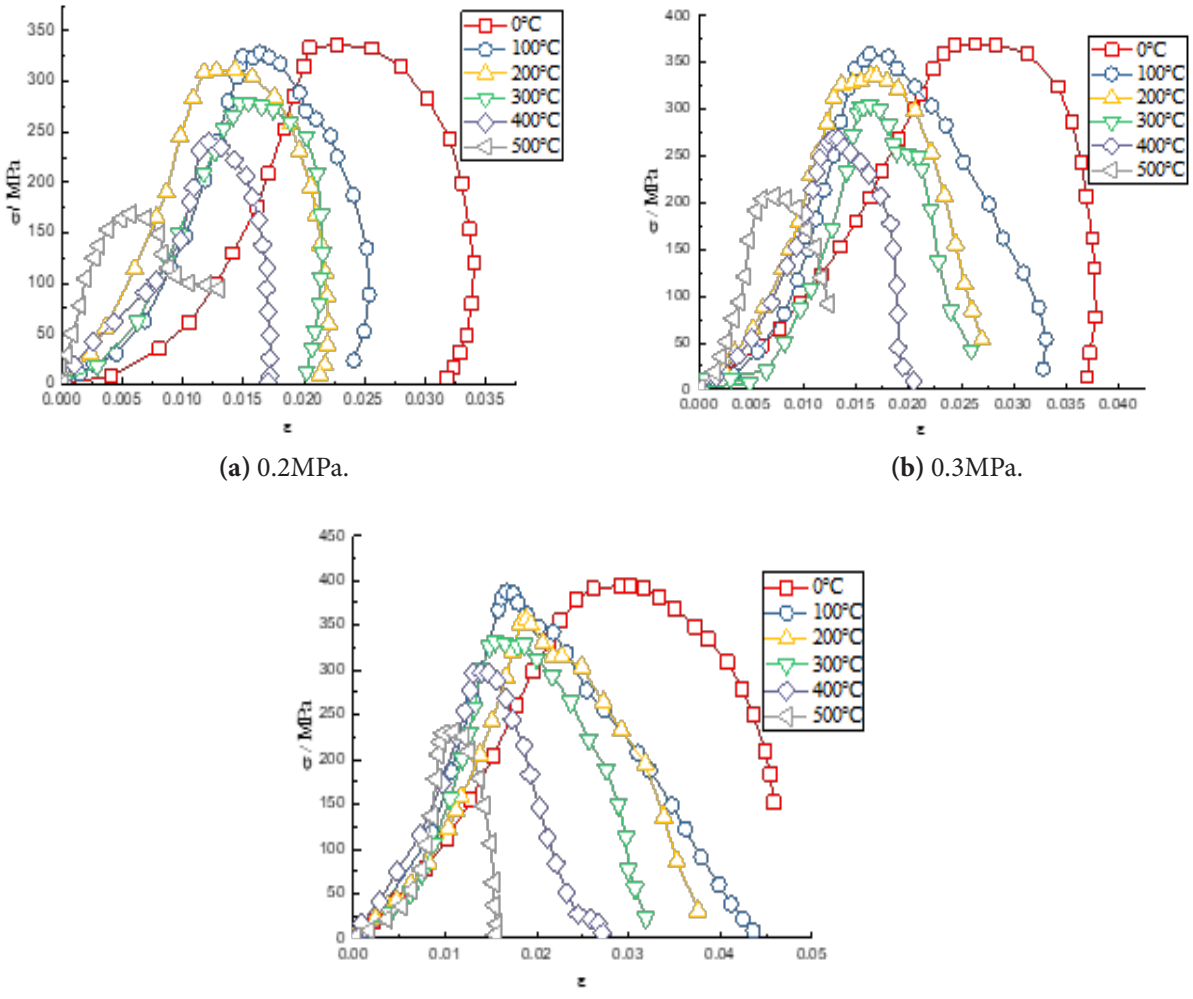
It can be obtained from Figure 5 that with the increase in heating temperature, internal cracks occur in local positions and continue to expand, and the direction of crack growth is connected to the composition of rock mass minerals, which usually occurs at the interface between heat-absorbing substances and non-heat-absorbing substances. Due to the difference in heat absorption capacity, the heating degree of rock composition minerals is different, which results in the formation of tensile or shear stress in the rock and makes the rock thermal fracture. When the temperature rises further to a certain extent, some minerals in the rock mass will melt, resulting in huge cracks or voids. According to the mineral composition and structural characteristics in the basalt, the tensile stress generated by the thermal expansion of pyroxene and plagioclase leads to the internal transgranular fracture, and the pyroxene minerals in the basalt are filled between the plagioclase, and the two expand differently in the heat field to form a fracture along the particle interface. When the temperature reaches a certain degree, the mineral will melt and with the gradual development of transgranular

fracture, the basalt sample will eventually lose its bearing capacity.

3.2 Dynamic Mechanical Properties

The dynamic characteristics of basalt samples under different heating temperatures, which are dominated by internal thermal damage, show different stress-strain curves and different degrees of breakage.

(1) Heating treatment has an important influence on the dynamic mechanical properties of basalt. With the heating temperature increasing, the peak stress and the peak strain of basalt during failure decrease. And with the heating temperature increasing, the influence of impact pressure on the stress-strain curve of the sample also gradually increases. As can be obtained from Figure 6, under the same heating temperature, when the impact pressure increases, the peak stress and the peak strain of the basalt sample during failure gradually increase. Under the same impact pressure, when the heating temperature increases, the arc degree of the post-peak stress-strain curve gradually decreases, and the rate of post-peak stress reduction gradually increases. Under the impact pressure of 0.2MPa and 0.3MPa, when the heating temperature exceeds 300°C, the stress-strain curve shape of the sample changes greatly, and the peak stress decreases greatly at 500°C. Under 0.4MPa impact pressure, the stress-strain curves of the samples with different heating temperatures are similar, and the peak stress decreases slightly at 500°C. The internal thermal damage of basalt samples under the action of large impact pressure has no obvious influence on the stress-strain curve shape.



(a) 0.2MPa.

(b) 0.3MPa.

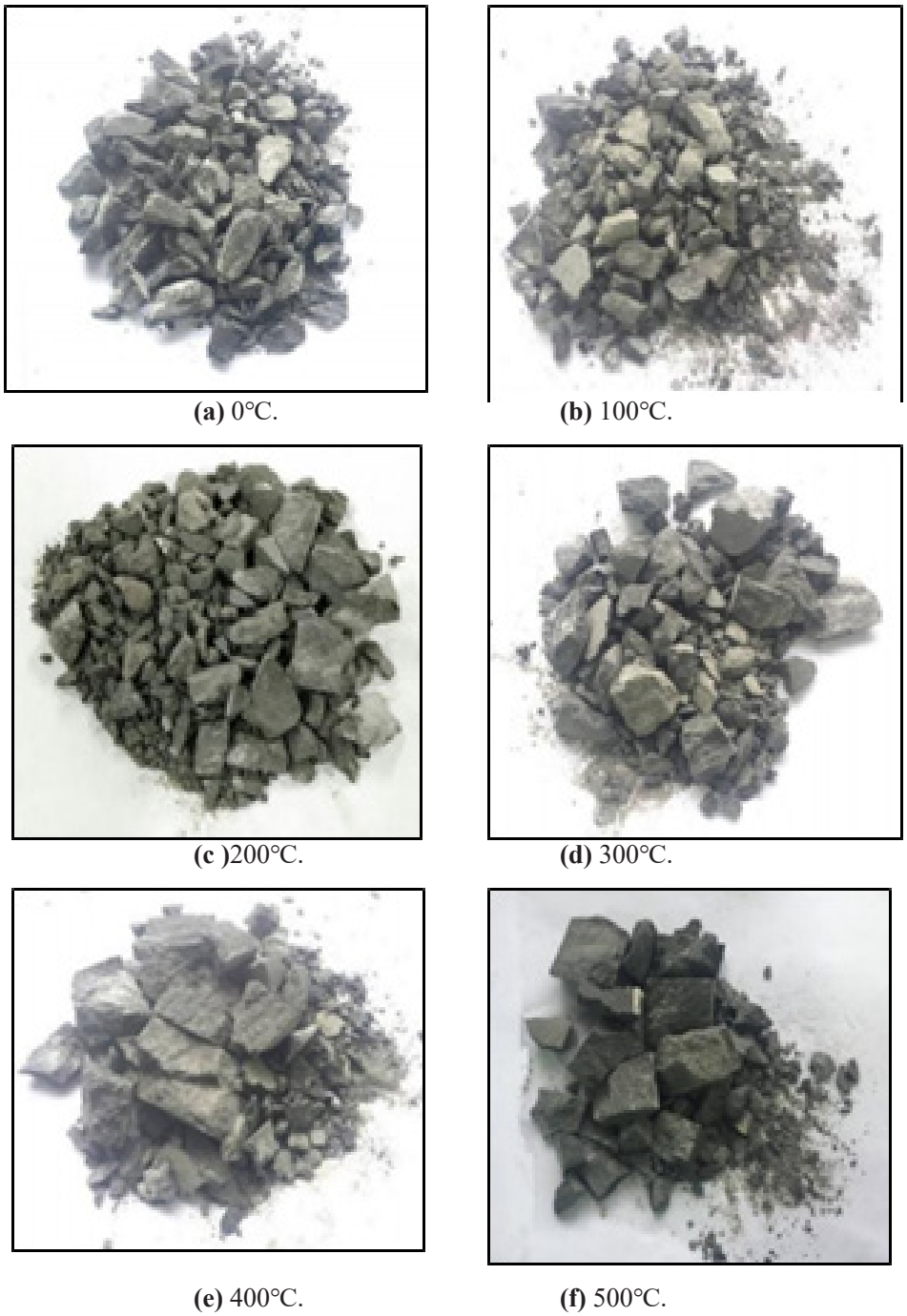
(c) 0.4MPa.

Figure 6. Stress-strain curve of basalt heated at different temperatures with impact pressure.

It can be seen from the influence of internal thermal damage on the stress-strain curves of basalt samples.

Internal thermal damage reduces the impact resistance of the sample. The larger the thermal damage is, the weaker the internal structure of the sample is to withstand the impact load, and the faster the sample will be destroyed.

- The internal thermal damage of the sample caused by mineral qualitative change makes it brittle under impact load. The cementation between



(a) 0°C. **(b)** 100°C.

(c)200°C. **(d)** 300°C.

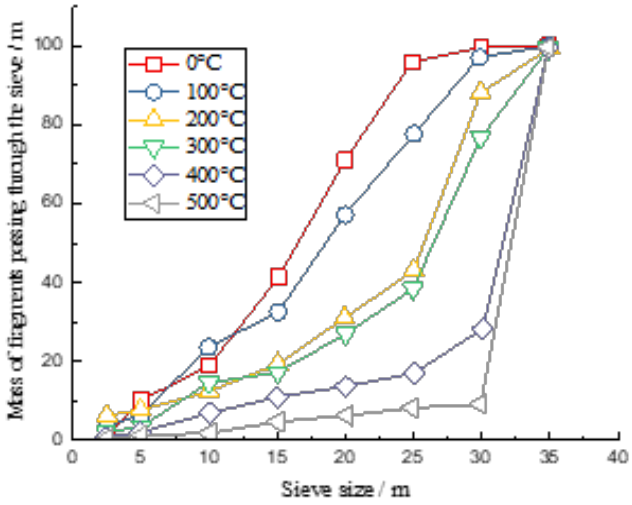
(e) 400°C. **(f)** 500°C.

Figure 7. Impact-breaking degree of basalt at different temperatures.

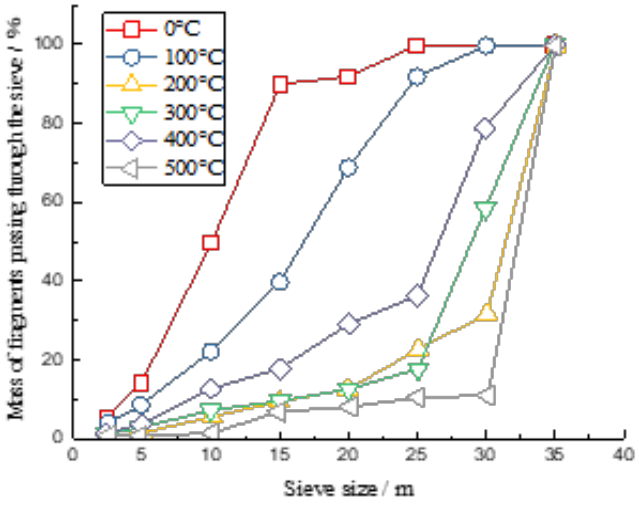
minerals is reduced, and the minerals are prone to fragmentation.

- The non-uniform stress inside the sample resulting from thermal damage makes the failure of the sample more likely to develop in the direction of stress concentration under impact load, and the ability to absorb the impact energy of the sample decreases.

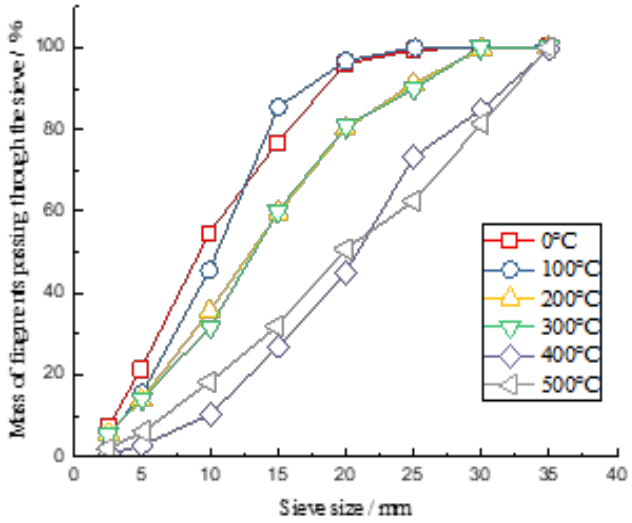
(2) As can be obtained from Figure 7, with the increasing heating temperature, the degree of fragmentation of basalt samples after the impact test gradually decreases. Before the impact test, weak structural planes such as cracks are formed inside the basalt sample by heating. During the impact test, the load is first released on the weak structural plane and the sample was locally damaged. As a result, the internal stress of the same part of the sample after heating is smaller than that caused by the impact load before heating, and the smaller stress does not cause the fracture of the part. From the perspective of energy, it can be seen that the degree of fragmentation of the sample is greater when the heating temperature is lower. The more energy required for the fragmentation of the sample, the larger the impact load required, and the higher the impact strength of the sample. The higher



(a)0.2MPa.



(b)0.3MPa.



(c)0.4MPa.

Figure 8. Accumulation curve of basalt impact fragments under different temperatures and impact pressure.

the heating temperature, the smaller the degree of fragmentation of the sample, that is, the fracture caused by heating on the weak structural surface requires a lower impact energy, the impact resistance of the sample is rapidly lost and the impact strength is reduced during the test.

As can be seen from Figure 8, under different impact pressures, the upward concave trend of the cumulative curve of sample fragments is bigger and bigger with the increase of heating temperature, showing that the proportion of large-sized fragments is increasing. Under different heating temperatures, with the impact load increasing, the upward convex trend of the cumulative curve of sample fragments is bigger and bigger, indicating that the larger the impact energy, the greater the degree of fragmentation of the test block. Under the impact pressure of 0.4MPa, the larger impact load reduces the dispersion of the sample fragment accumulation curve at each heating temperature, indicating that the larger impact energy will further impact the fragment after the failure of the sample, thus increasing the fraction of the small-size sample fragment. The reasons for the differences in the accumulation curves of sample fragments caused by different heating temperatures are as follows:

The higher the heating temperature is, the bigger the internal thermal damage of the sample, and the sample first fails along the thermal damage direction under the impact load.

The impact energy is mainly dissipated in the thermal damage area inside the sample, and the distribution of thermal damage inside the sample affects the fragment distribution of the sample after impact failure.

The thermal damage distribution inside the sample is mainly determined by the thermal reaction of different minerals, and the composition and structure of the internal minerals determine the thermal damage change mechanism of the basalt properties.

4.0 Conclusion

In this paper, the abandoned basalt is processed into standard samples, and after different heating treatments and heating times, the surface temperature, P-wave velocity, open porosity, SEM, impact stress-strain curve and the degree of breakage of the sample are measured. The main results are as follows:

- With the rise of heating temperature and the growth of heating time, the temperature rise rate of basalt samples first increases and then decreases, and the attenuation rate of ultrasonic wave velocity and the difference of open porosity gradually increases. The thermal damage caused by heating to rocks mainly occurs around heat-absorbing minerals. Ultrasonic parameters can reflect the degree of thermal damage in basalt, and can also be used to establish the constitutive model of rock thermal damage and mechanics.
- With the increase of heating temperature, the impact peak stress and peak strain of basalt samples decrease continuously. With the heating temperature increasing, the plasticity of basalt samples gradually decreases, the impact resistance gradually weakens, and the damage difference caused by impact pressure becomes more and more obvious.
- With the increase of heating temperature, the degree of fragmentation of the basalt sample becomes larger and larger, and the impact load is mainly discharged along the thermal damage interface. With the rise of heating temperature, the accumulation curve of basalt fragments gradually changes from convex to concave, and the degree of fragmentation gradually increases under the impact load.

5.0 Acknowledgements

This paper is funded by the Key Scientific Research Projects of Higher Education Institutions in Henan Province (25A560018).

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