Study of the effect of pre-existing crack and water saturation on strength of rock-like

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Abstract— In civil and mining engineering works, the strength and rigidity of the rock mass can be affected by the existence of many kinds of discontinuities related to shear zones, faults, and bedding planes. This paper focuses on analyzing the effect of a single pre-existing crack on the strength and deformation behavior of rock samples based on the experimental results and to elucidate the influence of water on crack development. The triaxial compression tests were carried out on a variety of the rock samples constituted of a pre-existing crack with plane surface and rough surface with a variety of slope 30°, 45°, and 60° in the dry state and saturated state. Test data show that the existence of cracks promotes the lessening in the overall strength of the rock; though, the extent of the decrease of strength is associated with the rock properties. The lowest strength was detected for the samples with the greatest slope value. The influence of the fracture angle on the strength is independent of the drying and saturated environment of the rock mass. The strength and compressive behavior of the mass of fractured rock with different slopes under saturated conditions is lower than under drying conditions.

I. INTRODUCTION

One of the most important aspects of rock mechanics is the study of the stability of underground excavations. Whether in the case of mining galleries, tunnels, or even oil drilling, the problem of work performance remains a major concern for industries for important reasons such as the safety and exploitation of these structures. The mechanical behavior of rock masses is a determining factor in the dimensioning of the structures which are executed there. This behavior is largely influenced by the presence of discontinuities. In order to understand, explain and model this behavior, it is necessary to know the geometric distribution model of fractures, as well as the mechanical properties of the rock and the discontinuities. The presence of discontinuities can significantly affect the mechanical behavior of the rock mass by introducing weaknesses in terms of deformability and resistance [1, 2]. In the presence of discontinuities, the deformation modulus of the rock mass decreases remarkably compared to that of intact rock [3]. At shallow depth or in non-containment areas, such as excavations and civil engineering constructions, the deformation of the rock mass is essentially controlled by the presence of discontinuities while at depth or in areas with a high concentration of stresses, the influence of the structure is less marked [4,5]. In recent years, many scholars have analyzed the process of initiation and propagation of pre-existing cracks in rocks and other geological materials (rock-like for example) [6, 7, 8, and 9] and, the effects of this process on the rock's overall strength have been widely studied using uniaxial tests [10, 11, 12, 13, 14, 15, 16, 17, 18], biaxial tests [19, 20], shear and tension tests

[21, 22, 23, 24, 25]. Through these studies, it has been observed that under the load conditions, the pre-existing crack is at the origin of the appearance and the propagation of the majority of the new cracks which transform into rock bridges. The existence of relatively small rock bridges at the discontinuities greatly increases their strength [24, 25, 26] which must first be broken before a rupture can take place.The above-mentioned studies also pointed out that, the propagation of cracks within a rock was a complex phenomenon and depended on the rock composition and the properties (geometry/ shape, orientation, and size) of the pre-existing cracks.

There is still the uncertainty of predicting the effects of pre-existing cracks on rock strength characteristics despite a good understanding of the mechanism of crack propagation. Many authors [14, 26, 27] have noted that the strength of the rock can be affected by the characteristics of the joints such as the number of joints and their orientation. The strength of rock and rock mass can also be influenced by the roughness of the joints and the friction of the filled material [1, 27].

This work aims to examine the influence of pre-existing cracks of plane and rough surfaces on the strength of rock-like material and clarifying the effect of water on the propagation of cracks.

II. SAMPLE DESCRIPTION AND EXPERIMENTAL PROCEDURES

2.1 Sample preparation

Faced with the difficulty of collecting natural rock samples with the same shape and same rough or plane surface, the method of artificially creating joints is usually used to obtain samples corresponding to the programmed experiment. There are several methods of creating artificial rock samples, but the cement mortar method has been used from this experiment in order to conceive a batch of artificial joints with the same inclination angle of the pre-existing crack and the same shape of the surface. Cylindrical samples were used in the test; the specimen has consisted of a mixture of water, fine sands which particle size 2 mm-0.5 mm, and Portland cement with a ratio of 1:2:3. The specimen size is 50 mm in diameter and 100 mm in length (Φ = 50 mm ×100 mm). A fracture was created in the rock samples from a three-dimensional printed model using a 3D printer. The 3D model was put on the mold and the mixture then was filled into the mold for 24 hours. The 3D model placed in the mold permitted to obtain the different surface shapes (plane and rough surface) and values of the inclination angle (30 °, 45 °, and 60 °).

The specimens took out from the mold and were kept in water for 28 days to increase the stability of the samples. This paper conducted two scenarios of the specimen which were plane and rough surface of the preexisting crack with a slope of 30°, 45°, and 60°. After creating the fracture, the rock sample is shown in figure 1.
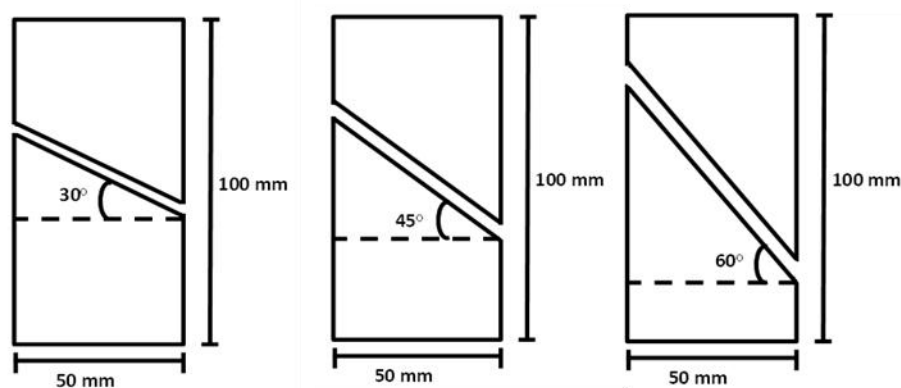

Fig.1: Specimen Slopes of 30°, 45°, and 60°

2.2 Triaxial compression test

The tri-axial compression test is administered on rock samples with a single pre-existing crack to determine the compressive strength of the rock.

This experiment uses the YAW-3000 microcomputer-controlled electro-hydraulic servo pressure testing machine

of the School of Mining and Engineering, Taiyuan University of Technology, and this testing machine was created by American AD company electronic devices. The test equipment required for inspection is an upgrade of the manual loading type and manual loading digital display universal testing machine currently in production and use. The tester uses a wide range of speed regulation ranges of

electro-hydraulic proportional valve group and computer digital control to form a fully digital closed-loop speed control system. It can automatically and accurately measure and control the whole process of loading and unloading of the tester., Wide control range, multiple functions, all operation keyboards, various test parameters are controlled, measured, displayed, processed, and printed by the computer, high integration, reliable to use. It can perform compression and various combined waveform tests on various metal and non-metal materials. It is

advanced testing equipment required for scientific research production and arbitration inspection. The maximum axial pressure and the maximum confining pressure of the tri-axial test system are 3000KN and 70 MPa, respectively. At constant flow, the injection of fluid can reach a maximum of 30 ml/min. The maximum pore water pressure is 40 MPa.

It has been applied a compression load with an increase of 0.5 kN / s until the sample is destroyed, and the test results of the relevant samples are presented in Table 1.

Table 1 test results of drying and saturated samples

	The samples serial number	Angle (°)	diameter (mm)	length (mm)	The compressive strength (MPa)	The largest load (KN)
Drying state	PDS01	30°	50.00	100.00	72.79	151.54
	PDS02	45°	50.02	100.01	34.18	53.29
	PDS03	60°	50.00	100.02	19.49	38.62
	RDS01	30°	50.01	100.00	70.55	132.46
	RDS02	45°	50.01	100.00	46.69	90.84
	RDS03	60°	50.00	100.01	39.72	82.14
Saturated state	PSS01	30°	50.00	100.00	51.69	84.08
	PSS02	45°	50.02	100.00	34.43	72.52
	PSS03	60°	50.00	100.01	17.57	41.14
	RSS01	30°	50.00	100.02	53.71	124.71
	RSS02	45°	50.01	100.00	41.89	88.99
	RSS03	60°	50.00	100.01	32.05	78.04

III.   RESULTS AND DISCUSSION

3.1 Stress-strain analysis of drying samples

The typical stress-strain behavior observed in this study on samples with a pre-existing crack through the test results obtained are shown in Figure 2 for samples with plane surface and Figure 3 for samples with a rough surface. As can be seen in Figure 2, the sample with the slope of 30 ° has higher break stress 72.79 MPa compared to the samples with a slope of 45 ° and 60 °. The sample with a slope of 45 ° has reached a strength value of 34.18 MPa while the sample with the largest pre-existing crack slope of 60 ° has the lowest strength of 19.49 MPa.

However, for specimens with a rough surface with a pre-existing crack (figure 3), a significant increase in strength is observed by an average of 39.72 MPa for specimens with a slope of 60 °, an average of 46.69 MPa for those with a slope of 45 ° and greater strength of 67 MPa for

specimens at 30 °. This difference characterized by a change in strength values can be explained by the stress behavior related to the surface property of the pre-existing crack of the rock. The figures show that the rough surface has higher compressive strength than the plane surface except for the specimen with a slope of 30 ° in the dry state for this scenario. It can be generally concluded that rough surfaces resist the load better than plane surfaces.

According to the curves obtained in Figures 2 and 3, we can also note that the inclination angle of the pre-existing crack can influence the behavior of the samples. Regardless of the shape of the pre-existing crack surface, the specimen having the smallest value of the slope (30 °) presented a higher strength (72.79 and 67 MPa) while the specimen with the greatest value of the slope (60 °) presented the lowest resistance (19,49 and 39,72 MPa respectively) that is in the saturated state or the dry state.

The results of figure 2 also indicate that a rise in the slope value of the crack decreases the strength of the samples.
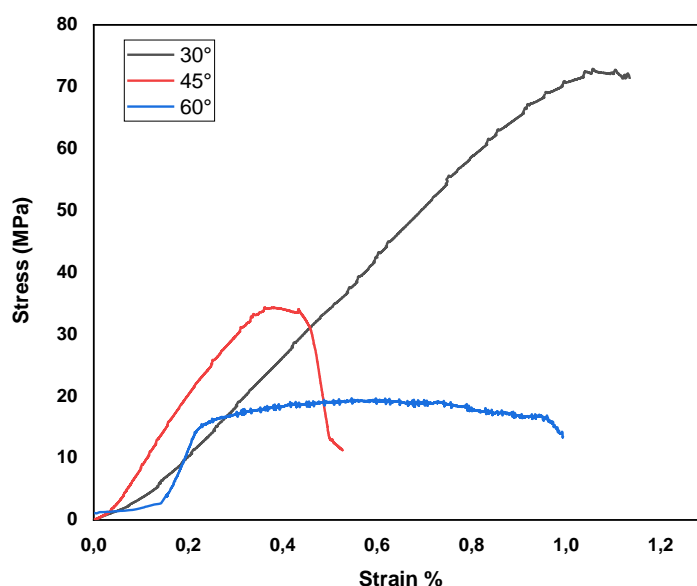

Fig.2: Experimental stress-strain curves for drying state specimens with plane surface.
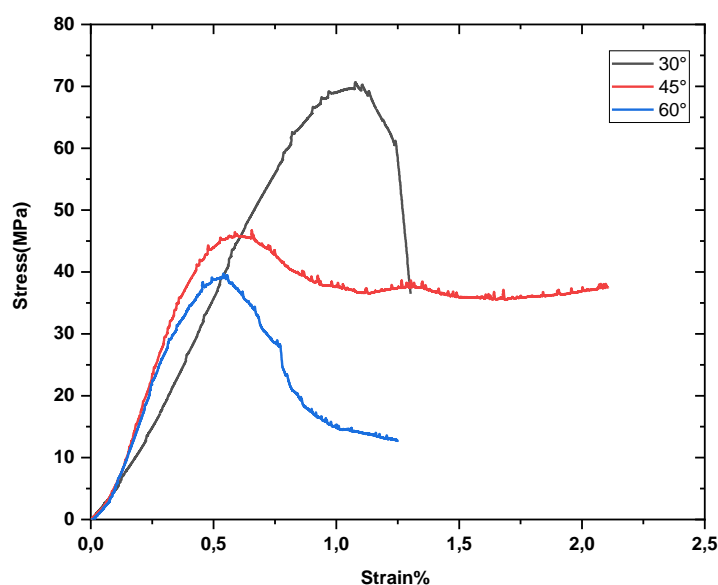

Fig.3: Experimental stress-strain curves for drying state specimens with rough surface.

3.2 Stress-strain analysis of saturated samples

The test results obtained for the samples in the saturated state are given in Figures 4 and 5, respectively. As shown in Figure 4 obtained from the test results, the samples with plane surface indicated that the sample at 60 ° produced a lower resistance 17,57 MPa compared to the sample of 45 ° with a value of 34,43 MPa and the sample at 30 ° which has a higher strength 51,69 MPa.

The same characteristics were observed for the samples with a rough surface. The sample with the 30 ° slope exhibited maximum strength with a mean stress value of 53,71 MPa, whereas the sample with the slope of 60° obtained the lowest strength with a stress value of 32,05

MPa. The samples with rough surfaces have undertaken higher deformations, generating larger stresses at failure, while brittle behavior has been observed in samples with plane surfaces under high loads.
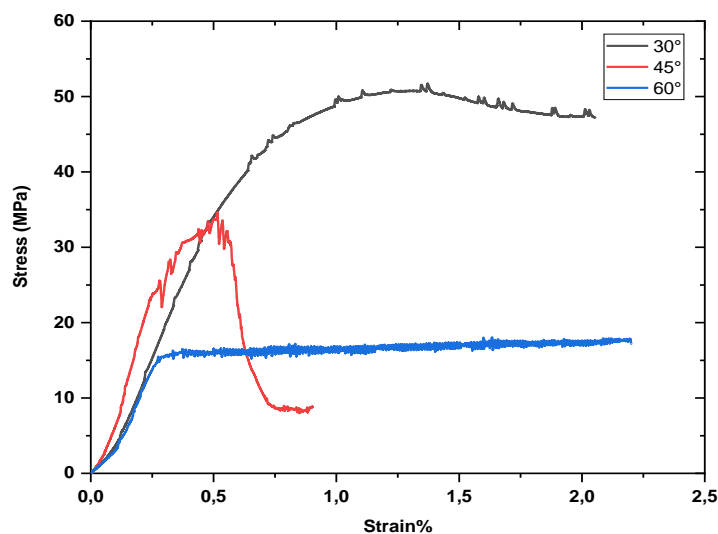

Fig.4: Experimental stress-strain curves for saturated state specimens with plane surface.
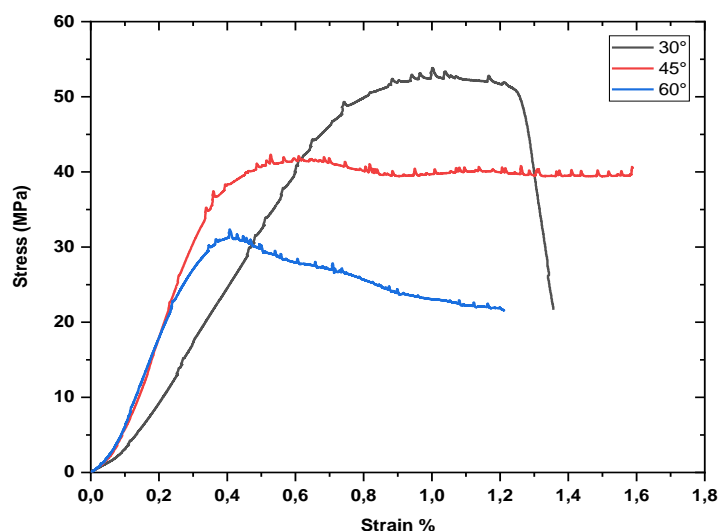

Fig.5: Experimental stress-strain curves for saturated state specimens with rough surface.

3.3 Failure patterns

The fracture mechanism behavior of the rock specimens is essentially constituted by a dynamic process, this process is constituted by different phases that are: initiation, propagation, coalesces of cracks, and finally failure.

Depending on the properties of the rock sample and the presence of grains, the grains have an influence on the propagation behavior of cracks by making the crack surface irregular on sliding and conduct the propagation of cracks lengthways of the specimen following a twisted pathway.

The sliding model estimates that under the compressive load of the model material, the shear stress at the crack surface will cause part of the rock mass on the crack to slide down, and the normal stress acting on the crack surface will consequently generate friction to prevent the upper part of the rock mass from moving down

so that it can be seen that there is friction between the two fracture surfaces.

From the relationship between friction resistance and shear force, it can be known that the effective shear stress on the crack surface is the cause of micro-cracks at the germination of the crack top. Therefore, under different fracture dip angles and different rock bridge lengths, the effective shear stress component along the fracture surface will directly affect the initiation and expansion of cracks at the crack top of the specimen.

Observations and analyzes of the images of the samples after testing were made and shown certain resemblances in the fracture pattern of the samples with diverse characteristics of pre-existing cracks. For the majority of samples, regardless of the type of surface, it was observed the appearance of new cracks which subsequently propagated throughout the sample leading to ruptures (as shown in Figure 6), unlike the samples with a higher slope, exhibited a distinct behavior under high stress.

It was observed that for all rock samples with a slope of 30 ° regardless of the shape of the plane or rough surface, the appearance of new cracks at the level of the pre-existing crack (as presented in Figure 6a). Subsequently, these cracks propagated (Figure 6b) through the entire sample causing failure (shown in Figure 6c). The analysis of the crack propagation model of rock samples with the rough surface was made with difficulty because, during the experiment, some samples (30 °) did not slide along the surface of the joint, but broke under the action of axial pressure; as a result, the joint surface was severely damaged.

Specimens with pre-existing cracks with a 45 ° slope failed in different ways. It was observed for the sample with a rough surface, the formation of new cracks which formed near the preexisting single crack, then propagated along with the sample, causing a failure shown in figure 7a. This is contrary to the samples with a plane surface presenting some special cases where new cracks did not occur at the level of the pre-existing crack or hardly at all, see figure 7b.

Concerning the samples presenting a single preexisting crack with a slope of 60 °, similarly to 45 °, the rock samples with plane surface did not show new cracks near the preexisting crack but by account, it was observed the presence of a new crack near the pre-existing crack for the rough rock sample that only developed on one of the sample halves (Figure 8). The new discontinuities developed through the samples at 30 ° and 45 ° are greater than those at 60 °, so we can conclude that the greater the slope, the less we observe new cracks.
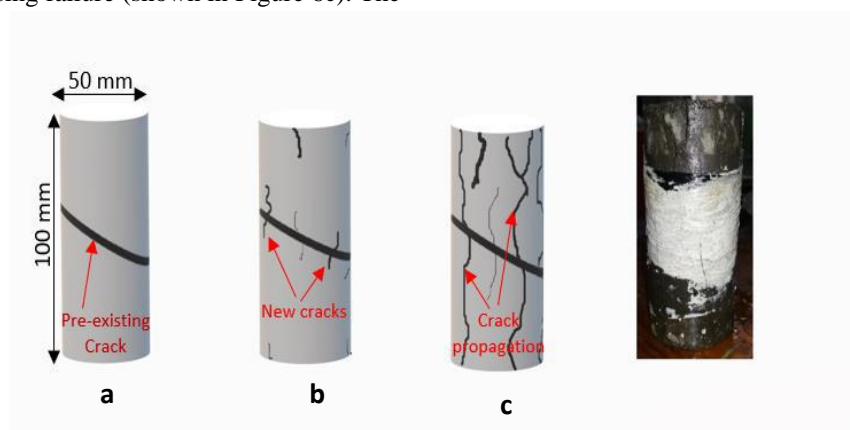

Fig.6: Initiation and propagation of cracks in the specimen with 30°

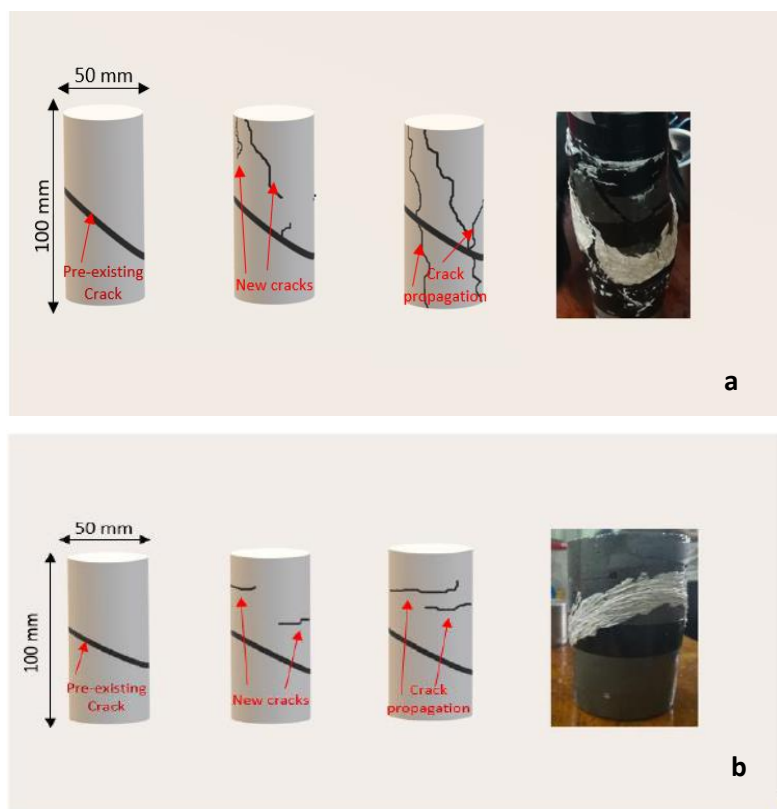*Typical failure patterns of specimen with 30°*

Fig.7: Typical failure patterns of specimen with 45°, rough surface(a)plane surface (b).
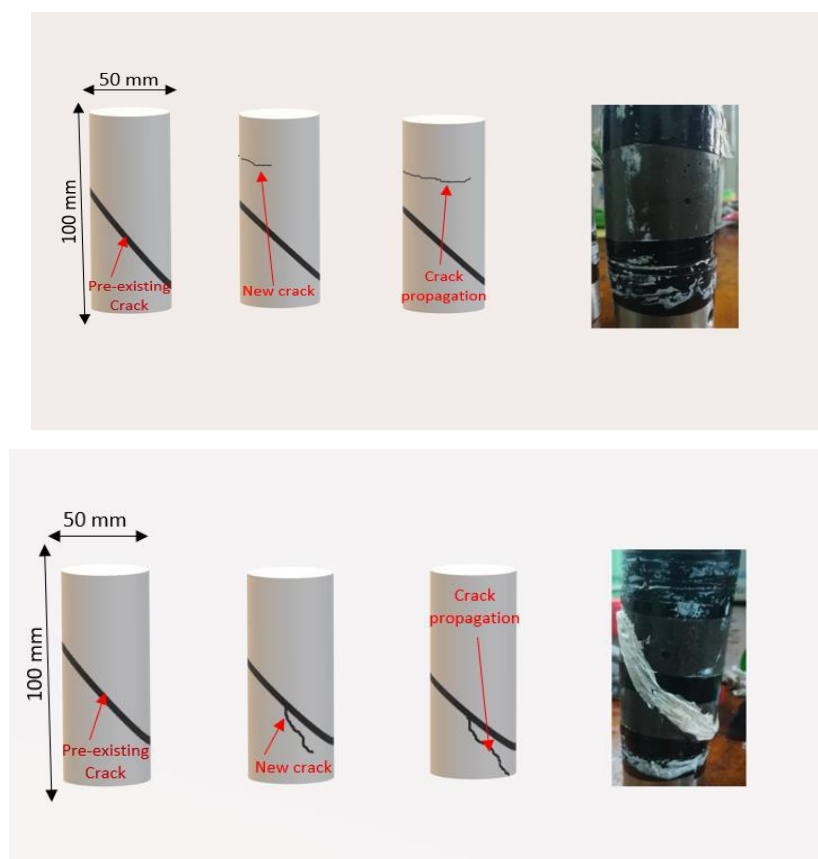

Fig.8: Typical failure patterns of specimen with 60°

3.4 Effect of water on rock behavior

To further analyze the effect of water saturation on the rock behavior, a sample batch has been drained before the test in order to saturate and reduce the infiltration time of our samples. A visualization analysis was performed on the faces of the sample containing the pre-existing crack after the test for better understanding.

By making a comparison between saturated and dry samples, there has been a difference in failure behavior. The water saturation failure of rock specimens takes into account the specimen of rock concerned and its properties, such as the topological structure, roughness of the crack surface, surface humidity, and adsorption and desorption properties, fissures of pore media and distribution of pores, wetness spreading and particulars of spreading of various stages.

The presence of the cracks and the porosity of a rock mass-produce an important role in rock mechanics, the distribution of pores and cracks of pores promote the circulation and the weakening influence of water on rock strength (the influence of water weakening). The presence of water in rock specimens in the saturated state reduces the strength of specimens, causing the specimens to be easier to damage, and the brittleness of specimens is lowered. For this reason, the rock specimens in the saturated state are easier to fail. It is important to note that except the strength of the specimen, the effect of the water affects too the failure process.

Figures 9, 10, and 11 show the failure behavior of the rock specimens in the saturated state under the compressive load. However, concerning the processes of failure of samples with a slope of 30 °, the cracks observed on the saturated rock sample are more visible than the cracks observed on the drying sample. Also, we can observe from Figure 9b that the new cracks observed at the pre-existing crack develop and penetrate in the sample, dividing almost the sample into several halves, which is not similar for the sample in the drying state Figure 9a. By following the sliding plant, the upper part of the drying state has submitted fewer new cracks but more visible compared to the lower part of the sample while the new cracks observed on both parts of the saturated state sample are almost identical. The observation is the same for the saturated rough samples where the new cracks are more visible and propagate more than those in the drying state.

For samples with a slope of 45 °, it was observed the appearance of new cracks at the pre-existing crack for saturated state samples and subsequently propagated on both halves (upper and lower parts) of the sample Figure 10b. Unlike the drying state samples that have a particular case where new cracks have been observed only on one of the halves of the sample and do not start at the pre-existing crack and are shown in Figure 10a.

Concerning the samples with a slop of 60 °, similarly to the samples with a slope of 45 °, it was observed the absence of the new cracks at the pre-existing crack for the samples in the drying state Figure 11a. While it has been noted the presence of new cracks near the pre-existing fissure and propagated just on one of the halves of the sample for saturated samples Figure 11b. The new discontinuities that appeared on the samples with a slope of 60 ° are less visible compared (by comparison) with samples with slopes of 30 ° and 45 ° slope.

By making a comparison between the saturated state specimens and those in the dry state, it can be seen that water saturation has a particular effect on the strength of rock specimens in the saturated state.
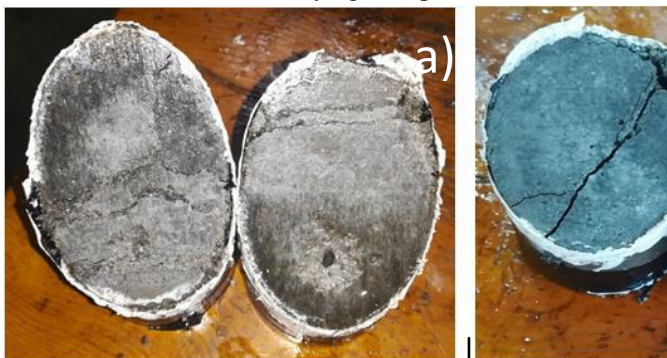

Fig. 9: Failure patterns observed in specimens with 30° a) drying state b) saturated state
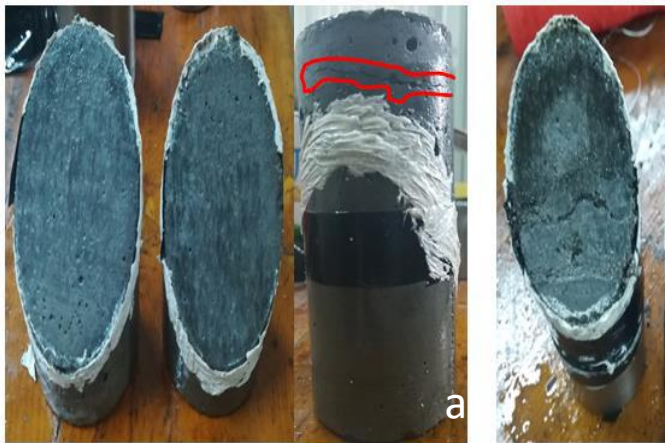
Fig.10: Failure patterns observed in specimens with 45° a) drying state b) saturated state
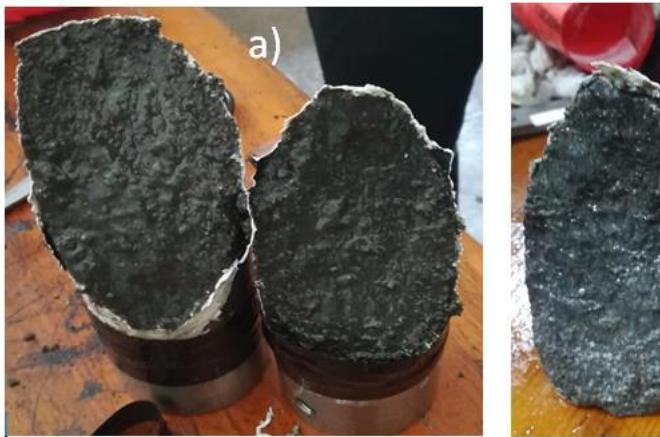

Fig.11: Failure patterns observed in specimens with 60° a) drying state b) saturated state

IV.   CONCLUSIONS

To better understand the pre-existing crack effects of rock specimens, a series of triaxial compression studies are made on specimens of rocks containing a plane surface and rough surface in the drying state and saturated state with a variation of inclination. The influence of the inclination, strength, the failure model, and the typical effect of water on the development of cracks are analyzed and discussed. The principal conclusions are as follows:

Regardless of the type of specimen, the pre-existing crack decreases the strength of the rock. The variation of the inclination angle of the fracture affects the compressive strength of the fractured rock mass and is independent of the dry or wet environment.

The maximum and minimum failure loads are obtained at an inclination of 30◦ and 60◦, respectively. Under compressive load conditions, the specimens with a slope of 30° were destroyed when the test force applied to the

sample reached its maximum due to the appearance and propagation of new cracks.

Further compressive strength of drying state specimens performed better than the saturated state.

It can be said that the damage to the sample is mainly affected by the texture of the surface of the fracture because the rough surface samples resist the load better than the flat surface samples.

The flow of water in the rock mass is one of the parameters that considerably affected the behavior, resistance, and stability of specimens. The presence of water pressure in the fractures increases, on the one hand, the active forces on the sliding of the blocks and decreases, on the other hand, the normal stresses and the resistance on the slip planes. New cracks that started at the pre-existing crack dominated the failure process.

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