Rock Mechanics Characterization of Columnar Sandstone of Cerro Koi (Paraguay) and Some Slope Stability Issues of the Associated Open Pits

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ABSTRACT: Unique columnar jointing in sandstone is observed in Cerro Koi site nearby Asuncion (Paraguay). The authors collected some sandstone columns and carried out on some physico-mechanical experiments on rock pieces for the rock mechanics characterization of this unique columns. The outcomes of experiments carried out rock mechanics characteristics of the columnar sandstone as well as frictional properties of natural column surface together with their base-friction angles are presented. Furthermore, the stability of the open pits is investigated and their short and long-term stability are discussed.

Keywords: Cerro Koi, columnar jointing, sandstone, open pit, mechanical properties, stability, frictional properties.

1 INTRODUCTION

Although columnar jointing is quite common in extrusive volcanics such as basalt, andesite, welded tuff, it is quite rare in other rocks. However, there are some reports that columnar jointing is also observed in rhyolite, sandstone and also dried clays (e.g. Aydan 2020). This jointing is associated with volumetric shrinkage due to cooling of magma in extrsuive rocks while it is related to shrinkage due to water-loss in sedimentary rocks. The authors have recently had the chance to visit Cerro Koi site nearby Asuncion (Paraguay), where columnar jointing was observed wide-spread in sandstone.

The authors collected some sandstone columns well as some rock samples for the rock mechanics characterization of this unique columns. The investigations involved classical density, water absorption porosity, wave velocity, Brazilian Tensile, Uniaxial Compression, Cantilever bending, and 3-point Bending tests. Furthermore, Mohr-Coulomb yield parameters were also determined and some frictional characteristics of saw-cut and natural surfaces were carried out.

Cerro Koi site involves multiple open-pits for the extraction of sandstone for construction purposes in the past and it is now under protection. The slopes of the open-pits also provide some unique data for their short and long-term stability in rock mass consisting of columnar jointing, which may be also utilized for the stability assessment and preservation of this unique rock ancient site.

The authors present the outcomes of experiments carried out rock mechanics characteristics of the columnar sandstone as well as frictional properties of natural column surface together with their base-friction angles. The observations on slopes of open-pits also provide some data on the short and long-term slope angles in rock masses with columnar jointing. It is presumed that the investigations of the authors for this site would be usefull for the preservation of the Cerro Koi as an ancient rock site.

2 GEOGRAPHY AND GEOLOGY OF CERRO KOI

2.1 Geography

It is reported there are several sandstone sites with columnar jointing in Eastern Paraguay as shown in Figure 1. Cerro Koi is located 1km outside Areguá, Paraguay and it is a hill. It is designated as a natural reserve in 1993. It is 24 km away from Asuncion, the capital city of Paraguay.

2.2 Geology

Eastern Paraguay lies in an inter-cratonic region which includes the westernmost side of the Brazilian Paraná Basin (PB). From stratigraphic evidences, almost five main alkaline magmatic events have been recognized in Eastern Paraguay and since Mesozoic times. The Patiño Formation sandstones crop out in Cerro Coi in the neighborhood of Areguá in Eastern Paraguay and columnar jointing are present in this sandstone formation (Figure 2). it is believed the sandstone was formed 40 million years ago.The mineralogical assemblage of the sandstone consists mainly monocrystalline quartz (80 to 83%), quartzite (2 to 3%), chert (3 to 5%), undifferentiated types of polycrystalline quartz (7 to 10%) and blue elbaitic tourmaline (up to 0.5%). Velázquez et al. (2008) suggested that the dyke intrusions nearby and their subsequent cooling might have caused the columnar jointing. Column ranges from 3 to 10 cm in diameter, reaching 15 m in length, and the polygonal forms have four to seven sides and the pentagonal form is predominant.

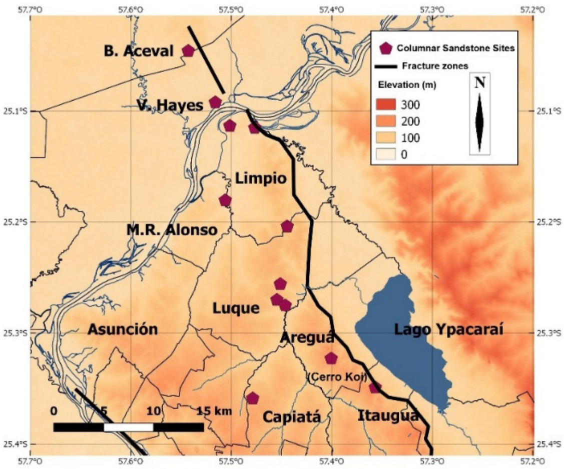


Figure 1. Locations of columnar sandstone (Modified from Gadea et al. 2020).

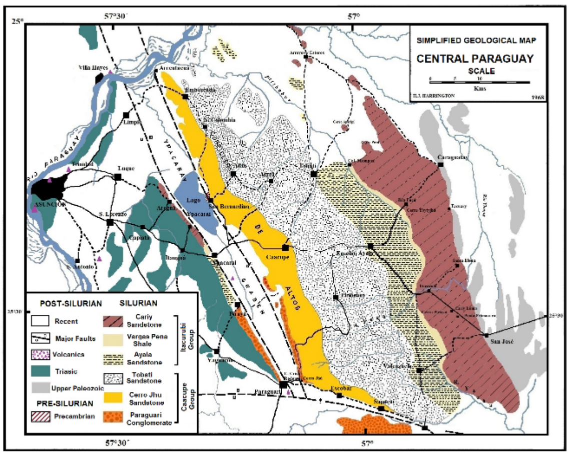


Figure 2. Geology (modified from Paraguay Geology Department, 1968).

3 IN-SITU SAMPLING AND PHYSICAL PARAMETERS

The authors visited Cerro Koi site in November, 2022. The authors selected some columns among the columns shown in Figure 3(a) and cut the ends of the selected columns shown in Figure 3(b,c) to obtain samples for physico-mechanical investigations. Samples were prepared from the pieces cut from sandstone. It should be noted that the size of samples could not be according to ISRM suggested methods due to the size of actual columns and the limitation of the column number. Nevertheless, the aspect ratio of ISRM suggested methods are followed.

(a) (b) (c)

Figure 3. Columnar sandstone (a) in-situ; (b) Side view of samples; (c) Top view of samples.

4 PHYSICAL PROPERTIES

Physical properties involve unit weight, porosity, elastic wave velocity measurements (p-wave, s-wave velocity). Furthermore, some thin sections were prepared and X-Ray analyses were carried out on the chemical composition of columnar sandstones. Table 1 summarizes the mean values of physical property measurement results.

Table 1. Physical properties of sandstone columns.

Property	S1	S2	S3	S4	S5	S6
Unit weight (kN/m^3)	19.15	19.10	20.14	18.95	20.10	19.25
P-wave velocity (km/s)	2.84	3.59	3.76	3.51	2.94	3.54
S-wave velocity (km/s)	1.99	2.13	1.79	2.22	1.60	2.61
Porosity (%)	6.68	-	7.30	9.11	10.1	10.9

5 MECHANICAL PROPERTIES

Experiments were carried out on samples prepared for Brazilian Tensile, Uniaxial Compression, 3-Point Bending tests according to the suggested aspect ratios of ISRM Suggested Methods while the sample sizes could not be in accordance with ISRM Suggested Methods for the reasons mentioned above. Figure 4 shows sample examples for Brazilian, 3-Point bending and Uniaxial compression experiments. In each testing group, samples exhibited brittle behavior.

(a) (b) (c)

Figure 4. Views of samples in (a) Brazilian, (b) uniaxial compression, and (c) 3-point bending tests.

5.1 Brazilian Tensile Tests

A number of Brazilian tests were carried out on Cerro Koi sandstone samples. Figure 5 shows the displacement versus tensile stress responses. As noted from the figure, Brazilian tensile strength (BTS) values range between 1.51 MPa and 4.66 MPa with a mean of 2.92 MPa.

5.2 Uniaxial Compression Tests

Six uniaxial compressive strength experiments were carried out and the strain-stress responses measured during experiments are shown in Figure 6. As noted from the figure, uniaxial compressive strength (UCS) values of Cerro Koi sandstone samples range between 5.65 MPa and 16.6 MPa with a mean of 9.47 MPa.

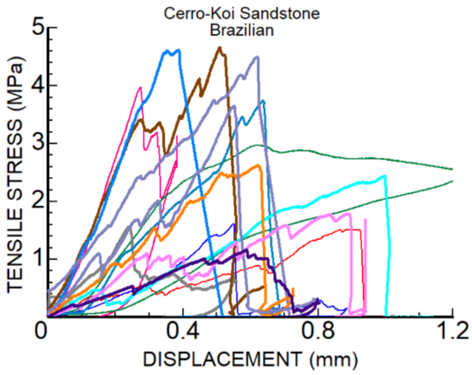


Figure 5. Displacement-stress responses in Brazilian tests.

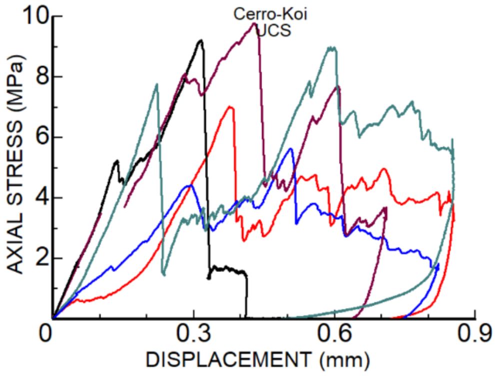


Figure 6. Strain-stress responses in uniaxial compression tests.

5.3 3-Point Bending Tests

Six 3-point bending tests were carried out and the displacement-stress responses measured during experiments are shown in Figure 7. As noted from the figure, bending strength values of Cerro Koi sandstone samples range between 4.2 MPa and 10.67 MPa with a mean of 8.81 MPa. Tensile strength obtained from 3-point bending tests are always 3-4 times higher than that obtained from Brazilian tensile tests. This observation is in accordance with the previous experimental results by the authors (Aydan 2022).

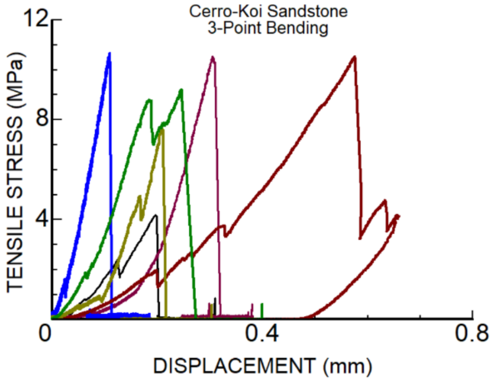


Figure 7. Displacement-stress responses in 3-point bending tests.

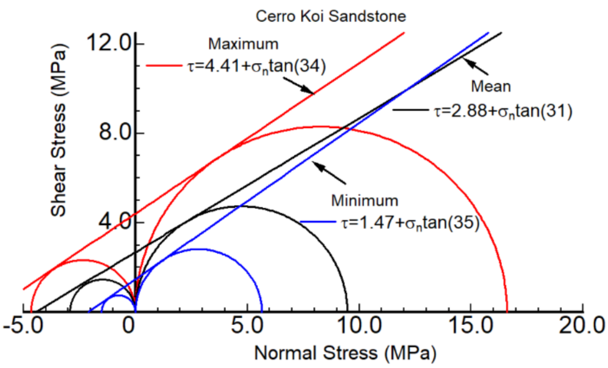


Figure 8. Mohr-Coulomb strength envelopes.

5.4 Mohr-Coulomb Strength Envelopes

Mohr-Coulomb failure criterion was selected and the values of Mohr-Coulomb failure criterion for Cerro Koi sandstone was evaluated by utilizing lower, mean and peak Brazilian tensile strength (BTS) and uniaxial compression strength (UCS) values and the results are shown in Figure 8. The cohesion for lower, mean and peak values are 1.47, 2.88 and 4.41 MPa and these values are quite similar to tensile strength values. Similarly, the friction angles for lower, mean and peak values of BTS and UCS are 35, 31 and 34 degrees. Although other failure criteria may be utilized, Mohr-Coulomb failure criterion is sufficient for engineering purposes.

6 FRICTION PROPERTIES OF COLUMNAR SURFACES

Frictional properties of columnar joints are of great importance when the stability of open pits is to be assessed. The simplest procedure is the utilization of tilt tests. As shown in Figure 9, a series of tilt tests are performed on the saw-cut surfaces as well as natural surfaces and Table 2 summarizes friction angles obtained from tilt tests. As noted from Table 2, the friction angle of natural surfaces is greater than that for saw-cut surfaces and the difference ranges between 12 and 14 degrees with a mean value 13.39.

(a) (b) (c)

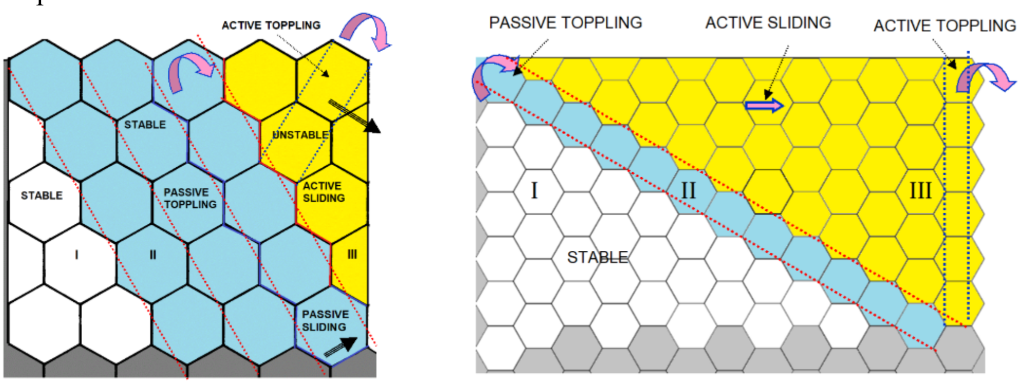
Figure 9. Views of (a) saw-cut and (b) natural surfaces of columns and (c) a tilt test.

Table 2. Frictional properties.

Surface	Lowest	Highest	Mean
Saw-cut (Basic)	23	27	24.53(15)
Natural surface	35	41	37.92(12)

7 EVALUATION OF STABILITY OF SLOPES IN OPEN PITS

Aydan et al. (2021, 2022) categorized the stability of slopes consisting of hexagonal jointing according discontinuity patterns denoted as Pattern A and Pattern B as illustrated in Figure 10. In short term, slopes for discontinuity pattern B may have very steep slope angles up to 90 degrees while the slope angle of slopes with discontinuity pattern A for short-term would be about 60 degrees. However, the slope angle for discontinuity pattern can be drastically reduced to 30 degrees while slopes with discontinuity pattern A would be almost 60 degrees for long-term also unless it is subjected to very high ground motions. Figure 11(a) shows the actual discontinuity pattern at Cerro Koi, which is mixture of discontinuity patterns A and B. While Figure 11(b,c) show the stable slopes for pattern A and B.



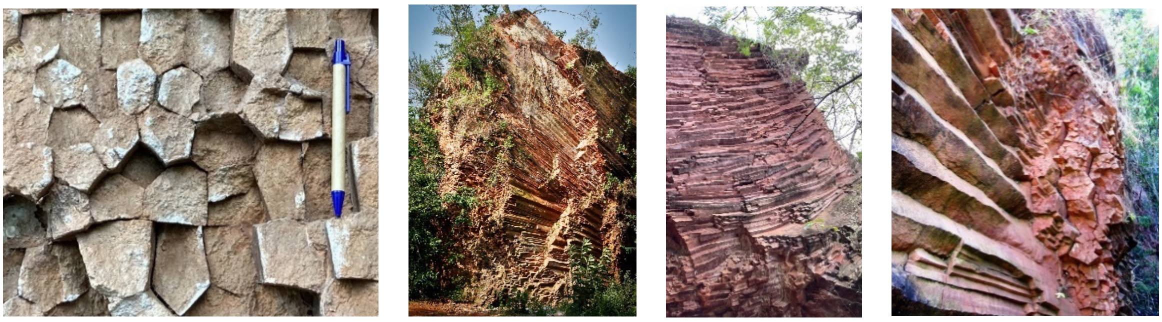
(a) Pattern A (b) Pattern B

Figure 10. Possible failure modes of rock slopes with hexagonal discontinuity patterns.

When the longitudinal axis of columns dipping out of slope or into the slope, planar sliding, flexural or columnar toppling and buckling failure may be possible as shown in Figure 12. Although the scale of such failures may vary, the abandoned open pits at Cerro Koi have such potential failure modes.

8 CONCLUSIONS

Cerro Koi site is a unique site of sandstone with columnar jointing. This study provides some quantitative data on the physico-mechanical properties of this sandstone formation from a Rock mechanics perspective for the first time. While experimental values provide some quantitative data, further experimental studies are necessary. In addition, the actual causes of columnar jointing are necessary besides the thermal contraction hypothesis. The site also provides an actual example of slope consisting of polygonal jointing and its stability issues. While preliminary evaluations are in accordance with recent studies by the authors, there is no doubt that further site explorations and stability evaluations are necessary for this unique site from a perspective of Rock Mechanics.



(a) (b) (c) (d)

Figure 11. Actual discontinuity pattern and stable slopes with different discontinuity patterns.

(a) Flexural toppling (b) Columnar toppling (c) Planar sliding (d) Buckling

Figure 12. Possible failure modes at abandoned open pits at Cerro Koi.

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