Research Article

The Friction Angle of the Leiyang Marble Surface after Exposure to High Temperature

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There is a lack of information about the temperature-dependent nature of the rock surface, which is one of the essential parameters to predict the surface friction. In the present study, we experimentally study the effect of temperature on the basic friction angle of the marble surface through the direct shear test under the low normal loading condition and tilting test (Stimpson/disk tilt test). The basic friction angle gradually decreases with the increase in temperature from 20°C to 600°C for the two kinds of the tilting test. The results indicate that the Stimpson test on samples with the length-to-diameter ratio of 2 can be more reliable to estimate the basic friction angle of the rock surface after exposure to high temperatures. The results illustrate that the sliding angle depends on the surface condition. With the increase in the repetitive measurements, the sliding angle decreases as the marble surface is cleaned, and the parameter increases as the marble surface is not cleaned.

1. Introduction

With the development of spiritual civilization in China, more attention has been paid to the protection of the culture. As for the stone cultural relics, the fire can cause major hidden disasters. The corresponding physical and mechanical properties can usually be altered by the fire-induced high temperature. The surface friction is one of the important properties, and it has not been comprehensively investigated in the past. Recently, the topic has motivated the research interest, including rock mechanics and historic preservation. In general, the surface friction can be reflected by the basic friction angle of the flat surface, which is an intrinsic property of a rock, determined by the mineral composition and texture of the material [1, 2], and used to estimate the shear strength of a rock joint [1, 3, 4]. According to Barton [1, 5], the basic friction angles of many rock types ranged from 21° to 38°, in which the sedimentary rock has a lower basic friction angle (ranging from 25° to 30°) than that of the igneous and metamorphic rocks (ranging from 30° to 35°). After that, many researchers have investigated the

property [6–14]. Recently, due to the demand for high temperature applications in underground engineering, many researchers have focused on understanding the temperature-dependent mechanical behavior of rocks. Although an ISRM-suggested method has been proposed by Alejano et al. [15], there is no experimental data available about the temperature-dependent nature of the basic friction angle [14]. Recent investigations indicated that the basic friction angle of the rock joint was greatly influenced by the testing method [2, 10, 11, 13, 16]. According to Ulusay and Karakul [2], the tilt test and direct shear test are the two commonly used methods to determine the basic friction angle of the rock joint in the laboratory. Experimental results showed that the value measured by the direct shear test is lower than that measured by the tilt test [10]. In essence, smooth surfaces are more suitable for determining the joint basic friction angle due to the parameter reflecting the adhesion of two contact surfaces [16]. From a practical point of view, such surfaces can hardly be available, and the measurement cannot be done. 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 [14].

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 [9, 10, 16], in which the number of repetitions usually ranged between three and five. Alejano et al. [11] 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 [6, 10, 13, 17] found that, with the increase in repetitions, the tilt test would probably provide an underestimation of the basic friction angle, especially when the surface was cleaned before each test. However, contradictory phenomena were also observed by Jang et al. [13].

In the present study, both the direct shear test and tilt test were performed to measure the friction angle of marble surfaces after exposure to different temperatures (20, 200, 400, and 600°C , respectively). The characteristics of the sliding angles in relation to exposed temperatures were statistically analyzed. The effect of surface conditions (not cleaned or cleaned) was also investigated by tilt tests through repetitive measurements. The present study would be the first step to comprehensively understand the temperature-dependent shear behavior of the rock joint after thermal treatment, which is helpful in providing some insights to the variation of the joint basic friction angle with the increase in temperature and also be a pioneer to establish a peak shear strength criterion for the rock joint by considering the temperature effect that has been rarely studied in the literature.

2. Materials and Methods

The Leiyang marble is relatively homogeneous in texture and composition and is composed of dolomite and calcite with a small amount of white mica. The grain size is about 0.5 to 1 mm. The UCS is approximately 122.2 MPa (by using 3 specimens with length of 100 mm and diameter of 50 mm), and the tensile strength is about 4.11 MPa (by the Brazilian test using 6 specimens with diameter of 50 mm and height of 25 mm). Laboratory core drill and saw machines were used to prepare cylindrical specimens with length-to-diameter ratios (L/D) of 0.5, 1, 2, and 4, respectively, as shown in Figure 1(a). The diameter of the samples was 50 mm. Samples with the length-to-diameter ratio of 1 were used to perform the direct shear test; samples with the length-to-diameter ratio of 0.5 were used to perform the disk tilt test; samples with the length-to-diameter ratio of 4 or 2 were used to perform the Simpson test.

In the present study, the post-high-temperature treatment is used to study the temperature-dependent surface friction nature of the three types of rocks, which means that the thermal treatment is first applied to the specimens alone by an electrical high-temperature furnace (Figure 1(b)). All the samples were firstly subjected to dry processing which was performed by putting the samples into a drying oven

and baking them at 105°C for 48 h to remove natural moisture content. According to the available experimental procedures, there is no well-recognized standard to heat the rock. According to the performance of the high-temperature furnace and also the work done by other researchers [18, 19], thermal treatment was performed on the dried samples in an electrical furnace with the following procedures:

- (i) Heat the dried samples at a rate of $5^\circ\text{C}/\text{min}$ until to a predetermined temperature in the furnace chamber, which is 200, 400, and 600°C (referred as the #200 surface, #400 surface, and #600 surface, respectively). The scenarios of thermal treatments are shown in Figure 1(c).
- (ii) Maintain the samples at the predetermined temperature for 120 min.
- (iii) Turn off the furnace and allow it to naturally cool to the room temperature (about 20°C).

A manually operated tilting apparatus combined with a free downloadable digital slope meter (Max Protractor), built into a Huawei cell phone, was used to measure the sliding angle (1.0° accuracy), as shown in Figure 1(d). Before each test, the horizontality was confirmed by the electrolytic bubble. The tilting procedures followed the approaches stated by Alejano et al. [7]. The tilting rate was about $0.5^\circ/\text{s}$ until the upper specimen began to slide. The tilting device was stopped when the upper block slides about 10% of the sample length. To examine the effect of wear on the friction angle of the rock surface, both cleaned and not cleaned after each measurement were considered. A soft brush was used to remove the abraded rock particles.

Direct shear tests were performed using the RMT-150 direct shear machine (Figure 1(e)). Hydraulic pressure sensors and displacement gauges were installed to accurately control and measure the shear force, vertical force, shear displacement, and vertical displacement. The shear rate was set as 0.5 mm/min. Five levels of normal stresses from 0.2 MPa to 1.0 MPa were applied (0.1, 0.4, 0.6, 0.8, and 1.0 MPa, respectively). The point on the stress–shear displacement curve, where the slope begins to stabilize, was selected as the shear strength of the rock surfaces.

3. Basic Friction Angle

3.1. Direct Shear Test. The shear strength increases linearly with the increase of normal stress, as shown in Figure 2, with a very good linear correlation coefficient of 0.98 or more. The basic friction angle was considered as the slope angle of the regression line. For samples after exposure to temperatures from the room temperature onward, the determined basic friction angles are 32.8° , 32.0° , 31.1° , and 29° , respectively. It can be observed that the basic friction angle becomes smaller as the surface exposed to higher temperature.

3.2. Tilt Test. Both the measured initial sliding angles obtained by tilt tests with no repetitive measurements and the statistical results are listed in Table 1 (the average values were used to analyze in the following). For samples with the

(a)

Electric furnace

The way to place the specimens
(top view)

- Silicon carbide bar
- Specimen

(b)

(c)

FIGURE 1: Continued.

FIGURE 1: (a) Leiyang marble samples, (b) electrical furnace, (c) scenario of thermal treatment with a natural cooling rate, (d) assembly photo of the cylindrical specimen in the tilt test, and (e) RMT-301 servo-hydraulic test equipment.

FIGURE 2: Shear strengths versus normal stresses measured by direct shear tests for surfaces after different temperatures (the solid line is the regression line).

length-to-diameter ratio of 4, the results showed the following: (1) the initial sliding angles of #20 and #200 surfaces were 33.9° and 33.4°, respectively, which are about 2° higher than that of the #400 surface (around 31.7°); (2) the initial sliding angle for the #600 surface declined to 26.9°; (3) the standard deviations generally increased with the increase of temperatures, indicating that the marble surfaces exhibit temperature-dependent properties and tend to be inhomogeneous after exposure to high temperatures. For samples with the length-to-diameter ratio of 2, the initial sliding angles decreased with the increase of exposed temperatures. The average initial sliding angle of the #20 surface was 4° higher than that of the #600 surface. The standard deviation of the #400 surface was the largest one. As for the disk tilt test ($L/D = 0.5$), the obtained initial sliding angles changed slightly with the increase of exposed temperatures, and the values, distributed in a narrow range of 21.8°–24.5°, were lower than that of Stimpson test results.

Generally, the average initial sliding angles decreased with the increase of exposure temperatures for each test type. Temperature has a greater influence on the Stimpson

TABLE 1: The initial sliding angles of marble surfaces after exposure to different temperatures.

No.	Experimental data under each temperature												Normalized by the average value at 20°C																							
	ST ($L/D=2$)						ST ($L/D=4$)						DT						ST ($L/D=2$)						ST ($L/D=4$)						DT					
	20	200	400	600	20	600	20	200	400	600	20	200	400	600	20	200	400	600	20	200	400	600	20	200	400	600	20	200	400	600	20	200	400	600		
1	34	36	31	30	34	31	30	31	30	27	26	25	23	1.00	1.06	0.91	0.88	1.00	0.97	0.91	0.88	1.00	0.97	0.91	0.88	1.00	0.97	0.91	0.88	1.00	0.96	0.93	0.85			
2	34	32	30	29	35	34	35	33	33	27	26	25	24	1.00	0.94	0.88	0.85	1.03	1.00	1.03	0.97	1.00	1.00	1.03	0.97	1.00	1.00	1.03	0.97	1.00	0.96	0.93	0.89			
3	33	32	34	26	34	30	35	30	35	25	27	26	25	0.97	0.94	1.00	0.76	1.00	0.88	1.03	0.88	1.00	0.88	1.03	0.88	1.00	0.88	1.03	0.88	1.00	1.08	1.04	1.00			
4	35	34	35	25	34	32	36	28	36	26	25	23	23	1.03	1.00	1.03	0.74	1.00	0.94	1.06	0.82	1.00	0.94	1.06	0.82	1.00	0.94	1.06	0.82	1.00	0.96	0.88	0.88			
5	34	36	32	28	34	33	38	27	38	26	25	24	23	1.00	1.06	0.94	0.82	1.00	0.97	1.12	0.79	1.00	0.97	1.12	0.79	1.00	0.97	1.12	0.79	1.00	0.96	0.92	0.88			
6	34	37	34	28	34	32	30	29	28	26	21	21	21	1.00	1.09	1.00	0.82	1.00	0.94	0.88	0.85	1.00	0.94	0.88	0.85	1.00	0.94	0.88	0.85	1.00	0.93	0.75	0.75			
7	34	32	35	26	33	31	31	30	25	24	27	22	22	1.00	0.94	1.03	0.76	0.97	0.91	0.91	0.88	1.00	0.97	0.91	0.88	1.00	0.97	0.91	0.88	1.00	0.96	1.08	1.08			
8	33	30	32	27	34	32	29	30	25	28	22	22	20	0.97	0.88	0.94	0.79	1.00	0.94	0.85	0.88	1.00	0.94	0.85	0.88	1.00	0.94	0.85	0.88	1.00	1.12	0.88	0.80			
9	33	33	30	29	34	33	35	31	23	24	22	22	22	0.97	0.97	0.88	0.85	1.00	0.97	1.03	0.91	1.00	0.97	1.03	0.91	1.00	0.97	1.03	0.91	1.04	0.96	0.96				
10	33	34	31	30	34	34	36	31	24	25	23	19	19	0.97	1.00	0.91	0.88	1.00	1.00	1.06	0.91	1.00	1.00	1.06	0.91	1.00	1.00	1.06	0.91	1.04	0.96	0.79				
11	35	34	29	24	34	36	32	33	25	24	23	23	23	1.03	1.00	0.85	0.71	1.00	1.06	0.94	0.97	1.00	1.06	0.94	0.97	1.00	1.06	0.94	0.97	1.00	0.96	0.92	0.92			
12	34	36	34	25	34	32	31	26	25	26	21	22	21	1.00	1.06	1.00	0.74	1.00	0.94	0.91	0.76	1.00	0.94	0.91	0.76	1.00	0.94	0.91	0.76	1.00	1.04	0.84	0.88			
13	32	32	31	26	35	30	30	28	25	27	21	22	21	0.94	0.94	0.91	0.76	1.03	0.88	0.88	0.82	1.00	0.88	0.88	0.82	1.00	0.88	0.88	0.82	1.00	1.08	0.84	0.88			
14	34	32	29	25	35	31	32	26	26	27	24	21	21	1.00	0.94	0.85	0.74	1.03	0.91	0.94	0.76	1.00	0.94	0.91	0.76	1.00	0.94	0.91	0.76	1.00	1.04	0.92	0.81			
15	35	31	30	25	33	36	31	33	25	26	24	20	20	1.03	0.91	0.88	0.74	0.97	1.06	0.91	0.97	1.00	1.06	0.91	0.97	1.00	1.06	0.91	0.97	1.00	1.04	0.96	0.80			
16	34	31	31	24	34	35	29	31	25	26	25	20	20	1.00	0.91	0.91	0.71	1.00	1.03	0.85	0.91	1.00	1.03	0.85	0.91	1.00	1.03	0.85	0.91	1.00	1.04	1.00	0.80			
17	35	30	33	23	35	35	34	34	26	25	23	19	19	1.03	0.88	0.97	0.68	1.03	1.03	1.03	1.00	1.00	1.03	1.00	1.00	1.00	1.03	1.00	1.00	0.96	0.88	0.73				
18	35	35	32	28	35	33	32	29	26	26	21	19	19	1.03	1.03	0.94	0.82	1.03	0.97	0.94	0.85	1.00	0.97	0.94	0.85	1.00	0.97	0.94	0.85	1.00	0.81	0.73				
19	33	35	32	29	34	32	33	29	26	26	21	22	21	0.97	1.03	0.94	0.85	1.00	0.94	0.97	0.85	1.00	0.94	0.97	0.85	1.00	0.94	0.97	0.85	1.00	0.81	0.85				
20	35	32	32	26	34	32	33	28	25	25	23	23	23	1.03	0.94	0.94	0.76	1.00	0.94	0.97	0.82	1.00	0.94	0.97	0.82	1.00	0.94	0.97	0.82	1.00	0.92	0.92				
21	34	33	31	26	33	33	31	30	24	25	23	20	20	1.00	0.97	0.91	0.76	0.97	0.97	0.91	0.88	1.00	0.97	0.91	0.88	1.00	0.97	0.91	0.88	1.00	1.04	0.96	0.83			
22	34	34	30	27	34	31	31	31	23	23	20	24	24	1.00	1.00	0.88	0.79	1.00	0.91	0.91	0.91	1.00	0.91	0.91	0.91	1.00	0.91	0.91	0.91	1.00	0.87	1.04				
23	32	34	34	25	33	34	32	33	23	28	23	23	24	0.94	1.00	1.00	0.74	0.97	1.00	0.94	0.97	1.00	0.94	0.97	1.00	0.94	0.97	1.00	0.94	1.00	1.00	1.04				
24	34	32	31	26	33	37	30	30	23	21	21	21	23	1.00	0.94	0.91	0.76	0.97	1.09	0.88	0.88	1.00	0.97	1.09	0.88	1.00	0.97	1.09	0.88	1.00	0.91	1.00				
25	—	33	28	29	—	30	30	31	23	23	22	22	22	—	0.97	0.82	0.85	—	0.88	0.88	0.91	1.00	0.88	0.88	0.91	1.00	0.88	0.88	0.91	1.00	0.96	0.96				
26	—	32	30	25	—	32	29	31	22	25	22	22	21	—	0.94	0.88	0.74	—	0.94	0.85	0.91	1.00	0.94	0.85	0.91	1.00	0.94	0.85	0.91	1.00	1.00	0.95				
27	—	35	34	26	—	31	30	30	24	24	21	20	20	—	1.03	1.00	0.76	—	0.91	0.88	0.88	1.00	0.94	0.88	0.88	1.00	0.94	0.88	1.00	1.00	0.88	0.83				
28	—	36	32	28	—	33	31	30	24	22	25	25	20	—	1.06	0.94	0.82	—	0.97	0.91	0.88	1.00	0.97	0.91	0.88	1.00	0.97	0.91	0.88	1.00	0.83	0.83				
29	—	34	31	28	—	33	34	29	23	21	23	23	21	—	1.00	0.91	0.82	—	0.97	1.00	0.85	1.00	0.97	1.00	0.85	1.00	0.97	1.00	0.85	1.00	0.91	0.91				
30	—	35	32	27	—	32	30	30	23	23	26	22	23	—	1.03	0.94	0.79	—	0.94	0.88	0.88	1.00	0.94	0.88	0.88	1.00	0.94	0.88	0.88	1.00	0.96	1.00				
31	—	—	—	—	—	—	—	—	24	24	21	21	21	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.00	0.88	0.88				
32	—	—	—	—	—	—	—	—	23	25	24	21	21	—	0.94	0.88	0.74	—	0.94	0.85	0.91	1.00	0.94	0.85	0.91	1.00	0.94	0.85	0.91	1.00	1.04	0.91				
33	—	—	—	—	—	—	—	—	23	23	23	22	22	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.00	1.00	0.96	0.96			
34	—	—	—	—	—	—	—	—	23	24	22	22	22	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.00	0.96	0.96	0.96			
35	—	—	—	—	—	—	—	—	24	23	20	20	20	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.00	0.96	0.83	0.83			
36	—	—	—	—	—	—	—	—	23	23	21	21	20	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.00	0.91	0.87	0.87			
Max	35	37	35	33	35	37	38	34	28	28	27	27	27	1.03	1.09	1.03	0.97	1.03	1.09	1.12	1.00	1.00	1.00	1.09	1.12	1.00	1.00	1.00	1.00	0.96	0.96	0.96				
Min	32	30	28	23	32	30	29	26	22	21	20	19	20	0.94	0.88	0.82	0.68	0.94	0.88	0.85	0.76	1.00	0.95	0.91	0.85	1.00	0.95	0.91	0.85	1.00	0.96	0.86				
Ave	33.9	33.4	31.7	26.9	34	32.7	32	30	24.5	24.9	22.7	21.8	21.8	1.00	0.98	0.93	0.79	1.00	0.96	0.94	0.88	1.00	1.02	0.93	0.88	1.00	1.02	0.93	0.88	1.00	1.02	0.93				
SD	0.9	1.89	1.83	2.16	0.66	1.80	2.37	1.99	1.44	1.71	1.70	1.83	1.70	0.03	0.06	0.05	0.06	0.02	0.05	0.07	0.06	1.00	1.19	1.18	0.06	1.00	1.19	1.18	0.06	1.00	1.19	1.27				

Max: maximum; Min: minimum; Ave: average; SD: standard deviation.

test than that of the disk tilt test, partly manifested by dispersion of measurements and calculated standard deviation. The temperature-dependent nature of the initial sliding angle was much more obvious for samples with the length-to-diameter ratio of 4.

3.3. Comparison. As shown in Figure 3, the difference was small (within 1.5°) for the results obtained by the direct shear test and Stimpson test as the exposed temperatures were no more than 400°C . For #600 surfaces ($L/D = 4$), the initial sliding angle was about 3.1° lower than that of the direct shear test. From the room temperature onward, the average initial sliding angle of samples ($L/D = 2$) was consistent with the basic friction angle (about 0.6° – 1.2° higher). However, the results obtained by the disk tilt test were about 7.1° – 8.3° lower than the basic friction angle. The Stimpson test on samples with the length-to-diameter ratio of 2 can be used to estimate the basic friction angle of the rock surface after exposure to high temperatures.

3.4. Mechanisms. In the literature, the following is considered to be the possible reasons for the variation of the joint basic friction angle after exposure to high temperatures [16]: (1) state change and loss of water; (2) change in physical and mechanical properties of minerals, especially the transition of crystals and the change of mineral composition; (3) microcracks induced by the unbalanced thermal stress and microroughness resulted from the dehydration process or changes/loss in mineral composition; (4) change in the thermodynamic property of the randomly distributed microasperities. As the temperature is relatively low, only physical changes occur. The chemical changes can usually be observed under the high temperature condition. In general, the competition among the abovementioned factors causes a change in the basic friction angle of rock surfaces.

To better understand the surface attribute of the Leiyang marble after different thermal treatments, Figure 4 presents the results of the SEM test for the rock (with a magnification ratio of 100). It is clear that the number of microcracks generally increase as the temperature increases from room temperature to 600°C . However, the microroughness seems to be smoother as the surface after exposure to higher temperature. Under the low normal stress condition, the microroughness on the marble surfaces would dominate the friction nature, and a decreasing trend with the increase in treatment temperature can be obtained.

4. Repetitive Measurement for Sliding Angles

Figure 5(a) shows the tilt test results of marble surfaces under the room temperature condition when not cleaned. The sliding angles increased as the measurements continued within the first 50 repetitions. After that, the values were kept almost constant. At the 50th measurement, the sliding angles were about 35° , 36° , and 26° for the surfaces with the length-

FIGURE 3: Variation and comparison of the friction angles obtained by tests.

to-diameter ratio of 4, 2, and 0.5, respectively. The first 20 repetitions caused the greatest influence on the friction behavior of the marble surface, in which the sliding angles were 33° – 43° ($L/D = 4$) and 33° – 38° ($L/D = 2$) for the Stimpson test, and distributed within a range of 21° – 34° for the disk tilt test. After 50 repetitions, the average sliding angles obtained by the Stimpson test were always higher than those by the disk tilt test. Figure 5(b) shows the tilt test results of marble surfaces under the room temperature condition when cleaned. The sliding angles showed a wave-like decrease change as the measurements continued within the first 25 repetitions. After that, the sliding angle slightly fluctuated in some ranges. At the first 10 measurements, the sliding angles obtained by the Stimpson test were 25° – 41° , obviously higher than those by the disk tilt test. After 30 repetitions, the difference between the results obtained by the Stimpson test on the sample with the length-to-diameter ratio of 2 and the disk tilt test was small.

The trend of sliding angle measurements for marble surfaces after exposure to high temperatures was similar to those under the room temperature condition, only excepting the results of the #200 surface obtained by the disk tilt test. In the first 50 repetitions, the sliding angles distributed in a range when not cleaned: (1) for #200 surfaces (Figure 6(a)), 25° – 43° ($L/D = 4$) and 31° – 40° ($L/D = 2$) for the Stimpson test and 22° – 33° for the disk tilt test; (2) for #400 surfaces (Figure 7(a)), 34° – 43° ($L/D = 4$) and 28° – 38° ($L/D = 2$) for the Stimpson test and 25° – 35° for disk tilt test; (3) for #600 surfaces (Figure 8(a)), 21° – 38° ($L/D = 4$) and 23° – 40° ($L/D = 2$) for Stimpson test and 19° – 32° for disk tilt test.

For #200 surfaces, the average sliding angles obtained by the Stimpson test were nearly equal after 90 repetitions (within around 1°). For #600 surfaces, the average sliding angles obtained by the Stimpson test were nearly equal after

FIGURE 4: SEM images for the marble surfaces after thermal treatments.

FIGURE 5: Results of tilt tests for the marble surface under room temperature. (a) Not cleaned after each measurement. (b) Cleaned after each measurement.

FIGURE 6: Results of tilt tests for the marble after 200°C. (a) Not cleaned after each measurement. (b) Cleaned after each measurement.

FIGURE 7: Results of tilt tests for the marble after 400°C. (a) Not cleaned after each measurement. (b) Cleaned after each measurement.

40 repetitions. For #400 surfaces, the difference was about 2° throughout the measurements. When cleaned, the distributed range of the sliding angles becomes narrower with the increase of temperatures. After 30 repetitions, the average sliding angles of #200 surfaces obtained by the Stimpson test were approximately equal (Figure 6(b)).

However, the average sliding angles for samples with the length-to-diameter ratio of 4 were higher than samples with the length-to-diameter ratio of 2 for other conditions (Figures 7(b) and 8(b)). Generally, the lower limits of sliding angles under the cleaned condition were smaller than those under the not-cleaned condition.

FIGURE 8: Results of tilt tests for the marble after 600°C. (a) Not cleaned after each measurement. (b) Cleaned after each measurement.

5. Conclusions

In order to study the effect of temperature on the basic friction angle of the rock surface, the direct shear test and tilt test on samples after 200°C, 400°C, and 600°C were performed by using the Leiyang marble. The surfaces exhibited temperature-dependent properties and tended to be inhomogeneous after exposure to high temperatures. The basic friction angle, determined by the direct shear test, decreased with the increase of temperatures. The Stimpson test on samples with the length-to-diameter ratio of 2 can be used to estimate the basic friction angle within the applied temperature range. Results showed that the disk tilt test tended to consistently underestimate the basic friction angle. Generally, the average sliding angles obtained by the Stimpson test using samples with the length-to-diameter ratio of 4 were higher than those of samples with the length-to-diameter ratio of 2. When the surfaces were not cleaned, the sliding angles generally increased with the increase of measurements. When the surfaces were cleaned, the sliding angles generally decreased with the increase of measurements. The first 20 repetitions have the greatest influence on the sliding angles for both surface conditions. The lower limits of sliding angles under the cleaned condition were smaller than those under the not-cleaned condition.

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 they have no conflicts of interest regarding the publication of this paper.

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References

- [1] N. Barton, "Review of a new shear-strength criterion for rock joints," *Engineering Geology*, vol. 7, no. 4, pp. 287–332, 1973.
- [2] R. Ulusay and H. Karakul, "Assessment of basic friction angles of various rock types from Turkey under dry, wet and submerged conditions and some considerations on tilt testing," *Bulletin of Engineering Geology and the Environment*, vol. 75, no. 4, pp. 1683–1699, 2016.
- [3] Z. C. Tang, "Experimental investigation on temperature-dependent shear behaviors of granite discontinuity," *Rock Mechanics and Rock Engineering*, vol. 53, no. 9, pp. 4043–4060, 2020.
- [4] Z. C. Tang and Y. Zhang, "Temperature-dependent peak shear-strength criterion for granite fractures," *Engineering Geology*, vol. 269, Article ID 105552, 2020.
- [5] N. Barton, "The shear strength of rock and rock joints," *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 13, no. 9, pp. 255–279, 1976.
- [6] S. R. Hencher, "A simple sliding apparatus for the measurement of rock friction," *Discussion. Géotechnique*, vol. 26, no. 4, pp. 641–644, 1976.
- [7] B. Stimpson, "A suggested technique for determining the basic friction angle of rock surfaces using core," *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 18, no. 1, pp. 63–65, 1981.
- [8] D. M. Cruden and X. Q. Hu, "Basic friction angles of carbonate rocks from Kananaskis country, Canada," *Bulletin of the International Association of Engineering Geology*, vol. 38, no. 59, 1988.
- [9] I. G. Bruce, D. M. Cruden, and T. M. Eaton, "Use of a tilting table to determine the basic friction angle of hard rock samples," *Canadian Geotechnical Journal*, vol. 26, no. 3, pp. 474–479, 1989.

- [10] S. R. Hencher, "Discussion of alejano, gonzalez and muralha," *Rock Mechanics and Rock Engineering*, vol. 45, no. 6, pp. 1137–1139, 2012.
- [11] L. R. Alejano, J. González, and J. Muralha, "Comparison of different techniques of tilt testing and basic friction angle variability assessment," *Rock Mechanics and Rock Engineering*, vol. 45, no. 6, pp. 1023–1035, 2012.
- [12] L. R. Alejano, J. Muralha, R. Ulusay et al., "A benchmark experiment to assess factors affecting tilt test results for sawcut rock surfaces," *Rock Mechanics and Rock Engineering*, vol. 50, no. 9, pp. 2547–2562, 2017.
- [13] H.-S. Jang, Q.-Z. Zhang, S.-S. Kang, and B.-A. Jang, "Determination of the basic friction angle of rock surfaces by tilt tests," *Rock Mechanics and Rock Engineering*, vol. 51, no. 4, p. 989, 2017.
- [14] Z. C. Tang, Q. Z. Zhang, and J. Peng, "Effect of thermal treatment on the basic friction angle of rock joint," *Rock Mechanics and Rock Engineering*, vol. 53, no. 4, pp. 1973–1990, 2020.
- [15] L. R. Alejano, J. Muralha, R. Ulusay et al., "ISRM suggested method for determining the basic friction angle of planar rock surfaces by means of tilt tests," *Rock Mechanics and Rock Engineering*, vol. 51, no. 12, pp. 3853–3859, 2018.
- [16] C. C. Li, N. Zhang, and J. Ruiz, "Measurement of the basic friction angle of planar rock discontinuities with three rock cores," *Bulletin of Engineering Geology*, vol. 78, no. 4, pp. 1–10, 2017.
- [17] N. S. Farrar and D. C. Cawsey, "Discussion: a simple sliding apparatus for the measurement of rock joint friction," *Géotechnique*, vol. 26, pp. 382–386, 1976.
- [18] G. Rong, J. Peng, M. Yao, Q. Jiang, and L. N. Y. Wong, "Effects of specimen size and thermal-damage on physical and mechanical behavior of a fine-grained marble," *Engineering Geology*, vol. 232, pp. 46–55, 2018.
- [19] Z. C. Tang, J. Sun, and J. Peng, "Influence of high temperature duration on physical, thermal and mechanical properties of a fine-grained marble," *Applied Thermal Engineering*, vol. 156, pp. 34–50, 2019.