



Effect of Thermal Treatment on the Basic Friction Angle of Rock Joint

Zhi Cheng Tang¹ · Qing Zhao Zhang² · Jun Peng³

Received: 9 January 2019 / Accepted: 26 November 2019 / Published online: 5 December 2019
© Springer-Verlag GmbH Austria, part of Springer Nature 2019

Abstract

There is a growing demand of knowledge on the behavior of rock masses after thermal treatment in both academic and practical aspects due to the high demand of construction of underground structures under the high-temperature environment. The peak shear strength of rock joints has a significant role in evaluating the stability problems of surrounding rocks. However, there is a lack of information about the temperature-dependent nature of the basic friction angle of rock joints, which serves as an essential parameter to evaluate the peak shear strength. The present study experimentally investigates the influences of temperature magnitude (20, 200, 400, 600, and 800 °C) on the basic friction angle of granite, marble, and red sandstone joints. The basic friction angles of the three kinds of rock joints exhibit linear trends with the increase in the treatment temperature. The basic friction angles of granite and red sandstone joints increase with the increase in the treatment temperature, while the values for marble joints continually decrease. The mechanisms for the thermally altered variations in the basic friction angle of rock joint are mainly related to dehydration process, uneven expansion of mineral grains, thermally weakened asperities distributed on the surfaces, and change in physical and mechanical properties of minerals. In addition, other test conditions, including tilting rate, specimen size, repetition number, and cooling rate, are also analyzed. The present study provides useful data in establishing a peak shear strength criterion for rock joints by considering the temperature effect.

Keywords Rock joint · Thermal treatment · Basic friction angle · Tilt test · Tilt rate · Specimen size · Repetition · Cooling rate

1 Introduction

1.1 Motivation

In recent years, there is an increasing demand for knowledge on behavior of rock masses after thermal treatment due to the utilization of deep underground rock engineering, such as high-level radioactive waste repository (Lomenick and Bradshaw 1969), underground compressed air energy storage (Zhou et al. 2015), and rock cavern thermal energy storage (Park et al. 2014). In some cases, the exposed temperature can be accumulated up to about 400 °C or even higher

to the melting point of rock. A large number of researchers around the world investigated the change in physical and mechanical properties of intact rock after thermal treatment, which were quite different from those without thermal treatment mainly due to the thermally induced physical and mineralogical variations within the rock (Tian et al. 2014; Tang et al. 2019). On the other hand, rock masses usually contain discontinuities/joints which cause a great influence on the mechanical behavior of rock masses (Barton 1976). Hence, accurate evaluation of the shear behaviors of rock joint after thermal treatment is critical for the stability of above-mentioned engineering structures. It is well recognized that heating can first increase the thermal stress and then generate micro-cracks within the intact rock, due to the anisotropic expansion of mineral grains, but the knowledge about how rock joints' shear behavior is affected by temperature is still limited. Only several researchers conducted laboratory tests to investigate the shear behaviors of rock joint with/after thermal treatment (Olsson 1974; Khamrat et al. 2018; Kim and Jeon 2019; Zhao et al. 2019).

✉ Jun Peng
jun.peng@whu.edu.cn

¹ Faculty of Engineering, China University of Geosciences, Wuhan 430074, Hubei, People's Republic of China

² Department of Geotechnical Engineering, Tongji University, Shanghai 200092, People's Republic of China

³ School of Civil Engineering, Wuhan University, Wuhan 430072, Hubei, People's Republic of China

Basic friction angle, one of the essential input parameters for determination of the peak shear strength of rock joint, was considered as an intrinsic property of rock surface (Patton 1966; Barton 1973, 1976; Ulusay and Karakul 2016). The basic friction angle of a rock joint can be measured by both tilt test and direct shear test. Although the related ISRM suggested method has been proposed (Alejano et al. 2018), there are still limited experimental results available in the literature about its temperature-dependent nature. To better understand the property, a large number of tilt tests have been performed using three types of common rock in South China. The present study would be the first step to comprehensively understand the temperature-dependent shear behavior of rock joint after thermal treatment, which is helpful to provide some insights to the variation of joint basic friction angle with the increase in temperature, and also be a pioneer to establish a peak shear strength criterion for rock joint by considering the temperature effect that has been rarely studied in the literature.

1.2 Literature Review

The original concept of basic friction angle of rock joints was first proposed by Patton (1966), which then served as a basic input parameter in most of peak shear strength criteria, such as Barton and Choubey (1977), Kulatilake et al. (1995), Zhao (1997), Grasselli (2006), Xia et al. (2014), and Tang and Wong (2016), etc. Barton (1973, 1976) studied the basic friction angles of various rock types, and summarized that the basic friction angles generally ranged from 21° to 38°. The basic friction angles measured on sedimentary rocks ranged from 25° to 30° and those on igneous and metamorphic rocks ranged from 30° to 35°. The results from recent studies indicated that experimental conditions affected the value of basic friction angle of rock joint (Alejano et al. 2012; Hencher 2012; Pérez-Rey et al. 2015; Ulusay and Karakul 2016; Alejano et al. 2017; Jang et al. 2017; Li et al. 2019). In the laboratory, tilt test and direct shear test are the two commonly used methods to determine the basic friction angle of rock joint (Ulusay and Karakul 2016). Several researchers compared the basic friction angle of rock joint measured by direct shear test with that measured by tilt test, and found that the value measured by the former is lower than that measured by the latter (Hencher and Richards 1989; Hencher 1995, 2012). Polished surfaces were suggested to determine the basic friction angle of rock joint (Wines and Lilly 2003; Ruiz and Li 2014; Jang et al. 2017). Essentially, the basic friction angle of rock joint reflects the adhesion of two contact surfaces, and hence, ideally smooth surfaces should be used (Li et al. 2019). However, the measurement cannot be done and also not necessary from the perspective of engineering practice. The basic friction angle measured on slightly rough surfaces could be considered as

a material parameter (Li et al. 2019), due to the widespread small-scale asperities randomly distributed on “real” rock surfaces. From a scientific point of view, as long as the surface finish is consistent on all tested rock specimens, the results can be used to analyze.

There are two methods widely used to obtain the above-mentioned smooth surfaces with statistically identical roughness. Diamond-drilled core is an optional method to make such surface finish to evaluate the basic friction angle of rock joints. Macroscopically, the cylindrical surface is smooth, although the small-scale roughness distributed on the cylindrical surface exists (Li et al. 2019). The basic friction angle of such cylindrical surfaces was first adopted by Stimpson (1981) through tilt tests on three cores. Several researchers also performed tilt test with two cores (Stimpson 1981; Li et al. 2019). It is thought that the sliding angle measured on cylindrical surfaces in tilt test is a good estimation of the basic friction angle of rock joint (Li et al. 2019). The other optional method for estimating the basic friction angle of rock joints is to use saw-cutting slabs in tilt test (Bruce et al. 1989; Alejano et al. 2012; González et al. 2014; Ruiz and Li 2014; Ulusay and Karakul 2016; Alejano et al. 2017; Jang et al. 2017; Li et al. 2019). The limitations of the saw-cutting method lie in two aspects (Li et al. 2019): (1) the flatness and roughness of the cutting surfaces vary from laboratory to laboratory, and it is relatively time-consuming for specimen preparation, and (2) different levels of wearing on the surface and plastic strain in the vicinity of the surface may be produced (which may lead to a lower friction angle than an unaffected surface). By comparing different techniques of tilt test, Alejano et al. (2012) pointed out that the tilt test with three cores tended to overestimate the basic friction angle of rock joints, who considered that the phenomenon was mainly due to the fact that sliding along generatrix of cylinders and along planar surfaces were different and also that three-core sticks caused a slight wedging problem. Alejano et al. (2012) also recommended to use cores drilled in the laboratory with a length-to-diameter ratio of 2 or larger, and rock slabs with at least 50 cm² surfaces and a length-to-height ratio of at least 2. Li et al. (2019) established a rule to estimate the basic friction angle of rock joints by tilt test on both three-core and saw-cutting specimens.

To better understand the effect of wearing on the basic friction angle of rock joints, researchers performed successive repetitions (tests) on the same specimens and the mean value of the first several repetitions was used as the basic friction angle (Bruce et al. 1989; Hu and Cruden 1992; Alejano et al. 2012; González et al. 2014; Ruiz and Li 2014; Li et al. 2019), in which the number of repetitions usually ranged between 3 and 5. Alejano et al. (2012) further recommended that three repetitions were sufficient, but a fourth supplementary repetition should be performed when the maximum difference between one of the results and the

median was larger than 3° . Other researchers (Farrar and Cawsey 1976; Hencher 1977, 2012; González et al. 2014; Pérez-Rey et al. 2015; Jang et al. 2017) found that, with the increase in repetitions, tilt test would probably provide an underestimation of basic friction angle, especially when the surface was cleaned before each test. However, contradictory phenomena were also observed by Jang et al. (2017).

In the literature, tilting rate is another factor influencing the value of basic friction angle in tilt tests. Alejano et al. (2012), González et al. (2014), Pérez-Rey et al. (2015), Ulusay and Karakul (2016), and Li et al. (2019) selected a tilting rate of about $24^\circ/\text{min}$ to perform the tilt test. A tilting rate of $8^\circ/\text{min}$ was used by Cruden and Hu (1988), Bruce et al. (1989), and Hu and Cruden (1992). In addition, a tilting rate of $15^\circ/\text{min}$ was used by Ruiz and Li (2014). The maximum tilting rate was about $96^\circ/\text{min}$ by Jang et al. (2017), while the minimum tilting rate was about $2.5^\circ/\text{min}$ by Bruce et al. (1989). The effect of tilting rate on the basic friction angle of rock joints was only discussed by Bruce et al. (1989) and Jang et al. (2017). Bruce et al. (1989) found that specimens tested at a tilting rate of $2.5^\circ/\text{min}$ had a mean increase of 0.3° over the results at the tilting rate of $8^\circ/\text{min}$, while the maximum difference was about 3.2° that seemed not to be ignored. However, Jang et al. (2017) recommended that the tilting rate did not affect the basic friction angle when the tilting rates were within the range of $0.2\text{--}1.6^\circ/\text{s}$. However, further research is still needed, especially for rock joint after thermal treatment.

The temperature-dependent nature of basic friction angle of rock joints has not been investigated, but the significance had been previously pointed out by Barton (1973, 2013). By consideration of the ascendant rock practices related to the high-temperature environment, further understanding on the temperature-dependent behavior of rock joints is desperately required. Determining the basic friction angle would be one of the points. In this study, the basic friction angle of three typical rock types after exposure to high temperatures is studied by tilt test with three-core method. The study mainly aims to investigate the thermally induced variations in the basic friction angle of rock joints. In addition, the effects of experimental factors (i.e., tilting rate, specimen size, repetition, and cooling rate) are also investigated.

2 Materials and Methodology

2.1 Sample Preparation

Three kinds of rocks (granite, marble, and red sandstone) are selected for the tilt test in the present study. Cylindrical specimens with a diameter of 50 mm and a length-to-diameter ratio of 2.0 or slightly larger are prepared. The drill bit is made of a bronze alloy matrix containing synthetic diamond

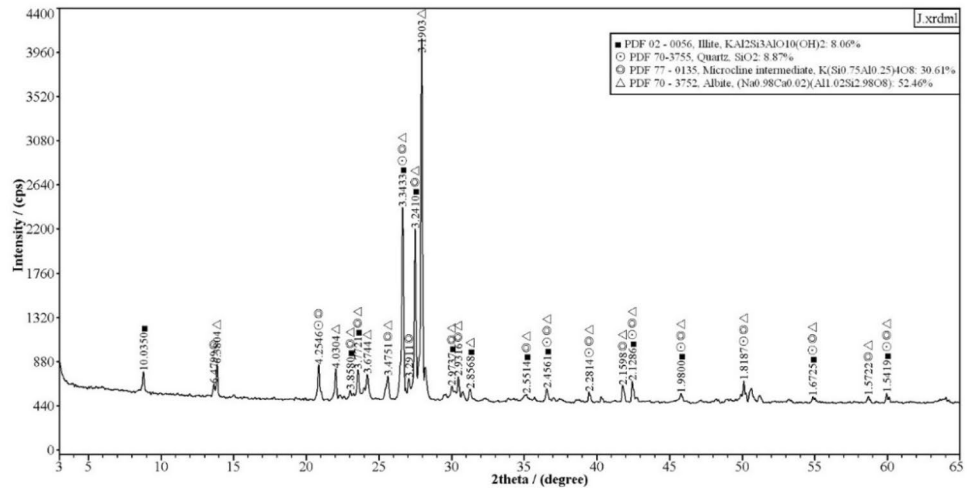
grits of approximately 40–60 US mesh with a content of $0.6\text{ ct}/\text{cm}^3$.

- Granite is retrieved from Suizhou, which is located in central north of Hubei province in middle China. The granite is gold ephedra and has a coarse-grained texture with grain sizes typically ranging from 1 to 7 mm. Modal analysis provided the following mineralogical composition in volumetric fraction (as shown in Fig. 1a), about 8.06% illite, 8.87% quartz, 30.61% micro-cline, and 52.46% albite. The unconfined compressive strength (UCS) is approximately 105.7 MPa (by three specimens with length of 100 mm and diameter of 50 mm) and the tensile strength is about 3.42 MPa (by Brazilian test using six specimens with diameter of 50 mm and height of 25 mm).
- Marble is retrieved from Leiyang, which is located in southeast of Hunan province in south China. The marble is pearly white and relatively homogeneous in texture and composition. The grain size is less than 1.0 mm. The rock is mainly made up of dolomite (93.05%) and calcite (6.95%), as shown in Fig. 1b. The UCS is approximately 122.2 MPa (by three specimens with length of 100 mm and diameter of 50 mm) and the tensile strength is about 4.11 MPa (by Brazilian test using six specimens with diameter of 50 mm and height of 25 mm).
- Red sandstone is retrieved from E'zhou, located in east of Hubei province in middle China. The red sandstone is dark in color and predominantly composed of albite (26.6%), quartz (22.1%), micro-cline (21.2%), calcite (14.3%), and kaolinite (10.8%), as shown in Fig. 1c. The UCS is approximately 52.3 MPa (by three specimens with length of 100 mm and diameter of 50 mm) and the tensile strength is about 2.28 MPa (by Brazilian test using six specimens with diameter of 50 mm and height of 25 mm).

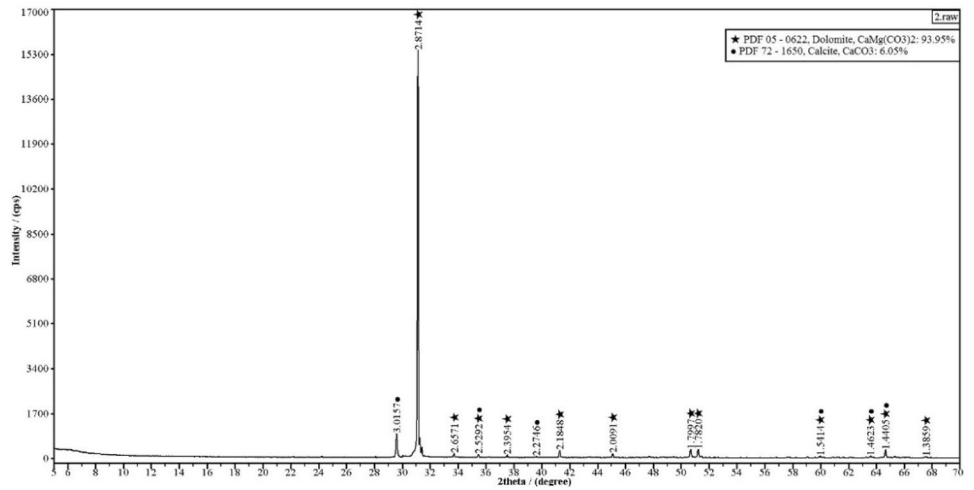
2.2 Thermal Treatment

Thermal treatment can be divided into real-time high-temperature treatment and post-high-temperature treatment (Tang et al. 2019). The post-high-temperature treatment only needs the conventional test facility plus high-temperature furnace, while the real-time high-temperature treatment needs stricter requirements of test facility and the testing is more expensive. In the present study, the post-high-temperature treatment is used to study the temperature-dependent surface friction nature of the three types of rock, which means that the thermal treatment is first applied to the specimens alone by an electrical high-temperature furnace (Fig. 2a), and as the specimens are cooled down to the room temperature, tilting test will be performed.

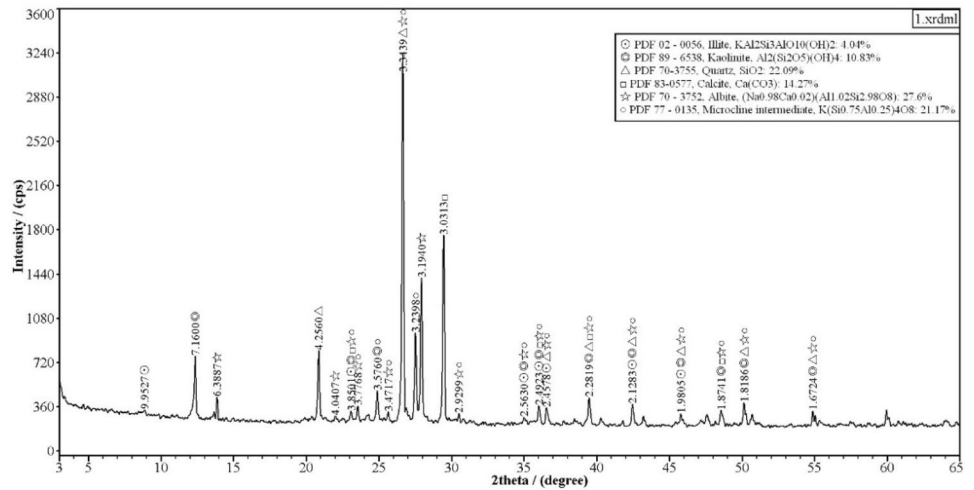
Fig. 1 X-ray diffraction (XRD) spectra for the powder of rocks under the room temperature: **a** granite, **b** marble, and **c** red sandstone



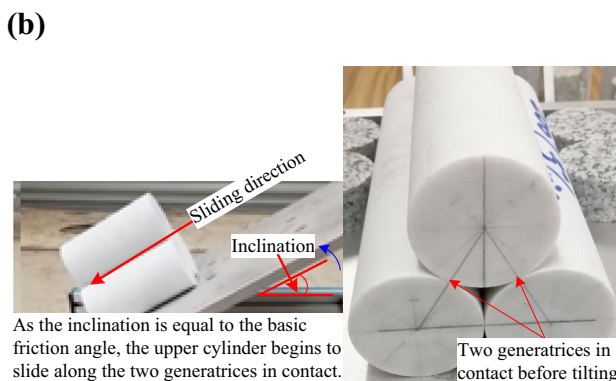
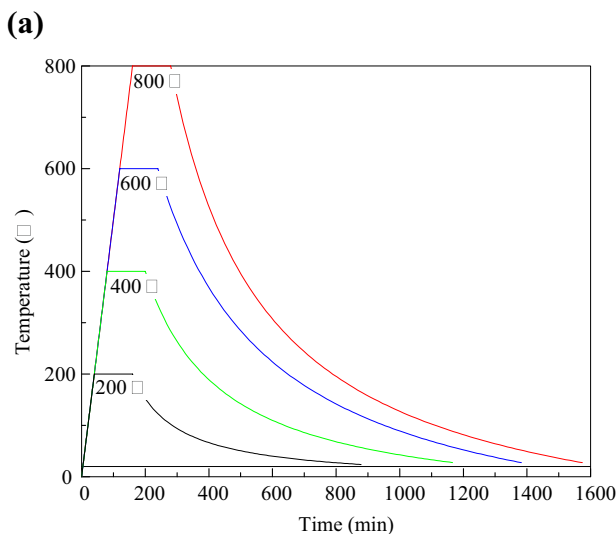
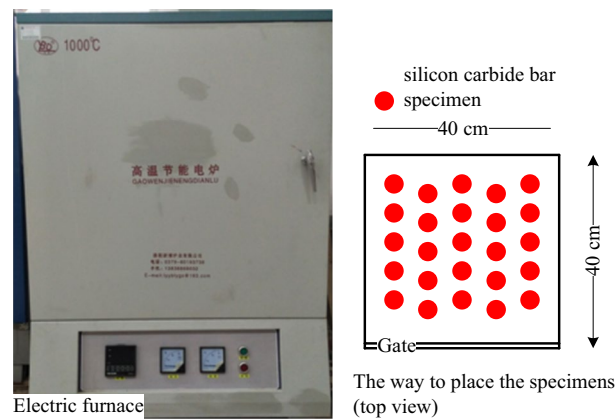
(a) Granite



(b) Marble



(c) Red sandstone



(c)

Fig. 2 a Electrical furnace, b scenario of thermal treatment with natural cooling rate, and c assembly photo of the cylindrical specimen in title test

Besides the high temperature, several other factors related to the post-high-temperature treatment also have great influence on the mechanical properties of rock, such as duration of high temperature, heating rate, and cooling rate. According to the available experimental procedures, there is no

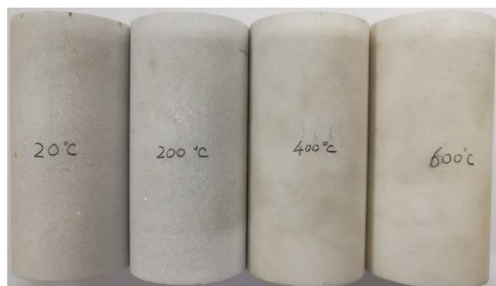
well-recognized standard to heating the rock. The duration of high temperature includes 0.5, 1, 2, 4, and even more than 12 h in the previous studies (Tang et al. 2019), among which the duration of 2 h was selected by a number of researchers around the world to ensure that the inside of the rock specimen was heated evenly (Tian et al. 2014; Zhang et al. 2016, 2017a, b, c; Kumari et al. 2017; Tian et al. 2017; Tang et al. 2019). As for the heating rate, different heating rates within the range from 0.5 to 10 °C/min were usually adopted in the previous studies, among which the heating rate of 5 °C/min was widely used (Shao et al. 2015; Kumari et al. 2017; Yang et al. 2017; Tang et al. 2019). With consideration of the performance of high temperature furnace and also the security regulation of our laboratory, 5 °C/min was used in the present study. As such, the heating even up to 800 °C can be finished within the working hours. In addition, the cooling rate can be generally divided into natural cooling and rapid cooling (by water or liquid nitrogen). In the present study, only the natural cooling and the water cooling were considered, and the effect of cooling by liquid nitrogen will be investigated in the future. As mentioned above, the procedures of the thermal treatments are summarized in the following (the scenarios of thermal treatments are shown in Fig. 2b, only with natural cooling rate):

- Place the specimens in the electric furnace (to ensure even heating, the specimens were kept about 3 cm apart from each other, and the minimum distance between the silicon carbide bar heating elements and the specimens was about 5 cm, top view, as shown in Fig. 2a);
- Heat the specimens at a rate of 5 °C/min in the furnace chamber to a predetermined high temperature, i.e., 200, 400, 600, and 800 °C, respectively;
- Maintain the predetermined temperature for 2 h;
- Turn off the furnace and allow the specimens to cool down to room temperature naturally.

Figure 3 presents the typical specimens after thermal treatment in different temperatures. The highest temperature for the marble specimen is 600 °C, due to that the specimen can be broken by hand when the marble is heated to a temperature of 800 °C. As such, it cannot be treated as a brittle material. For the three types of rock with thermal treatment in temperature of 200 °C, no obvious color change can be observed when compared to those without thermal treatment. As the temperature increases from 400 to 800 °C, the color of granite gradually became lighter, but the number of dark red spot increases due to the dehydration process of ferric oxide hydrate. For the marble, the color gradually became milk white as the temperature increases from 400 to 600 °C. For the red sandstone, the color gradually became fresh brick-red as the temperature increases from 400 to 800 °C. In addition, a limited number of specimens



(a) Granite



(b) Marble



(c) Red sandstone

Fig. 3 Photographs of specimens after thermal treatments (from left to right: 20, 200, 400, 600, and 800 °C, respectively): **a** granite, **b** marble, and **c** red sandstone

are cooled by water in a container with a volume of about 30 L under the room-temperature condition. The cooling time from the predetermined temperature to room temperature is about 10, 25, 35, and 40 min, respectively, for the heating temperature of 200, 400, 600, and 800 °C. In other words, the mean cooling rate is about 18–20 °C/min, which is significantly greater than 1–2 °C/min for the natural cooling. The wet specimens are then placed in the electrical furnace with a temperature of 40 °C for drying until the quality keeps constant.

After thermal treatments, six specimens under each temperature condition are randomly selected to measure the P-wave velocity for the three kinds of rock, respectively, which is closely related to the internal structure of rock and is one of the widely used parameters for the characterization of material damage and evolution. The

Table 1 P-wave velocity of the three kinds of rock after thermal treatments (unit: km/s)

T (°C)	Granite	Marble	Red sandstone
20	4.776	4.833	3.447
200	4.507	4.207	3.014
400	3.966	2.902	2.553
600	3.216	1.627	2.172
800	2.005	–	1.829

results are listed in Table 1. The P-wave velocity decreases for the three kinds of rock with the increase in treatment temperature, indicating that the number of micro-defects (typically, micro-cracks) increases.

2.3 Procedures of Tilt Test

A tilting apparatus (see Fig. 2c) combined with a free downloadable digital slope meter (Max Protractor) with an accuracy of 0.1°, which is built into Huawei cell phone, is used to measure the basic friction angle of rock surfaces. The device consists of a rigid frame supporting a hinged table and a manually rotated arm with a screw feed which can rotate the table from 0° to about 80°. A metal specimen holder is mounted in front of the table to prevent the movement of the lower specimens during the process of tilting. Before each test, the horizontality is confirmed by an electrolytic bubble.

Following the ISRM suggested method (Alejano et al. 2018) and also referring to other procedures available for performing the tilt tests (Alejano et al. 2012, 2017; Ulusay and Karakul 2016; Jang et al. 2017; Li et al. 2019), the following procedures are adopted in the present study:

- Check the horizontality of the plane-tilting platform prior to each test using a bubble level.
- Clean the surface of specimens to remove dust and free particles.
- Place the two cores horizontally side by side along the long dimension.
- Place one core horizontally upon the two lower specimens and mark the generatrices for the repetition tests.
- Rotating the tilt table steadily at a rate of about 24°/min (or other rates when considering the effect of tilting rate) until the upper specimen slides.
- Record the angle corresponding to sliding displacements of at least 10% of the specimen length.
- Clean the surfaces by a dry soft brush. Place the specimens in the same initial positions. Repeat the test for at least three times.

2.4 Calculation of Basic Friction Angle

The following steps are utilized to calculate the value of basic friction angle of rock joints for each test (Ulusay and Karakul 2016):

- If the standard deviation among three repetitions is no more than $\pm 3^\circ$, the mean obtained from the three repetition tests is considered as the basic friction angle of rock joint.
- If the standard deviation among the three repetition tests is greater than $\pm 3^\circ$, a fourth test is performed. If the deviation of the four tests is no more than $\pm 3^\circ$, one of the four tests, which has the largest deviation is omitted, and the mean value obtained from the rest of them is treated as the basic friction angle of rock joint.
- If the standard deviation among the fourth test and the three previous tests is still greater than $\pm 3^\circ$, a fifth test is performed. The two of the five tests which have the largest deviations are omitted and the mean value obtained from the rest three is treated as the basic friction angle of rock joint.

3 Results and Discussion

3.1 Variability of Basic Friction Angle

Table 2 summarizes the median, the mean, and the standard deviation resulting from about 1000 tilt tests of the three kinds of rocks after treatment with different temperatures. The sliding surfaces have almost suffered no wearing under each temperature condition during the first several repetitions. Figure 4 shows the variation of basic friction angle with the number of repetitions (tests) for the three kinds of rocks at their highest treatment temperature. The small variation indicates that the effect of wearing on the sliding surfaces is negligible. Hence, the number of no more than five repetitions (tests) which was suggested by Alejano et al. (2012) and González et al. (2014) is desirable. The median instead of the mean value was recommended by Alejano et al. (2012) and Ulusay and Karakul (2016) as the basic friction angle of rock joint. The present results show that the values of the median and the mean are close to each other with a difference no more than 0.8° . In the following analysis, the mean value is used only due to that most previous researchers used the mean value.

3.2 Temperature-Dependent Nature

Alejano et al. (2017) found that the effect of temperature on the tilt test results was negligible, in which the temperature only ranged from 19 to 32°C . However, as shown in Table 1, the

Table 2 Main results of the experimental investigation

T (°C)	Granite				Marble				Red sandstone			
	Number of tests	Median (°)	Mean (°)	SD (°)	Number of tests	Median (°)	Mean (°)	SD (°)	Number of tests	Median (°)	Mean (°)	SD (°)
20	200	33.0	33.1	0.86	90	34.1	34.2	0.66	200	32.8	32.9	0.78
200	50	34.8	34.7	0.97	30	32.8	32.7	1.80	50	34.8	34.8	0.86
400	50	35.1	35.0	1.08	30	31.9	31.9	2.37	50	36.2	36.0	0.97
600	50	36.1	36.0	1.24	30	30.1	30.3	1.99	50	38.2	38.2	0.99
800	50	36.9	36.6	1.46	-	-	-	-	50	38.6	38.6	1.05

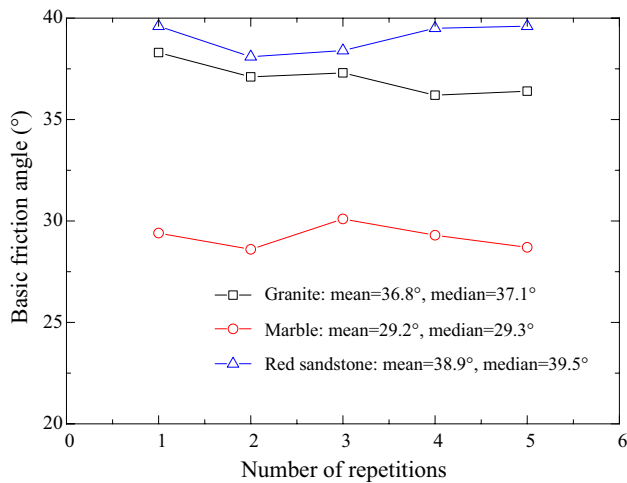
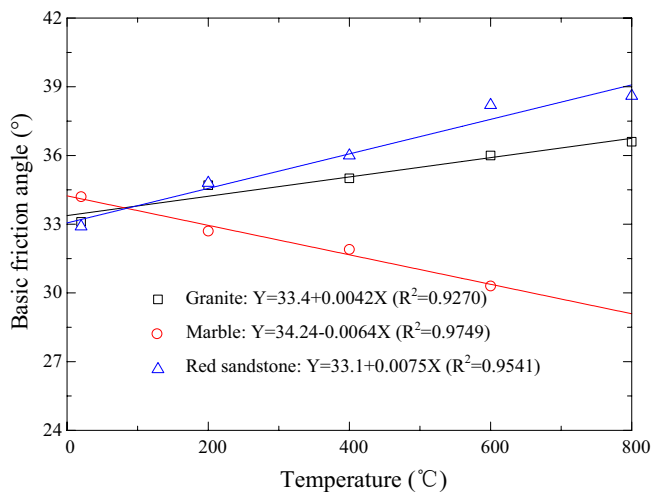


Fig. 4 Variations of the basic friction angle of the three kinds of rock surfaces after thermal treatments

basic friction angles of the granite and the red sandstone joints generally increase with the increase of temperature in the treatment, while the value for marble continually decreases. The basic friction angle of the three kinds of rock joints exhibits a linear trend with the increase of temperature (see Fig. 5). Based on the least-squares analysis, the following equation with a high coefficient of correlation can generally capture the temperature-dependent nature for the basic friction angle of the three kinds of rock joints after thermal treatment. The regression coefficients for granite, marble, and red sandstone joints are 0.0042 ($R^2=0.9270$), -0.0064 ($R^2=0.9749$), and 0.0075 ($R^2=0.9541$), respectively.

$$\varphi_{b_T} = \varphi_b + aT, \tag{1}$$



where φ_b is the basic friction angle of rock joint without thermal treatment, φ_{b_T} is the temperature-dependent basic friction angle of rock joint after exposure to high temperature (T), T is the exposed temperature (in $^{\circ}\text{C}$), and a is the regression coefficient, mainly reflecting the effects of surface conditions (such as the number of micro-cracks, the micro-scale roughness, and the content of rock-forming minerals, etc.).

The friction behavior of mineral grains such as albite, cline, quartz, dolomite, and calcite (main minerals of the three rock types) after thermal treatment is seldom studied. Cruden and Hu (1988) and Ulusay and Karakul (2016) established empirical equations, respectively, to evaluate the basic friction angle of rock joint using the content of minerals in the entire specimen. In fact, the friction occurs on the mineral grains which only distributed on the contact surfaces. Thus, a regression function considering the content of mineral composition on the surface should be more realistic. Comprehensive investigations are still desperately required, such as the surface mineral analysis. This study would only be a start about the temperature-dependent nature of the basic friction angle of rock joints, which should not be generalized (in spite of the results are obtained from a large number of tilt tests).

The standard deviations of the basic friction angles for the three kinds of rock joints are also presented in Fig. 5. In general, the standard deviation increases with the increase in the treatment temperature. Marble joint has the minimum standard deviation and granite joint has the maximum one under the room-temperature condition. After thermal treatment, the standard deviation of marble joint increases rapidly with a declining rate. The red sandstone joint has the minimum value of standard deviation when compared with that of the other two rock joints. The standard deviations for

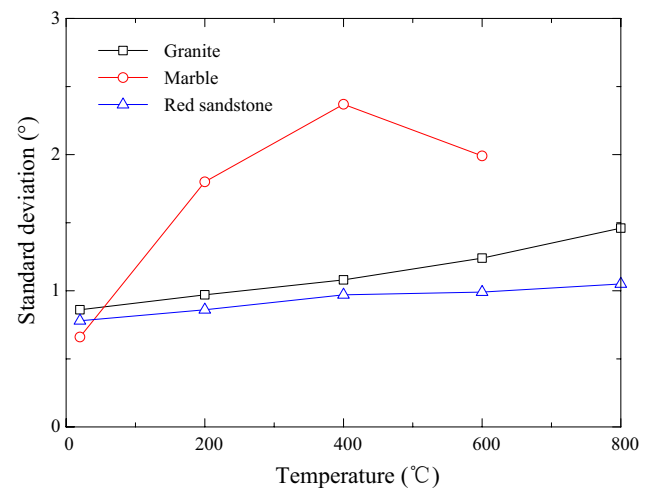


Fig. 5 Variations of the basic friction angle and its standard deviation with the increase in temperature

both granite and red sandstone joints show a liner trend with the increase in the treatment temperature. The larger standard deviation of the basic friction angle indicates that the uniformity of tested surfaces decreases. The reason would be partly related to the thermally induced micro-cracks (by the varied thermal expansibility of mineral grains) and micro-roughness (by the non-uniform loss of mass) distributed on the surfaces.

3.3 Mechanism

Essentially, the basic friction angle of a rock joint reflects the friction behavior of the two contact surfaces under the extreme low normal stress (i.e., self-weight of upper specimen), which could be influenced by the physical properties (water, mineralogy, etc.) and the surface attributes (micro-crack, micro-roughness, etc.). Several reasons are found to interpret the variation of the basic friction angle of rock joint after thermal treatment to some extents: (1) state change and loss of water, including absorbed, bounded, crystal, and structural waters; (2) change in physical and mechanical properties of minerals, especially the transition of crystals and the change of mineral composition; (3) micro-cracks induced by the unbalanced thermal stress, and micro-roughness resulted from the dehydration process or changes/loss in mineral composition; and (4) change in thermodynamic property of the random distributed micro-asperities. Physical changes usually occur under the relatively low-temperature condition, while the chemical changes mainly occur under the high-temperature condition. The competition among the above-mentioned factors causes a change in the basic friction angle of rock surfaces.

Water distributed on the surface usually serves as the lubrication during the process of sliding and results in a lower value of basic friction angle (Patton 1966; Barton 1976; Barton and Choubey 1977; Alejano et al. 2012). However, the dehydration process would produce a larger friction coefficient of mineral grains (Sun et al. 2016; Zhu et al. 2017). The absorbed-water would escape around 100–110 °C and the bounded-water would escape between 100 and 300 °C. The crystal water would escape below 400 °C and the structural water of mineral would escape above 300 °C. For example, changes in color of the granite surface (see Fig. 3) are mainly due to the dehydration process of the ferric oxide hydrate as the treatment temperature is higher than 400 °C. The uneven expansion of mineral grains induced by the unbalanced thermal stress (due to the difference in the thermal expansivity of mineral grains) causes inhomogeneous deformation and probably results in micro-cracks on the surface (Peng et al. 2016). Both the thermally induced micro-cracks and micro-roughness distributed on the surface alter its friction behavior. By an optical microscopy observation, the number of thermally

induced micro-cracks is the smallest for the marble joint, especially after thermal treatment of 600 °C, when compared with those of the other two rock joints. This is mainly due to the homogeneous/compacted texture and composition in the marble specimen. The thermally induced micro-roughness is obvious for the surfaces of red sandstone joints, especially after exposure to 600 and 800 °C, which would be mainly related to the change/loss in mineral composition. To better understand the surface attribute of the three kinds of rock after thermal treatments, Figs. 6, 7, 8 present the results of SEM test for each rock (with a magnification ratio of 100), respectively. For the granite and red sandstone, the number of micro-cracks generally increases and the micro-surface becomes rougher with the increase in the treatment temperature. As such, the basic friction angle of the two kinds of rock surface becomes larger with the increase in the treatment temperature. For the marble, the number of micro-cracks generally increases as the temperature increases from room temperature to 600 °C, while the roughness of micro-surface seems to be smoother. The micro-roughness on the marble surfaces would dominate the friction nature under the low normal stress condition, leading to a decreasing trend with the increase in treatment temperature.

The mechanisms for sliding behavior under the low normal stress are still not very clear, which is related to the shear behavior of micro-asperities. Due to the lack of equipment with high precision in our rock laboratory, such an experiment in micro-scale cannot be performed. If the upper specimen is lightly pressed on the two base specimens by manually applying a force of about 10 N and are ground longitudinally back and forth a few times as following the method used by Li et al. (2019), rock powder appears on the sliding tracks after 20–25 times for marble surfaces and 5–8 times for red sandstone surfaces (both after exposure to 400 °C). However, no powder appears on the fresh surfaces (without thermal treatment). Hence, the thermally altered micro-asperities would weaken the friction nature even under the extreme low normal stress condition.

4 Analysis for Influencing Factors

4.1 Tilting Rate

Laboratories around the world performed tilt tests using different tilting rates generally ranging from 2 to 96°/min (see Sect. 1.2). However, a common understanding about the effect of tilting rate on the basic friction angle of rock joints has not been obtained. Since there are still no standard procedures to perform tilt tests, the rate-dependent nature of the basic friction angle would be a matter of concern. Furthermore, the basic friction angle of rock joint after thermal treatment has been seldom investigated. As such, four tilting

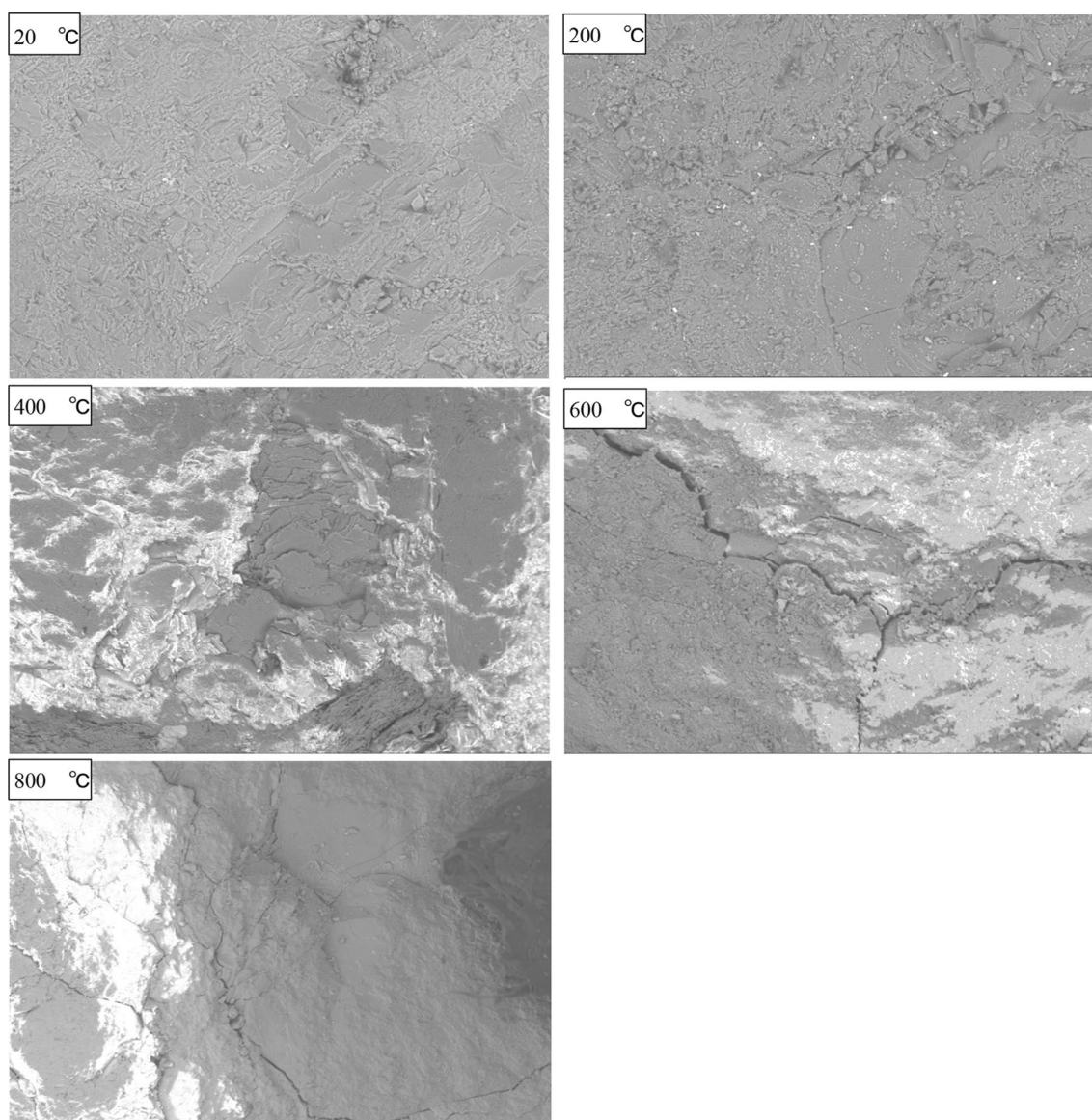


Fig. 6 SEM images for the granite surfaces after thermal treatments

rates of about 5, 10, 20, and 40°/min are used in this study. Due to the limited specimens, only the specimens with no thermal treatment and the ones after the highest temperature for each rock type are used. Under each condition, a total of 15 tilt tests are performed following the mentioned procedures in Sect. 2.3.

Under the room-temperature condition, the basic friction angles of granite joints obtained by the four tilting rates range from 31.6° to 36.8° (see the left in Fig. 9a), and the means distribute in a narrow range of 32.9° to 33.9°. As for the granite joints after exposure to 800 °C, the basic friction angles range from 32.4° to 40.5° (see the right in Fig. 9a), and the means distribute in a narrow range of 35.7° to 36.6°. The results indicate that the basic friction angles

of granite joints under the two temperature conditions are almost the same regardless of the tilting rate (only with difference of less than 1° in this study). The effect of tilting rate on the basic friction angle of marble joints is similar to the one of granite joints (see Fig. 9b) and no clear trend can be observed. The basic friction angle of the red sandstone joints without thermal treatment also exhibits a rate-independent behavior (see the left in Fig. 9c). However, a decreasing trend can be observed for the joints after thermal treatment as the tilting rate increases from 5 to 40°/min (see the right in Fig. 9c). One interesting phenomenon should be noted that, for the joints after thermal treatment, the basic friction angles distribute in a larger range than the one without thermal treatment, which should be mainly due to the thermally

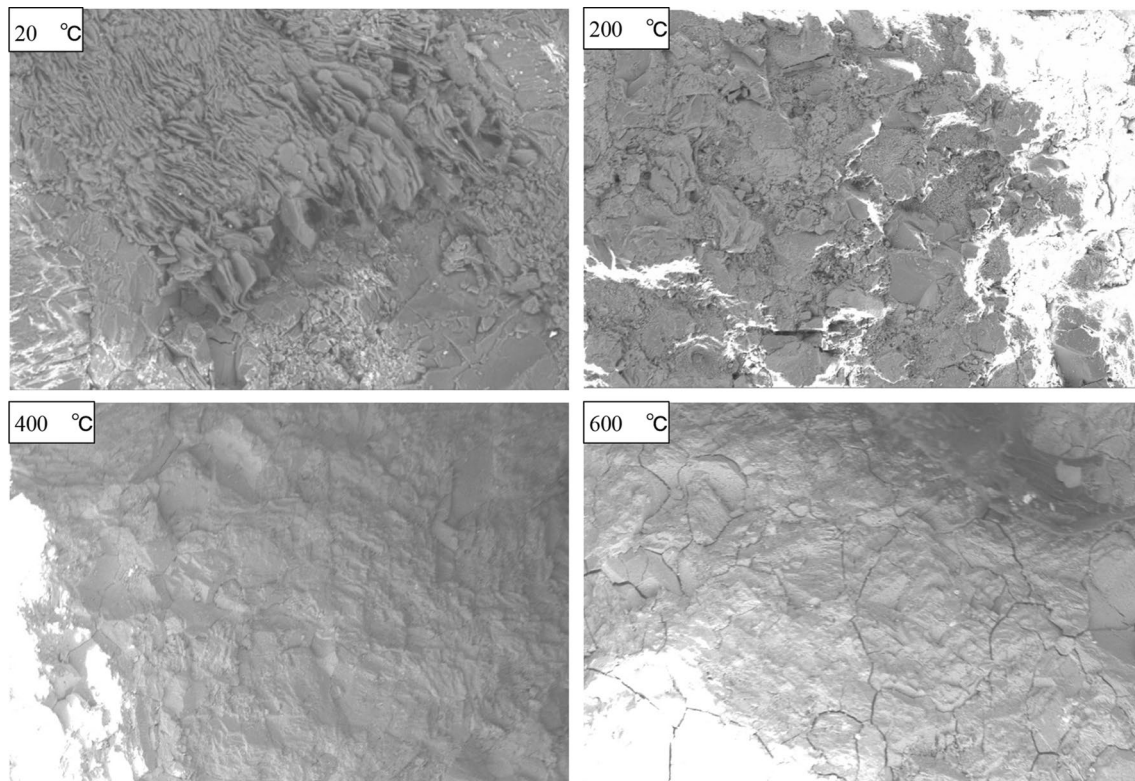


Fig. 7 SEM images for the marble surfaces after thermal treatments

induced micro-cracks which are randomly distributed and micro-roughness on the contact surfaces.

The irregular variations in basic friction angle of rock joints under the same temperature condition are mainly related to the surface condition of the specimens. One of the possible reasons is that the inner surface of drill bit, which looks similar at the visual level, touches smoothly, while its micro-structures from one to one are different, and thus, the drilled core surfaces have different micro-roughness (Cruden and Hu 1988). On the other hand, the interactions between rock and drill bit are affected by both rock attributes (such as the abrasivity) and drilling power, which could be treated as another reason responsible to the varied surface micro-roughness of the tested specimens. In addition, for specimens after exposure to high temperature, the surface condition would be more complex due to the induced physical and chemical changes. The above-mentioned phenomenon can hardly be controlled even in the laboratory. Thus, more accurate experiments should be conducted to explain the mechanism of the rate-dependent behavior for basic friction angle of rock joints. However, from the perspective of rock practice, both drilled cores and saw-cutting surfaces can provide an accurate value for the basic friction angle of rock joints. Similar to other observations (Bruce et al. 1989; Pérez-Rey et al. 2016; Jang et al. 2017), the mean basic friction angle of rock joints in this study generally exhibits a

rate-independent property, and its volatility distributes in a narrow range.

4.2 Specimen Size

The effect of specimen size on the basic friction angle of rock joints has been investigated using saw-cutting slabs with areas ranging from $4 \times 4 \text{ cm}^2$ to $10 \times 10 \text{ cm}^2$ (Alejano et al. 2012, 2017; Jang et al. 2017). In consideration that the size of rock joints used in both academia and practice ranges widely from $5 \times 5 \text{ cm}^2$ to $20 \times 20 \text{ cm}^2$, the size effect should be further investigated. Although the mechanisms of sliding along cylinder generatrices and planar surfaces are quite different (Alejano et al. 2012), it is also thought that the angle measured on the cylindrical surfaces of core specimens in tilt test is a good approach to estimate the basic friction angle of rock joints (Barton 2013; Li et al. 2019). Alejano et al. (2012) found that tests in lengthwise cut cylinder specimens (54 mm in diameter and no less than 108 mm in length) can provide more reliable value of basic friction angle, while other sizes were also used by Barton (2013) and Li et al. (2019), etc. In this study, four different sizes having lengths of about 30, 60, 110, and 210 mm (length-to-diameter ratio is no less than 2 for all the specimens) are used. However, only the red sandstone joints with no thermal treatment and with $800 \text{ }^\circ\text{C}$ in the treatment are used due to

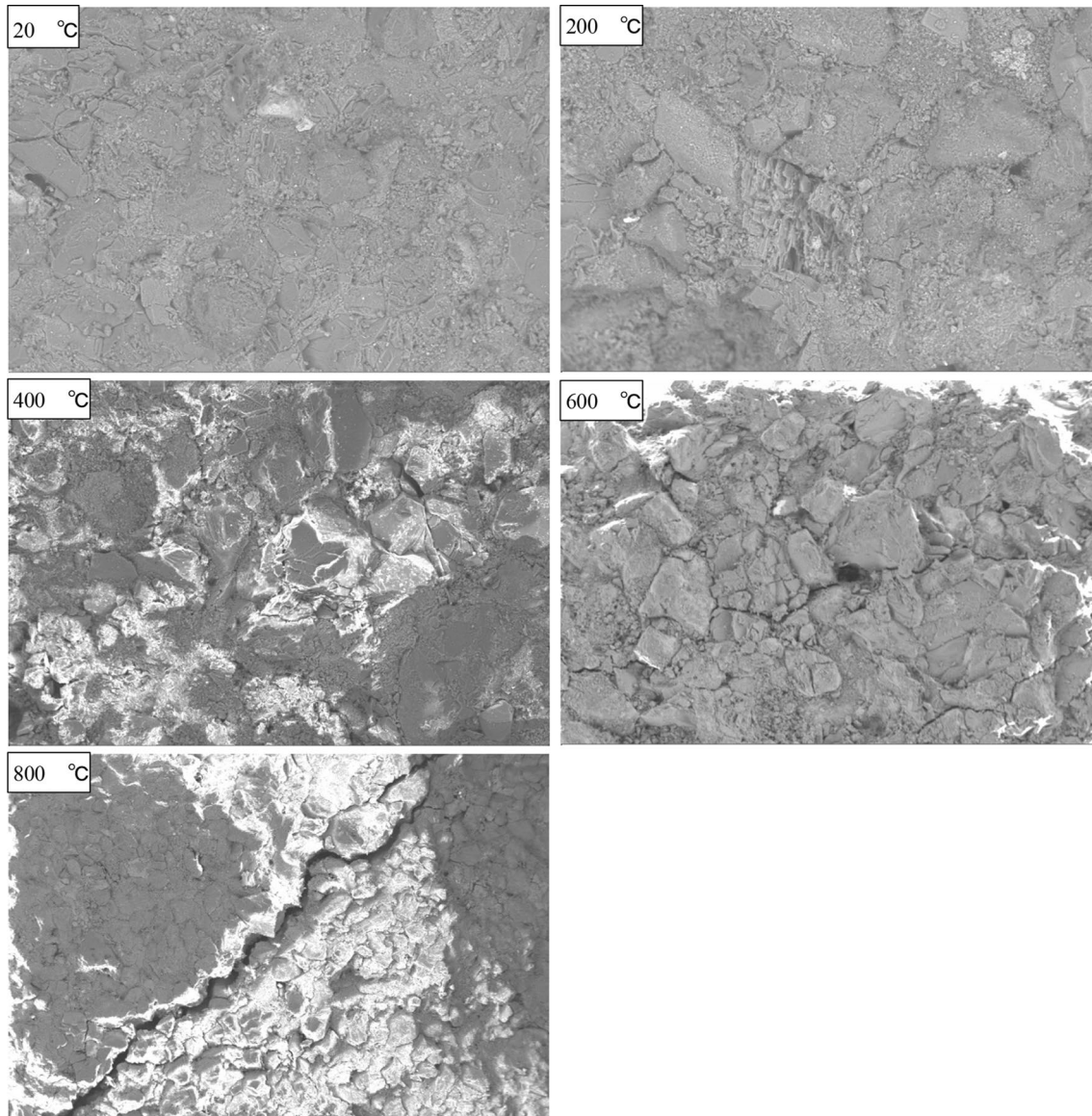
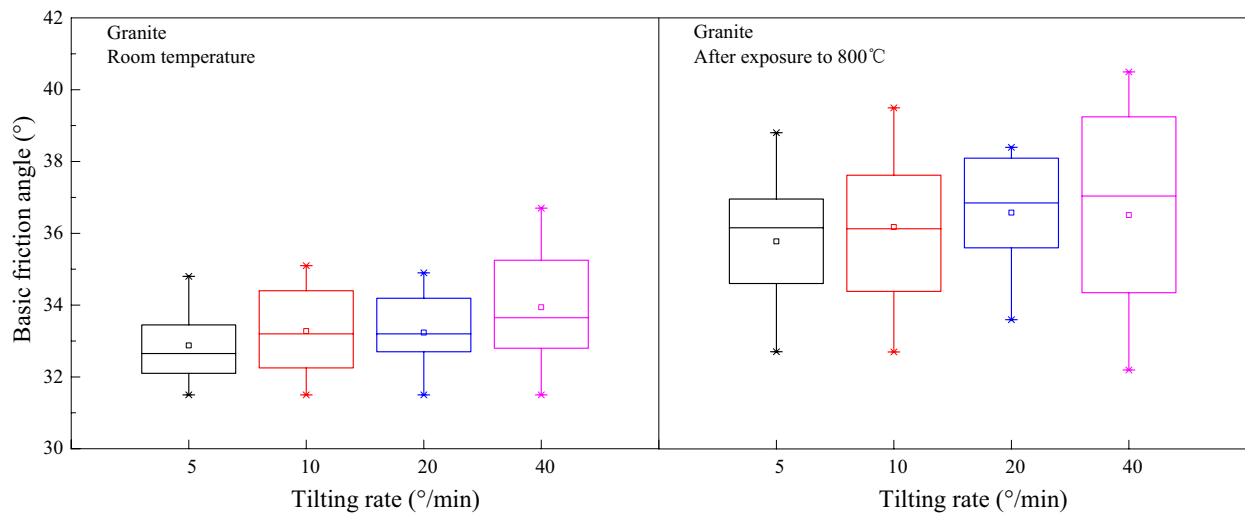


Fig. 8 SEM images for the red sandstone surfaces after thermal treatments

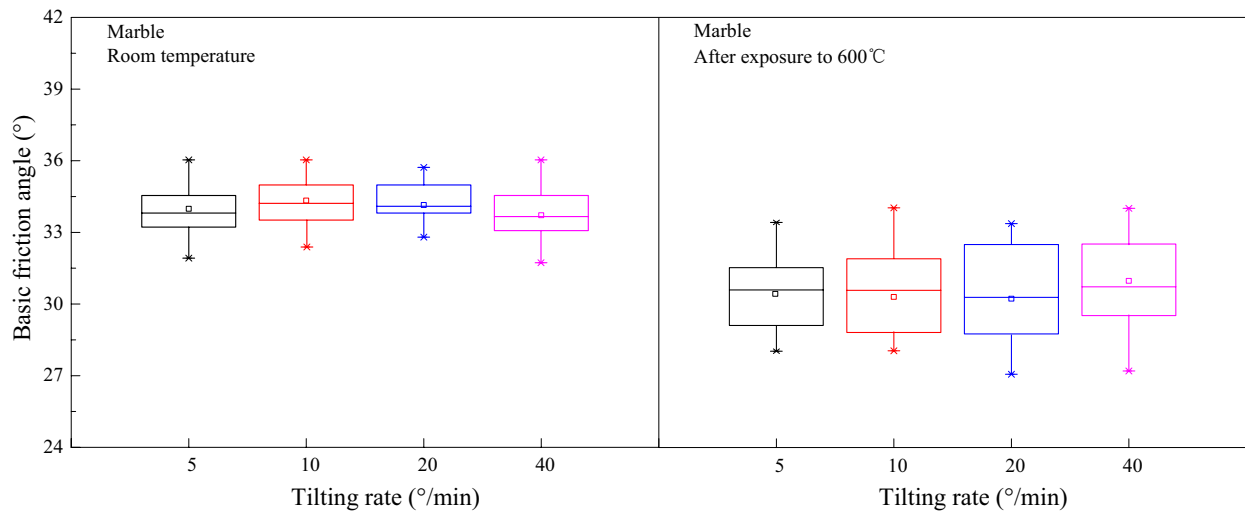
the limited specimens. Twenty sliding angles are measured under the tilting rate of $20^\circ/\text{min}$ for the two temperature conditions following the procedures described in Sect. 2.3.

Figure 10 shows the mean, maximum, and minimum basic friction angles for the red sandstone joints with the four sizes under the two temperature conditions. It is found that the largest sliding angle does not always occur at the first measurement, which is different from the results observed by Jang et al. (2017). For the specimens without thermal treatment, no clear tendency can be observed as the cylinder generatrix increases from 30 to 210 mm. For the specimens after exposure to 800°C , the basic friction angle linearly increases with the increase in the specimen size. The basic friction angle is larger for specimens

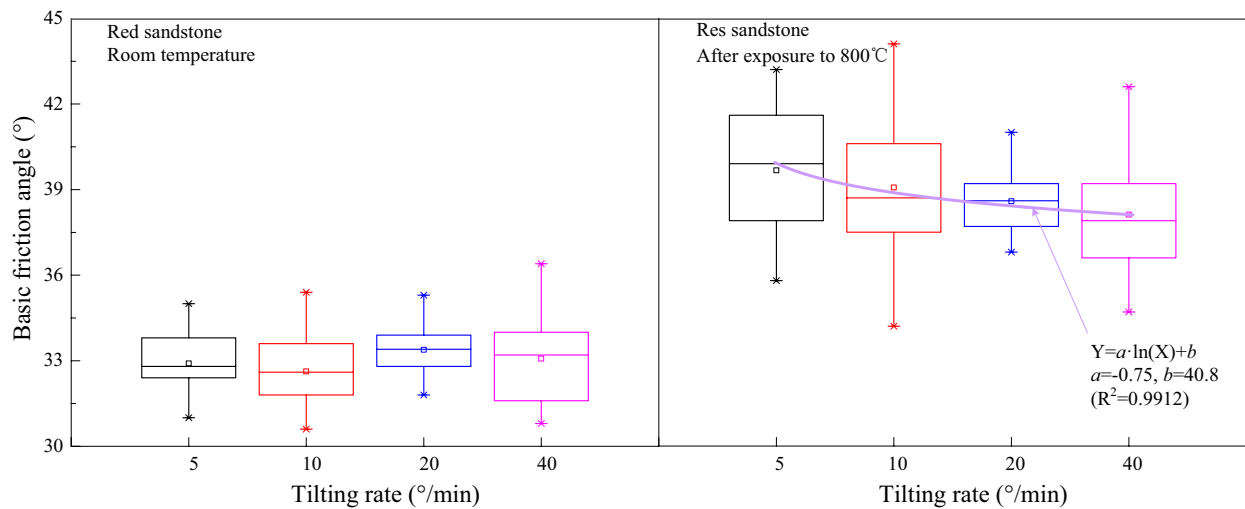
with thermal treatment when compared with that without thermal treatment, and the difference is much more obvious with the increase in the specimen size. An interesting phenomenon is that the basic friction angles distribute in a narrower range for the specimens with larger size under the two temperature conditions. The basic friction angles for specimens with generatrix length of 30 and 60 mm almost exhibit the same distribution under the same temperature condition. It ranges from 27.5° to 36.5° for those without thermal treatment and ranges from 30.2° to 38.1° for those treated with a temperature of 800°C . The larger distribution range would be due to the thermally induced micro-cracks/roughness.



(a) Granite



(b) Marble



(c) Red sandstone

Fig. 9 Ranges and means of the basic friction angles with different tilting rates

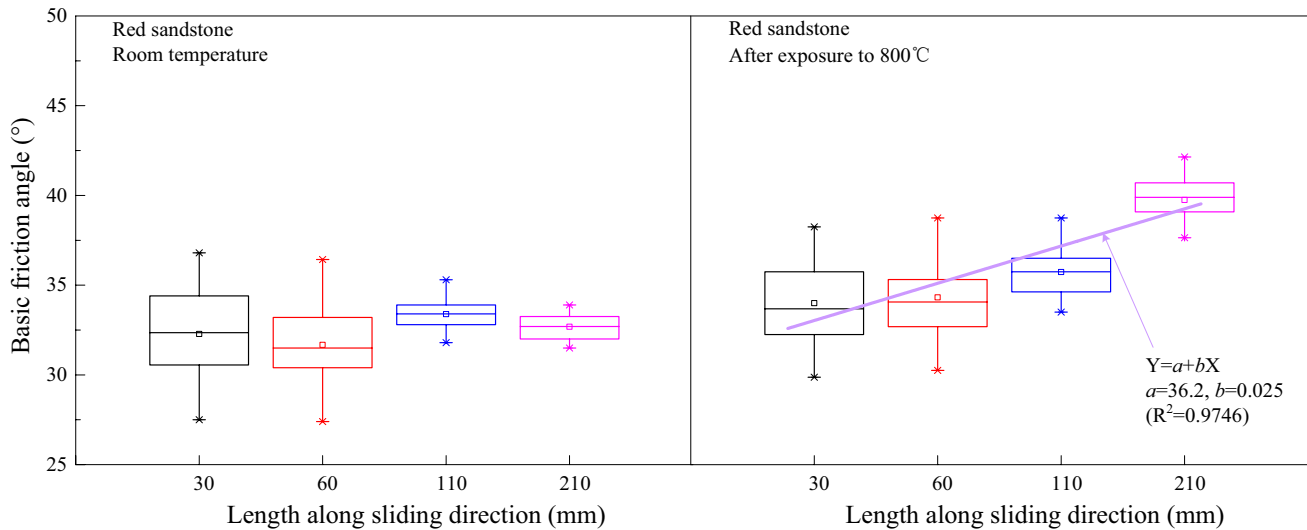


Fig. 10 Ranges and means of the basic friction angles with different specimen sizes (red sandstone)

4.3 Repetition Number

As stated by some researchers (González et al. 2014; Jang et al. 2017; Li et al. 2019), the mean basic friction angle would not be representative if the number of test repetitions is too small. In this study, several tilt tests are repeated 50 times following the procedures described in Sect. 2.3, and the mean basic friction angle is calculated at an interval of five repetitions. The calculated mean values are presented in Fig. 11 for the three kinds of rock joints after different thermal treatments.

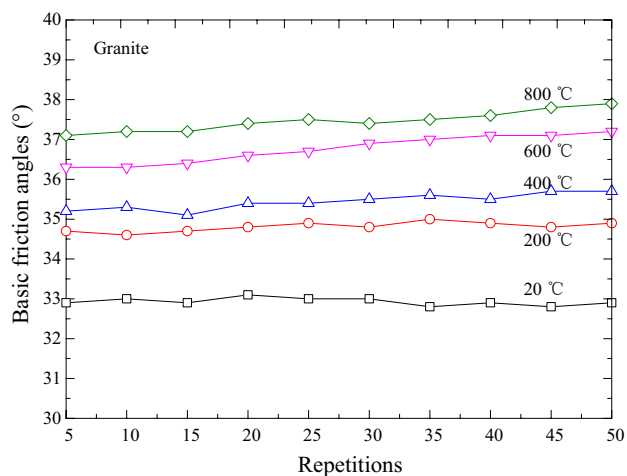
The mean basic friction angle keeps almost the same with the repetition number for the granite joints without thermal treatment. The phenomenon is also observed for the joints after exposure to 200 °C. For the granite joints after exposure to 400 °C, the mean basic friction angle slightly increases from 35.2° to 35.7° with the increase in repetition number. However, the thermal effect would be more obvious for the granite joints after treatment with temperatures of 600 and 800 °C, where a meaningful increase in the basic friction angle can be observed when the repetitions are about 50. The basic friction angle of marble joints under the four temperature conditions exhibits an obvious declining trend as the repetition increases. In general, the mean value of basic friction angle reduces by about 5° when the repetitions are about 50 (only except the one after exposure to 200 °C). The main reason for the similar phenomena of marble joints would be due to the homogeneous nature in mineral texture and composition. For the red sandstone joints after exposure to no more than

200 °C, the repetition causes little influence on the variation of basic friction angle. While a slight declining trend can be observed for the specimens after exposure to no less than 400 °C as the repetitions increase from 5 to 50.

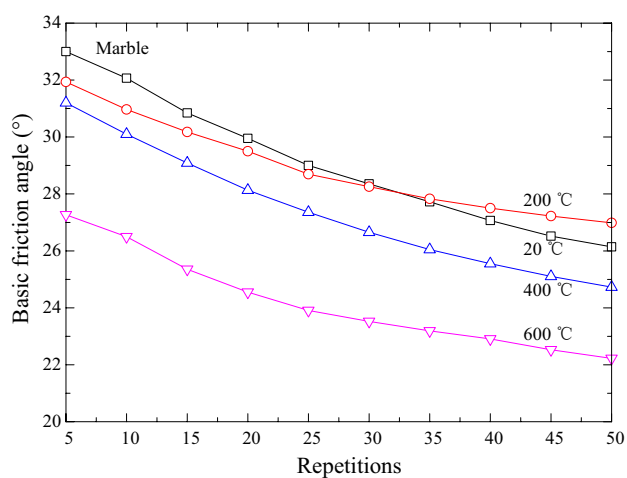
4.4 Cooling Rate

Mechanical properties of rock are generally influenced by heating–cooling treatments (Kumari et al. 2017; Zhang et al. 2018), which are mainly associated with the number and extent of thermally induced micro-cracks. The thermally induced micro-cracks could still be randomly distributed on the rock surfaces. In addition, the cooling process would also produce a series of physical and chemical changes. Both above-mentioned factors may influence the surface friction nature. Considering that seldom studies have been conducted to capture the effect of cooling treatment on the basic friction angle of rock joints, the present study intends to fill the gap and provides some pioneer studies, which would be helpful to many deep geological applications. As shown in Fig. 12, the following phenomena can be observed for the rock joints under two different cooling treatments (see Sect. 2.2):

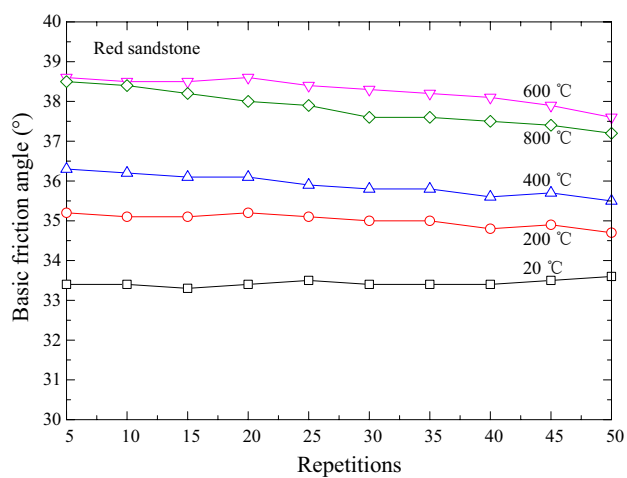
- The basic friction angle of rock joints under the rapid cooling treatment is larger than the one under the natural cooling condition (except the data set of red sandstone joint after exposure to 600 °C). However, the two cooling treatments do not change the general trend of basic



(a) Granite



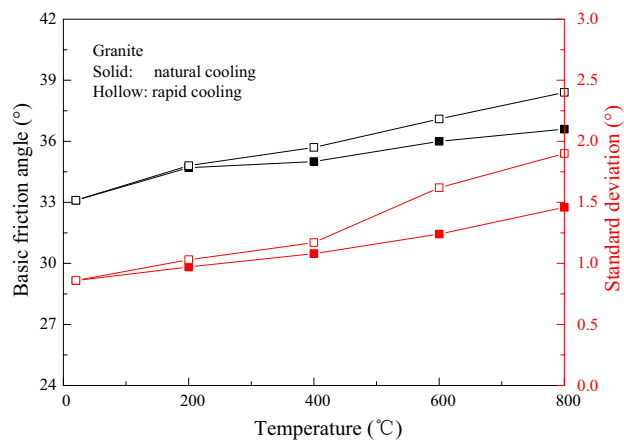
(b) Marble



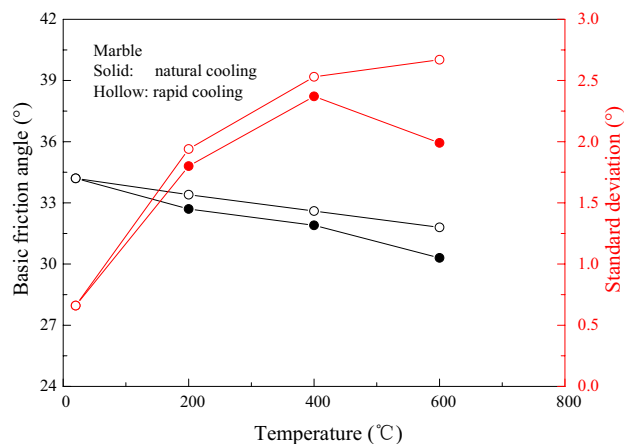
(c) Red sandstone

Fig. 11 Mean basic friction angles after different repetitions

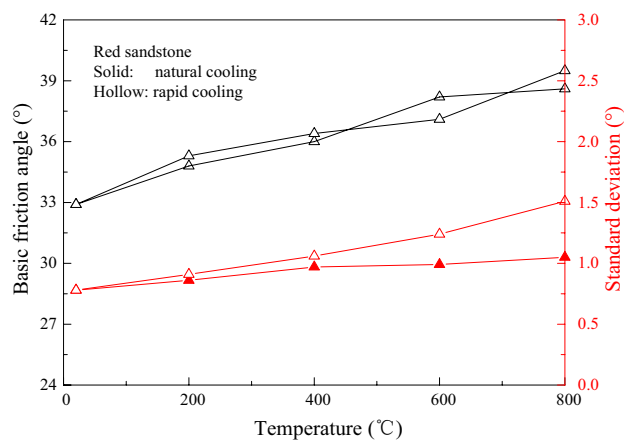
friction angle as the temperature increases from 20 °C onwards. The difference of the basic friction angle under



(a) Granite



(b) Marble



(c) Red sandstone

Fig. 12 Mean basic friction angles and standard deviations under different cooling treatments

the two cooling conditions gradually increases as the temperature increases.

- By comparison, it is found that the cooling treatment has a negligible influence on the basic friction angle of red

sandstone joint, while it is more obvious for the granite and marble joints as the temperature increases.

- The standard deviations for the three kinds of rock joints consistently increase under the two cooling treatments (except the data set of marble joint after exposure to 600 °C). Interestingly, it generally shows a larger increasing rate with the increase in treatment temperature under the rapid cooling condition, indicating that the rapid cooling treatment would lead inhomogeneity on the surfaces to a larger extent.

5 Conclusions

The effect of thermal treatment on the basic friction angle of rock surfaces is experimentally investigated by conducting three-core tilt tests on granite, marble, and red sandstone specimens. Overall, the basic friction angles of the three kinds of rock joints exhibit linear trends with the increase of heating temperature, respectively. Based on the results from a large number of tilt tests, the following conclusions can be drawn:

- With the increase in the treatment temperature, a monotonous increase in the basic friction angle of granite and red sandstone joints can be found, while those of marble joints exhibit a continual decrease. A linear function considering the effect of treatment temperature is proposed to characterize the temperature-dependent behavior. In addition, the standard deviations of basic friction angles for the three rock surfaces become larger as the temperature in treatment increases. The rising standard deviation indicates that the homogeneity of the three kinds of rock surfaces decreases.
- Under the room-temperature and the highest temperature conditions, the tilting rate causes little influence on the basic friction angles of granite and marble joints. Under the room-temperature condition, the basic friction angle of the red sandstone joints exhibits a rate-independent behavior, while a decreasing trend can be observed when the treatment temperature is 800 °C. In addition, the basic friction angle of rock joints with highest temperature in the treatment distributes in a larger range than that without thermal treatment as the tilting rate increases from 5 to 40°/min.
- Size effect is not prominent for the basic friction angle of red sandstone joints without thermal treatment as the size (cylinder generatrix) increases from 30 to 210 mm. However, there is a linear increasing trend for the basic friction angle of specimens after thermal treatment with the increase in the specimen size. When the size is the same, the specimen with thermal treatment gen-

erally has a larger basic friction angle. An interesting phenomenon is that the basic friction angles distribute in a narrower range for the specimens with larger size under the two temperature conditions.

- In general, the effect of repetition on the basic friction angle of granite and red sandstone joints is not obvious, distributing in a narrow range within about $\pm 1^\circ$ as the repetitions increase from 5 to 50. However, the repetition tests cause great influence on the basic friction angle of marble joints. An obvious declining trend can be observed with the increase of repetition number, and the mean value of basic friction angle reduces by about 5° when repetitions are about 50.
- Natural and rapid cooling treatments do not change the general trend of basic friction angle as the treatment temperature increases. However, the latter would produce a larger basic friction angle for the three kinds of rock joints when the treatment temperature is the same. The standard deviations generally increase with the increase in the treatment temperature under the two cooling treatments.

Acknowledgements The authors gratefully acknowledge the support from the Natural Science Foundation of China (Grant nos. 41672302, 51578408, 41731284, and 51609178) and the Fundamental Research Funds for the Central Universities, China University of Geosciences (Wuhan) (Grant no. CUG170603). Many thanks are also given to Yu Tang, Yu Feng Zhang, and Yong Yi Li for their assistance in performing the tilt tests.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflicts of interest.

References

- Alejano LR, González J, Muralha J (2012) Comparison of different techniques of tilt testing and basic friction angle variability assessment. *Rock Mech Rock Eng* 45:1023–1035
- Alejano LR, Muralha J, Ulusay R, Li CC, Pérez-Rey I, Karakul H, Chryssanthakis P, Aydan Ö, Martínez J, Zhang N (2017) A benchmark experiment to assess factors affecting tilt test results for sawcut rock surfaces. *Rock Mech Rock Eng* 50:2547–2562
- Alejano LR, Muralha J, Ulusay R, Li CC, Pérez-Rey I, Karakul H, Chryssanthakis P, Aydan Ö (2018) ISRM suggested method for determining the basic friction angle of planar rock surfaces by means of tilt tests. *Rock Mech Rock Eng* 51:3853–3859
- Barton N (1973) Review of a new shear-strength criterion for rock joints. *Eng Geol* 7:287–332
- Barton N (1976) The shear strength of rock and rock joints. *Int J Rock Mech Min Sci Geomech Abstr* 13:255–279
- Barton N (2013) Shear strength criteria for rock, rock joints, rockfill and rock masses: problems and some solutions. *J Rock Mech Geotech Eng* 5:249–261

- Barton N, Choubey V (1977) The shear strength of rock joints in theory and practice. *Rock Mech Rock Eng* 10:1–54
- Bruce IG, Cruden DM, Eaton TM (1989) Use of a tilting table to determine the basic friction angle of hard rock samples. *Can Geotech J* 26:474–479
- Cruden DM, Hu XQ (1988) Basic friction angles of carbonate rocks from Kananaskis country, Canada. *Bull Int Assoc Eng Geol* 38:55–59
- Farrar NS, Cawsey DC (1976) Discussion: a simple sliding apparatus for the measurement of rock joint friction. *Géotechnique* 26:382–386
- González J, González-Pastoriza N, Castro U, Alejano LR, Muralha J (2014) Considerations on the laboratory estimate of the basic friction angle of rock joints. In: *Rock engineering and rock mechanics: structures in and on rock masses—proceedings of EUROCK 2014, ISRM European Regional Symposium*, pp 199–204
- Grasselli G (2006) Manuel Rocha Medal Recipient Shear Strength of rock joints based on quantified surface description. *Rock Mech Rock Eng* 39:295
- Hencher SR (1977) The effect of vibration on the friction between planar rock surfaces, Ph.D. Imperial College of Science and Technology, London
- Hencher SR (1995) Interpretation of direct shear tests on rock joints
- Hencher SR (2012) Discussion of Alejano, Gonzalez and Muralha (2012). *Rock Mech Rock Eng* 45:1137–1139
- Hencher SR, Richards LR (1989) Laboratory direct shear testing of rock discontinuities. *Ground Eng* 22:24–31
- Hu XQ, Cruden DM (1992) A portable tilting table for on-site tests of the friction angles of discontinuities in rock masses. *Bull Int Assoc Eng Geol* 46:59–62
- Jang HS, Zhang QZ, Kang SS, Jang BA (2017) Determination of the basic friction angle of rock surfaces by tilt tests. *Rock Mech Rock Eng* 51:989–1004
- Khamrat S, Thongprapha T, Fuenkajorn K (2018) Thermal effects on shearing resistance of fractures in Tak granite. *J Struct Geol* 111:64–74
- Kim T, Jeon S (2019) Experimental study on shear behavior of a rock discontinuity under various thermal, hydraulic and mechanical conditions. *Rock Mech Rock Eng*. <https://doi.org/10.1007/s00603-018-1723-7>
- Kulatilake PHSW, Shou G, Huang TH, Morgan RM (1995) New peak shear strength criteria for anisotropic rock joints. *Int J Rock Mech Min Sci Geomech Abstr* 32:673–697
- Kumari WGP, Ranjith PG, Perera MSA, Chen BK, Abdulatov IM (2017) Temperature-dependent mechanical behaviour of Australian Strathbogie granite with different cooling treatments. *Eng Geol* 229:31–44
- Li CC, Zhang N, Ruiz J (2019) Measurement of the basic friction angle of planar rock discontinuities with three rock cores. *Bull Eng Geol Environ* 78:847–856
- Lomenick TF, Bradshaw RL (1969) Deformation of rock salt in openings mined for the disposal of radioactive wastes. *Rock Mech* 1:5–29
- Olsson WA (1974) Effects of temperature, pressure and displacement rate on the frictional characteristics of a limestone. *Int J Rock Mech Min Sci Geomech Abstr* 11:267–278
- Park J-W, Park D, Ryu D-W, Choi B-H, Park E-S (2014) Analysis on heat transfer and heat loss characteristics of rock cavern thermal energy storage. *Eng Geol* 181:142–156
- Patton FD (1966) Multiple modes of shear failure in rock 1st ISRM Congress. International Society for Rock Mechanics and Rock Engineering, Lisbon
- Peng J, Rong G, Cai M, Yao M-D, Zhou C-B (2016) Physical and mechanical behaviors of a thermal-damaged coarse marble under uniaxial compression. *Eng Geol* 200:88–93
- Pérez-Rey I, Alejano LR, González-Pastoriza N, González J, Arzúa J (2015) Effect of time and wear on the basic friction angle of rock discontinuities. In: *ISRM European regional symposium: Eurock 2015 and geomechanics colloquium*
- Pérez-Rey I, Alejano LR, Arzúa J, Muralha J (2016) The role of tilting rate and wear of surfaces on basic friction angle testing ISRM international symposium—EUROCK 2016. International Society for Rock Mechanics and Rock Engineering, Ürgüp, p 6
- Ruiz J, Li C (2014) Measurement of the basic friction angle of rock by three different tilt test methods. Taylor and Francis, London
- Shao S, Ranjith PG, Wasantha PLP, Chen BK (2015) Experimental and numerical studies on the mechanical behaviour of Australian Strathbogie granite at high temperatures: an application to geothermal energy. *Geothermics* 54:96–108
- Stimpson B (1981) A suggested technique for determining the basic friction angle of rock surfaces using core. *Int J Rock Mech Min Sci Geomech Abstr* 18:63–65
- Sun Q, Lü C, Cao L, Li W, Geng J, Zhang W (2016) Thermal properties of sandstone after treatment at high temperature. *Int J Rock Mech Min Sci* 85:60–66
- Tang ZC, Wong LNY (2016) New criterion for evaluating the peak shear strength of rock joints under different contact states. *Rock Mech Rock Eng* 49:1191–1199
- Tang ZC, Sun M, Peng J (2019) Influence of high temperature duration on physical, thermal and mechanical properties of a fine-grained marble. *Appl Therm Eng* 156:34–50
- Tian H, Ziegler M, Kempka T (2014) Physical and mechanical behavior of claystone exposed to temperatures up to 1000 °C. *Int J Rock Mech Min Sci* 70:144–153
- Tian H, Mei G, Jiang GS, Qin Y (2017) High-temperature influence on mechanical properties of diorite. *Rock Mech Rock Eng* 50:1661–1666
- Ulusay R, Karakul H (2016) Assessment of basic friction angles of various rock types from Turkey under dry, wet and submerged conditions and some considerations on tilt testing. *Bull Eng Geol Environ* 75:1683–1699
- Wines DR, Lilly PA (2003) Estimates of rock joint shear strength in part of the Fimiston open pit operation in Western Australia. *Int J Rock Mech Min Sci* 40:929–937
- Xia CC, Tang ZC, Xiao WM, Song YL (2014) New peak shear strength criterion of rock joints based on quantified surface description. *Rock Mech Rock Eng* 47:387–400
- Yang S-Q, Xu P, Li Y-B, Huang Y-H (2017) Experimental investigation on triaxial mechanical and permeability behavior of sandstone after exposure to different high temperature treatments. *Geothermics* 69:93–109
- Zhang W, Sun Q, Hao S, Geng J, Chao L (2016) Experimental study on the variation of physical and mechanical properties of rock after high temperature treatment. *Appl Therm Eng* 98:1297–1304
- Zhang W, Sun Q, Zhu S, Bo W (2017a) Experimental study on mechanical and porous characteristics of limestone affected by high temperature. *Appl Therm Eng* 110:356–362
- Zhang Y, Sun Q, Cao L, Geng J (2017b) Pore, mechanics and acoustic emission characteristics of limestone under the influence of temperature. *Appl Therm Eng* 123:1237–1244
- Zhang Y, Sun Q, He H, Cao L, Zhang W, Bo W (2017c) Pore characteristics and mechanical properties of sandstone under the influence of temperature. *Appl Therm Eng* 113:537–543
- Zhang F, Zhao J, Hu D, Skoczylas F, Shao J (2018) Laboratory investigation on physical and mechanical properties of granite after heating and water-cooling treatment. *Rock Mech Rock Eng* 51:677–694
- Zhao J (1997) Joint surface matching and shear strength part B: JRC-JMC shear strength criterion. *Int J Rock Mech Min Sci* 34:179–185

- Zhao Z, Dou Z, Xu H, Liu Z (2019) Shear behavior of Beishan granite fractures after thermal treatment. *Eng Fract Mech* 213:223–240
- Zhou SW, Xia CC, Du SG, Zhang PY, Zhou Y (2015) An analytical solution for mechanical responses induced by temperature and air pressure in a lined rock cavern for underground compressed air energy storage. *Rock Mech Rock Eng* 48:749–770
- Zhu S, Zhang W, Sun Q, Deng S, Geng J, Li C (2017) Thermally induced variation of primary wave velocity in granite from

Yantai: experimental and modeling results. *Int J Therm Sci* 114:320–326

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.