

Research Article

Influence of Real-Time Heating on Mechanical Behaviours of Rocks

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The rock mechanical properties under the effect of high temperature present a great significance on underground rock engineering. In this paper, the mechanical properties of sandstones, marbles, and granites under real-time heating were investigated with a servo-controlled compression apparatus. The results show that mechanical behaviours of all the three types of rocks are influenced by real-time heating to different degrees. Due to thermal cracking, the uniaxial compressive strengths decrease as the heating temperature rises from room temperature to 400°C. Above 400°C, the sandstone exhibits a significant increase in UCS because of the sintering reaction. The sintering enlarges the contact area and friction between crystal grains in the sandstone, which strengthens the bearing capacity. For marbles, the UCS continues to decrease from 400°C to 600°C due to thermal cracking. However, the carbonate in the marble begins to decompose after 600°C. The generated particles would fill the cracks in the marble and increase the strength. For granites, their UCS presents a sharp decline after 400°C because of thermal cracking. For all rock elastic modulus, they present a decreasing trend, and this indicates that the rock's ability to resist deformation gradually weakens under the effect of temperature. In general, rock mechanical behaviours under real-time heating differ from those in normal situations, and use of the parameters presented here is important for underground rock engineering related to high temperature and can improve the precision in theoretical and numerical analysis.

1. Introduction

Physical and mechanical properties of the rock have attracted significant attention in a number of research fields, such as coal mining, underground coal gasification, and geothermal resource exploitation [1–3]. In physical experimental tests, characteristics of rock matrix permeability, failure mode, and mechanical parameters present large changes after loading process [4, 5]. There is a growing demand for extensive understanding of rock behaviours under the influence of heating, especially above 200°C where material properties change dramatically [6]. Previous research on rock properties generally focused on sandstones, granites, and calcarenites. It is well known that rock

mechanical properties and the corresponding internal mechanism at high temperature are dependent on the rock type. Previous studies have shown that thermal cracking, phase transition, and decomposition all contribute to variation of rock mechanical properties [7, 8].

Sandstone is a typical sedimentary rock in the Earth crust, and some scholars have conducted a series of experiments on its physical and mechanical characteristics under different experimental conditions, such as cyclic loads [9–11] and crack angle [12]. However, with temperature changes, sandstones present a different variation than those in normal condition. Török and Hajpál [13] found that the cementing agents and minerals of sandstones undergoing thermal treatment affect the rock physicomaterial

properties. Santos et al. [14] conducted a series of tests on sandstones (including some artificial materials) under different heating regimes and reported no clear distinctions of rock mechanical properties below 200°C, while mechanical properties decrease uniformly with a temperature above 200°C. In an experimental study, McCabe et al. [15] measured weight loss and visual surface damage to sandstones after exposure to fires and reported that the fracture structure and the soot are the primary factors that affect rock mechanical properties. The soot is hydrophobic in character, so surface permeability is reduced. The decomposition of minerals after exposure to high temperature results in an expansion of internal rock fractures, leading to weight loss and surface visual damage. Liu and Xu [16] performed a series of tests on the uniaxial compressive strength (UCS) of sandstones up to 1000°C and found that the temperature threshold for brittle-ductile deformation of sandstones is 600°C. Within this temperature range, the UCS generally decreases with increase in the temperature; UCS changes are insignificant below 800°C but increase slightly above 800°C and then decrease sharply further, as does the elastic modulus. Many similar physical tests have been conducted to measure the UCS and elastic modulus of sandstone [17–19], as summarized by Tian et al. [20]. Overall, under the effect of temperature, physicochemical properties of sandstones differ from those in natural condition.

These factors also affect the mechanical properties of calcarenites [21–24]. Yavuz and Topal [25] conducted experiments to study the effect of drying temperature on marble physicochemical properties and reported that higher temperature causes significant damage. Mao et al. [26] concluded that mechanical properties of limestone change pronouncedly above 600°C when samples undergo plastic deformation. The p-wave velocity of the carbonate rock has been reported to negatively correlate with temperature [27]. Carbonate rocks at 800°C have also been reported to undergo a sharp decrease in rock's UCS compared with sandstone and granite due to the composition of the carbonate [24].

However for granites, many studies concentrate on burial depths of granite and the fracture mode [28–30]. Under the effect of temperature, previous studies have shown a small decrease in UCS with temperature below 400°C, followed by a significant decrease above 400°C [31–33]. Chen et al. [34] reported a decrease in granite UCS, elastic modulus, and fracture toughness up to 800°C, above which no further changes were observed. A freeze-thaw cycling test demonstrated that granite peak strain increases with temperature, while UCS and elastic modulus decrease [35]. Kumari et al. [36] conducted a series of hydraulic fracturing experiments and reported a linear reduction of granite breakdown pressure with a temperature up to 300°C. Upon heating of granite samples, the evaporation of free water, asymmetrical thermal expansion, phase transition of quartz, and thermal cracking induced by thermal stress contribute to the propagation of cracks, all of which affect the mechanical properties of granite [6, 37–39].

The literature shows that rock mechanical properties fluctuate only slightly with temperature rising up to

approximately 400°C–600°C, above which substantial changes occur. The main factors that influence rock mechanical properties are thermal cracking and the asymmetric thermal expansion of minerals [18]. In terms of specific applications (e.g., underground coal gasification, enhanced geothermal system, and even building fire), the rock matrix is under the influence of a range of real-time temperatures. Under the real-time temperature, the rock mechanical behaviour varies significantly. The majority of previous studies are normally addressed to rock samples with heat treatment rather than under real-time temperature, and it is insufficient for conducting engineering design due to different rock categories in rock underground engineering.

In this study, we investigated igneous, sedimentary, and metamorphic rocks to better understand the different rock mechanical behaviours at high temperature and to establish a framework to compare mechanical properties of different rocks during real-time heating. The results obtained here have important implications for the prediction of rock behaviour in real high-temperature scenarios and can prevent serious damage with the help of a new technique, like 3D seismic technology [40]. We compare the rock failure mechanism of each type of rocks with a particular focus on UCS and elastic modulus.

2. Materials and Methods

2.1. Sample Collection and Specifications. Sandstone and marble samples were, respectively, collected from Jvxian, Laizhou, and Wenshang in Shandong Province, China. All samples were cut into $\phi 50 \times 100$ mm with a surface parallelism value of within 0.05 mm, in correspondence with the ISRM standard [41]. No visible flaws were observed on the sample surfaces.

2.2. Experimental Apparatus and Methods. The experimental setup included WAW-600, a furnace, and a temperature controller. As in previous studies [42], all specimens were oven-dried for 24h at 105°C to remove moisture. A temperature controller was used to heat the specimens at a rate of 2°C/min, ensuring a homogenous internal and external sample temperature, which is more representative of a natural setting. Furthermore, fast heating rates lead to larger thermal stress, which is beyond the scope of the present study.

Samples were held at the target temperature for 2 hours to allow for equilibration [43] and then compressed at a rate of 0.5 MPa/s until the sample fails. Tests were performed at room temperature (25°C), 200°C, 400°C, 600°C, and 800°C, respectively. Additional temperature points were added when appropriate to better constrain the UCS variation. At least three samples were tested at each temperature point.

3. Results

3.1. Rock Stress-Strain Characteristics. The uniaxial compression results for each rock type are shown in Figure 1. The stress-strain behaviours and failure photographs of sandstone are quite different from that of marble during the

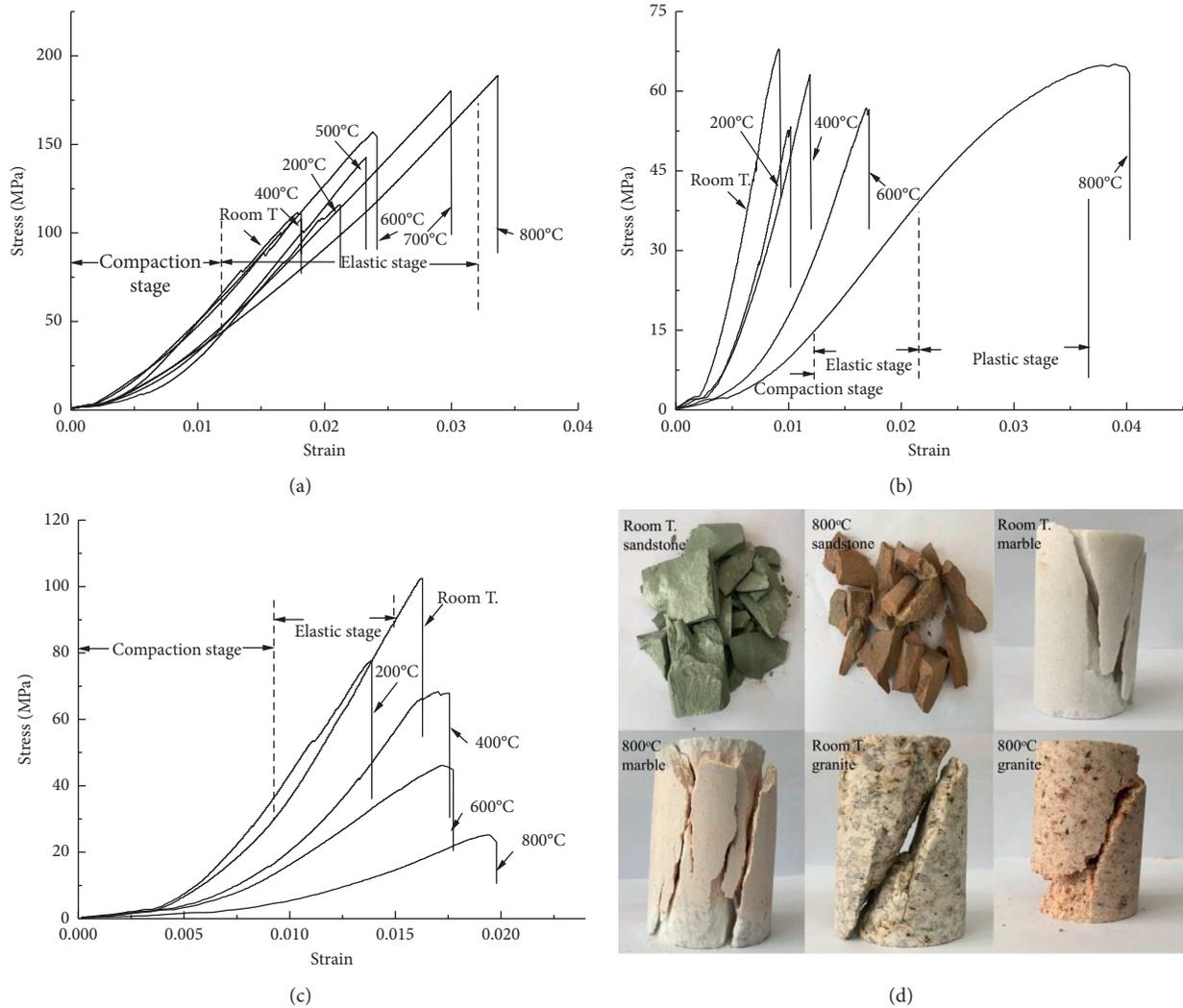


FIGURE 1: Stress-strain curve and failure photographs of rock samples as a function of temperature: (a) sandstone samples, (b) marble samples, (c) granite samples, and (d) failure photograph.

compaction and elastic stages at the same temperature (Figure 1). The stress-strain curve of marbles clearly shows a ductile stage at 800°C, as shown in Figure 1. Figure 2 shows the peak strain of rock samples at different temperatures. Before 800°C, failure pictures are similar for all temperature points.

The characteristics of peak strain variation can be summarized as follows.

The sandstone peak strain rises by 85.3% from 0.01815 at 25°C to 0.03364 at 800°C. However, no distinct plastic stage is observed after the elastic stage on the stress-strain curve (Figure 1(a)), which indicates that the failure mode of sandstone remains brittle over this temperature range.

For marbles, the peak strain increases by 325% from 0.0092 at 25°C to 0.0391 at 800°C. The stress-strain curves in Figure 1(b) demonstrate the distinct failure mode transition from brittle to ductile between 600°C and 800°C.

The granite peak strain increases only by 33.36% from 0.01484 at 25°C to 0.01979 at 800°C with a continuous decrease in the peak stress. At 800°C, the compaction stage of

the stress-strain curve is extended and the elastic stage is shortened, which implies that a subsequent transition from brittle to ductile failure modes occurs at the higher temperature.

3.2. Variation Characteristics of Rock Uniaxial Compressive Strength. The UCS is the peak stress experienced by a rock sample during the loading process. Variations in average UCS are plotted in Figure 3.

From which, the following characteristics can be summarized.

The UCS of sandstone samples below 400°C decreases gradually with the temperature from 117.16 MPa at 25°C to 108.62 MPa at 200°C and 107.3 MPa at 400°C. However, above 400°C, UCS values increase sharply, reaching 196.63 MPa at 800°C. Compared with values at room temperature, sandstone UCS changes by 34.5%, 36.4%, 45.4%, and 67.8% at 200, 400, 600, and 800°C, respectively. Therefore, the reversal point should be in the range of 400°C to 500°C.

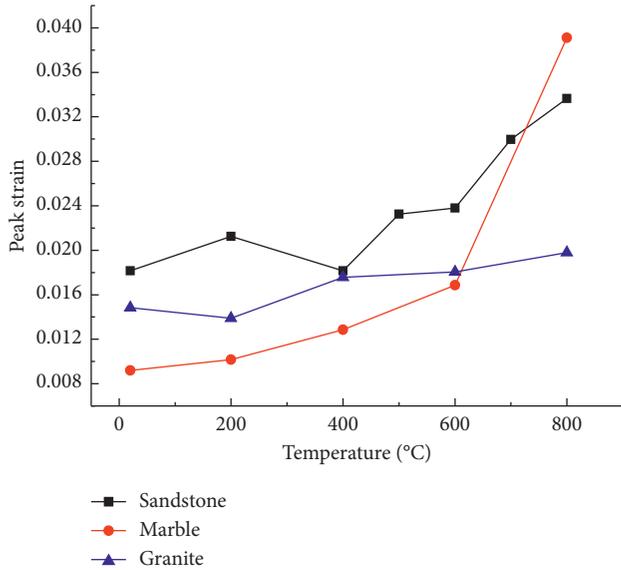


FIGURE 2: Peak strain for the three rock samples as a function of temperature.

The UCS of marble samples decreases linearly with temperature to a minimum of 55.84 MPa at 600°C and then increases slightly to 64.45 MPa at 800°C. Granites' UCS decreases with temperature to 32.3 MPa at 800°C, a reduction of about 70% from that at the room temperature.

In summary, the effect of temperature on UCS is strongly dependent on the rock type. Marbles' UCS values demonstrate only slight changes with an increase in the temperature, while the sandstone behaves quite differently above 400°C with a sharp increase in UCS. Below 400°C, the UCS of both types of rocks decreases slightly, demonstrating a weak temperature effect over this interval. Temperature effect above 400°C, however, is markedly different for each type of the rocks and therefore requires appropriate consideration.

3.3. Variation Characteristics of Rock Elastic Modulus. The elastic modulus is an important rock mechanical parameter commonly used in rock engineering. The elastic modulus can be calculated as a linear fitting to the stress-strain curve. In this study, we fit curves to values from 30% to 70% of the rock UCS. Elastic modulus variations are plotted in Figure 4. In general, the elastic modulus of all samples decreases, while each type of the rock demonstrates its own specific characteristics.

The elastic modulus of sandstone samples increases from 7.97 GPa at 400°C to 8.69 GPa at 500°C, both of which are lower than the value 9.17 GPa at the ambient temperature. From Figure 1, it is observed that sandstone's UCS increases sharply at 500°C with a stronger temperature dependence than that of the peak strain, which results in the small increase in the sandstone elastic modulus. These results are also indicative of strengthening of the sandstone mechanical properties.

The elastic modulus of marbles decreases linearly from 10.03 GPa at 25°C to 2.5 GPa at 800°C. Although the marble

UCS increases between 600 and 800°C, the peak strain over the full temperature range increases by about a factor of four, and the decrease in elastic modulus is observed.

The elastic modulus of granite samples generally decreases with temperature from 10.47 GPa at room temperature to 3.32 GPa at 800°C. The elastic modulus at 400°C is higher than those values at 200°C, which we speculate to be due to mechanical property changes at this temperature that increase the data scatter.

Although the elastic modulus of both rock samples decreases with temperature, each rock type shows markedly different magnitudes. The elastic modulus of marbles decreases by several times compared with their ambient temperature, while the sandstone elastic modulus decreases by about 25%. The UCS values of marbles decrease and peak strain increases with temperature, while sandstone UCS values increase sharply above 500°C. The variations of the rock elastic modulus are influenced by the combined effect of rock strain and UCS.

4. Analysis and Discussion

Previous investigations have shown that rock mechanical properties may change at high temperature due to the evaporation of free water, microcrack propagation, mineral dehydration, decomposition, and phase changes [37, 44]. A number of tests have been conducted to evaluate the internal relationship between rock mechanical parameters and external factors.

4.1. Rock Uniaxial Compression Strength (UCS). The temperature threshold for the α - β quartz phase change is 573°C [7], and the temperature threshold for the decomposition of calcium carbonate is about 800°C [15]. These phenomena would therefore not contribute to the increasing UCS trend observed in sandstone samples above 500°C. Furthermore, thermal cracking during heating leads to the propagation of microcracks that also diminishes rock bearing capacity.

The mineral composition of sandstone samples was measured by X-ray diffraction (XRD) (Table 1) and found to contain quartz, potassium feldspar, and TCCM (kaoline, etc., clay minerals), similar to the raw materials found in many ceramics. When temperature reached 450°C, the mineral of Fe^{2+} in sandstone experiences the following chemical reaction. In the process, the colour of sandstone changes from greyish-green into red (Figure 1(d)). Compared with the previous research work [45], the composition of sandstone is 20% mica, 30% kaolinite, 30% quartz, 15% albite, and 10% siderite, which is different with the contents of sandstone in this paper. Under real-time heating, no sintering reaction as following was found in that study, and thus sandstone UCS experienced a decreasing trend after 400°C rather than a sharp increasing trend:



In the manufacture of certain ceramics, the percentage of potassium feldspar is usually 20% to 30%, and the temperature for the sintering reaction is 0.5 to 0.8 Tm

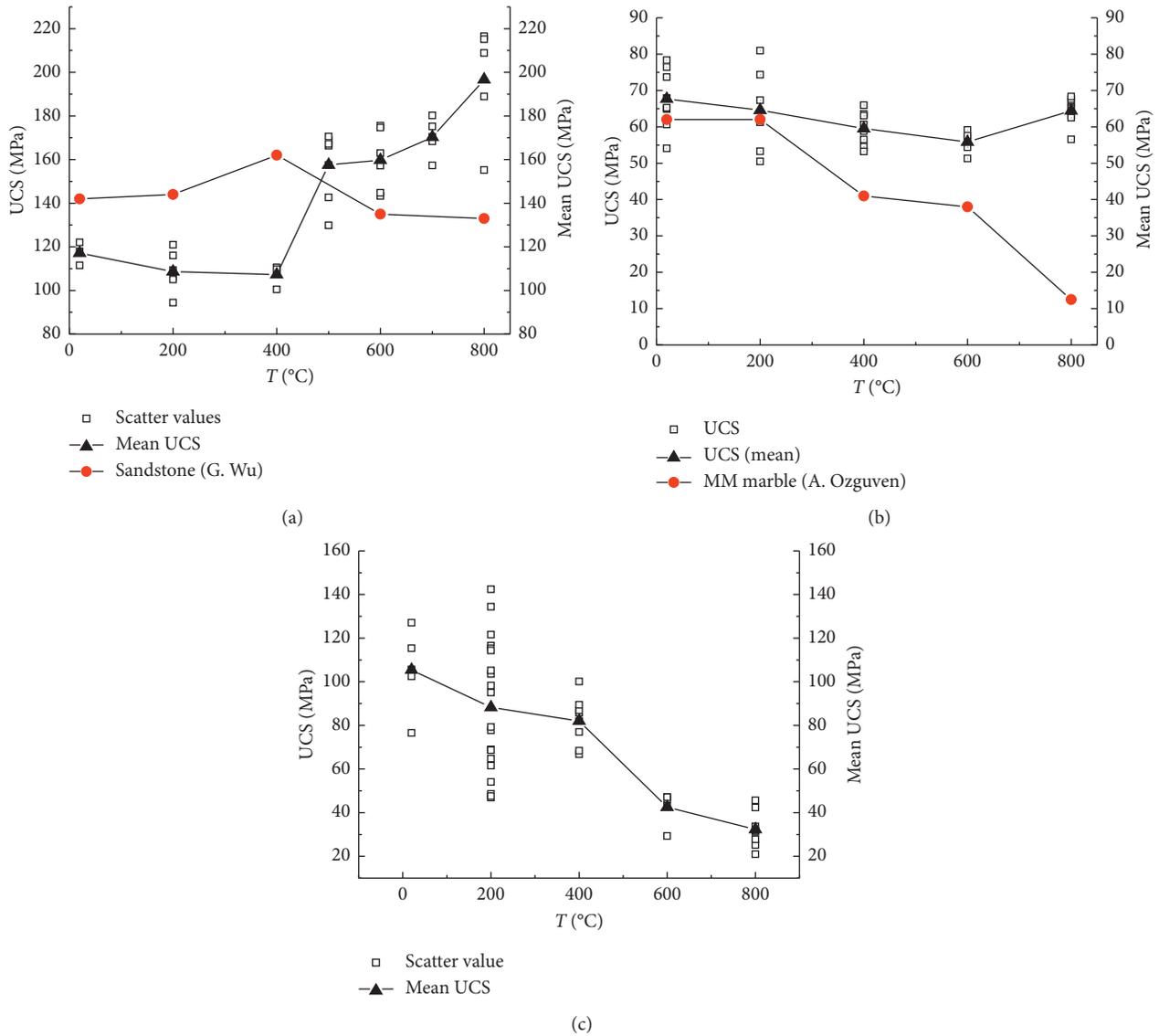


FIGURE 3: Variation of rock uniaxial compressive strength with temperature: (a) sandstone samples, (b) marble samples, and (c) granite samples.

where T_m is the melting point of the raw material. The melting point of potassium feldspar is about 1150°C, and the melting point of anorthose is between 1100 and 1150°C. When the raw material is blended with Al_2O_3 and Fe_2O_3 , the melting point further decreases to about 500°C [46, 47]. The sintering reaction in sandstone can be simply described as in Figure 5.

In the initial state, the crystal grain in sandstone is in loose contact; with temperature reaching about 500°C, the generation of Fe and Al oxides gradually fills the space between crystal grains and then forms into a eutectic material under the effect of high temperature. After that, the feldspar in sandstone samples gradually softens, causing an increase in the peak strain of sandstone, and then melts into this eutectic material until forming a new close contact crystal grain (shown in Figure 5(c)). In the whole process, the contact area between mineral grains is

enlarged [48] and then leads to an increase in the sandstone UCS above 500°C.

However, for marbles and granites, the internal mechanical mechanism is similar to sandstones below 600°C and 800°C, respectively. Under the effect of real-time heating, thermal cracking induced by thermal stress and asymmetric thermal expansion prompts the propagation of microcracks and causes the decline in rock UCS. When the temperature reached 800°C, the marble UCS slightly increases compared with values obtained from the previous work, which decreases sharply at 800°C [25]. In the process, the dolomite in marble decomposes into calcium oxide and magnesium oxide at about 800°C; the marble composition is shown in Table 2. The decomposition of dolomite leads to a reduction in the size of crystal grains and increases the padding minerals between crystal grains, shown in Figure 6. In this case, the main factor for controlling marble UCS is

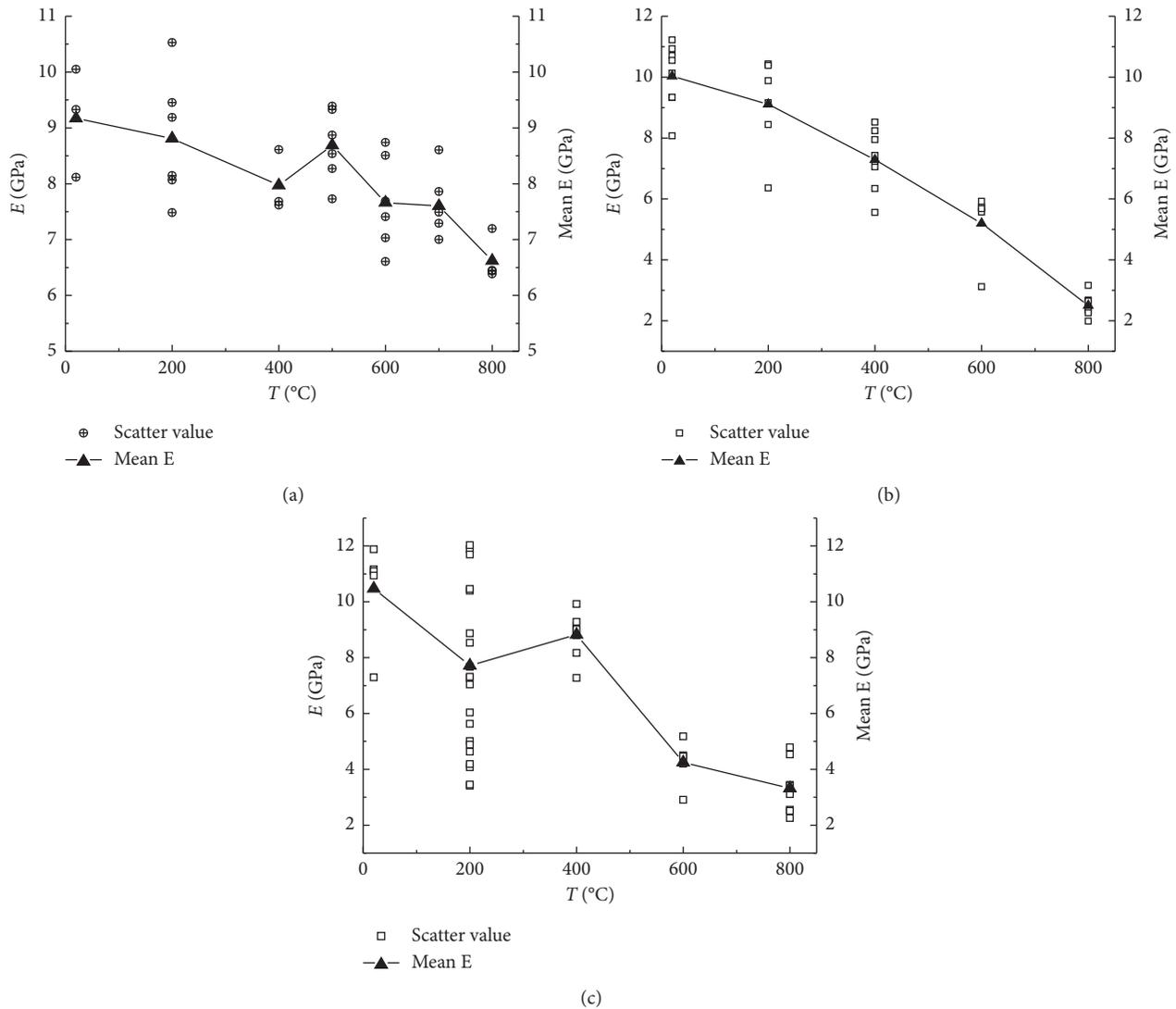


FIGURE 4: Change in the elastic modulus with temperature: (a) sandstone samples, (b) marble samples, and (c) granite samples.

TABLE 1: Mineral composition of sandstone used in this study.

Mineral	Quartz	Potassium feldspar	Anorthose	Calcite	Dolomite	TCCM
Content (%)	17.0	31.0	38.0	3.0	5.0	6.0

TCCM means clay minerals in the XRD test.

the padding mineral produced by decomposition of dolomite, filling the space between crystal grains and then enlarging the friction between crystal grains during the loading process.

4.2. Rock Elastic Modulus. For the rock elastic modulus, they are all presenting a decreasing trend with temperature. Rock elastic modulus is a mechanical property to describe rock's ability to resist deformation. Under the real-time heating, all rock samples gradually soften which is represented by an increase in the rock peak strain. And, the failure mode of rock samples becomes from brittle failure to ductile failure.

It can be clearly seen at 800°C of marbles from its stress-strain curve. It is clear that all rock types experience a process of gradual softening under real-time heating which then diminishes the rock's ability to resist deformation.

From the above analysis, it is shown that the internal mechanism of different rock samples' mechanical properties with temperature has similarities and differences. They can be summarized as follows:

- (1) Thermal cracking induced by thermal stress and asymmetric thermal expansion of crystal grains results in propagation of microcracks in all rock samples. Increase in the microcracks in rock samples

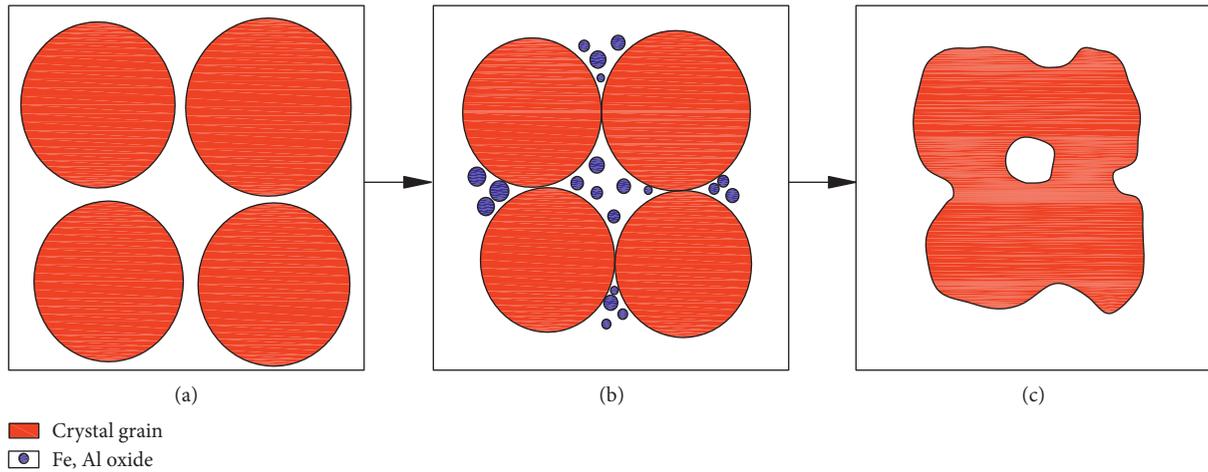


FIGURE 5: Schematic diagram of sintering reaction in sandstone: (a) initial state, (b) eutectic state, and (c) final state.

TABLE 2: Mineral composition of marble used in this study.

Mineral	Dolomite	Hornblende	White mica	Fe, Al, etc.
Content (%)	92.2	6.3	0.4	1.1

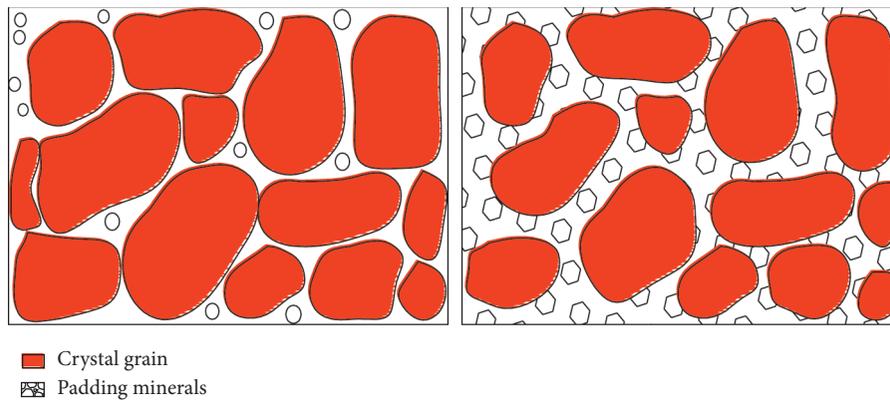


FIGURE 6: Grain model of the marble sample in this paper.

weakens the rock bearing capacity. This is the reason why sandstone, marble, and granite experience a decreasing trend in their UCS below 400°C, before 600°C, and at the whole experimental temperature range, respectively.

- (2) When the rock samples consisted of quartz, potassium feldspar, anorthose, clay minerals, etc., and in a proper percentage, the sintering reaction would exist under the effect of real-time heating. In the process, the melting and recombination of crystal grain prompt enlarging of the contact area between crystal grains and then strengthening of the rock bearing capacity. Due to the lack of clay minerals in granites (shown in Table 3), no sintering reaction exists in the whole heating process, and the granite UCS continuously declines.

TABLE 3: Mineral composition of granite used in this study.

Mineral	Quartz	Potassium feldspar	Anorthose
Content (%)	33.0	23.0	44.0

- (3) When the majority of the composition of rock samples is carbonate, it decomposes at about 800°C, and the generation of the related oxide filling the crystal grains would enhance the friction between crystal grains. In this case, rock bearing capacity may increase slightly compared with the last experimental temperature point.
- (4) In the whole heating process, all rock crystal grains gradually soften and result in an increase in rock ductility. It can simply be demonstrated by the increase in the rock peak strain with temperature. It

shows that the temperature will weaken the rock's ability to resist deformation.

When conducting underground rock engineering, for example, underground coal gasification, it is hard to measure and monitor the deformation of the coal roof, so theoretical and numerical calculation will be adopted to calculate the relative technical parameters. In this case, some conclusions like variations of sandstone mechanical properties and its internal mechanism are helpful to evaluate the safety and economy of the underground rock engineering.

5. Conclusion

In this paper, mechanical characteristics of three types of rocks representing igneous, sedimentary, and metamorphic rocks have been investigated up to 800°C. We find that the internal mechanism of variations of mechanical properties for different rock types has similarities and differences. With the whole heating process, thermal cracking induced by thermal stress and asymmetric thermal expansion is the main controlled factor to influence the rock bearing capacity. In this case, sandstone, marble, and granite UCS experience a decreasing trend below 400°C, 600°C, and 800°C, respectively. When rock samples consisted of some particular minerals and proper percentage, like sandstone in this paper, the sintering reaction exists in these minerals under the effect of high temperature and results in enlarging the contact area between crystal grains. Then, the rock bearing capacity would be strengthened. Besides, decomposition of carbonate and generated oxide filling the space between crystal grains enlarge the friction of crystal grains, which would enhance rock bearing capacity, like marble UCS at 800°C. For the rock's ability to resist deformation, due to the effect of temperature, all three types of rocks experience a decreasing trend in the elastic modulus. The softening of the crystal grain under high temperature prompts the ductility of rock samples and then weakens the rock's ability to resist deformation.

The variation of mechanical properties of three rock types illustrates the significant importance of the real-time temperature effect. When conducting underground rock engineering involving temperature, it is necessary to consider the temperature effect on rock mechanical parameters.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

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