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Experimental Study of the Strength of Rock Containing Tubular Discontinuities

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الملخص العربي:

تتكون الصخور الطبيعية من طبقات صخرية تحتوي على فواصل، وتعتبر الفواصل هي تغيرات في تجانس الكتلة الصخرية تكونت نتيجة حركات في الكتلة الصخرية أثناء الانشطة الجيولوجية. تتواجد الفواصل في اشكال مختلفة ومن هذه الأشكال الشكل الأنبوبي مختلفة الاقطار والأطوال والتي تتسبب في اضعاف قدرة الكتلة الصخرية علي تحمل الضغوط بدرجات متفاوتة. تمت هذه الدراسة على مكعب طول ضلعه 15سم من مونة الاسمنتية تمثل صخر ذو مقاومة متوسطة للضغط المحوري ثم اختبارها بجهاز اختبار الضغط احادي المحور بعد وضع فواصل متغيرة الأحجام والاتجاهات .تم دراسة تأثير تلك المتغيرات لحالات الفواصل على مقاومة الضغط للمكعب لتعطي تصور لمعرفة سلوك الصخر في تلك الحالات عند الحاجة لتنفيذ المنشآت الهندسية المختلفة على التربة الصخرية وداخلها.

Abstract :

When inner cavities of different dimensions exist in natural rock, problems arise due to effect of building, bridge or other structures load. The cylindrical shape of cavity is common in nature particularly in limestone at shallow depths, which is exposed to climatic variation and different environmental factors. The main objective of this study is to obtain the effect of tubular discontinuities with different sizes and positions on the rock strength. The study focuses on rock-like mass having medium strength. The unconfined compressive strength (UCS) is determined relative to several mixtures with the presence of the tubular discontinuity of different positions and sizes. The discontinuities were located in random, parallel, perpendicular and diagonal orientations with respect compression load direction.

Keywords: Uniaxial compressive strength (UCS); Rock like material; discontinuities ratio (V_t/V_c); Discontinuities

1. Introduction

Discontinuity is a general term denoting any separation in a rock mass having zero or low tensile strength. It is the collective term for most types of joints, weak bedding planes, weakness zones, and faults. Underground natural discontinuities are founded in different regions of the world including USA, China, South Africa, Yugoslavia, Vietnam (Blyth and de Freitas, 1985). A cavity is also structurally classified as a discontinuity. In this research work study is concerned with the effects of the presence of tubular discontinuities inside the rocks with different sizes, orientations and frequencies. The impact of tubular discontinuities on rock strength and capacity endurance force of pressure are studied through laboratory tests and analytical investigation.

1-Cavernous limestone – tubular joints

William (1990) noted that in sedimentary rock, free air surface develops and the dissolution of the ceiling will cease, even though the passage will continue to enlarge through dissolution of the lower walls and floor. This transition from pipe flow to open-channel flow results in a change in passage shape from that of an elliptical tube to that of a canyon to deepen, resulting in canyon passages 30 to 50 meters high and only one meter or less wide.

According to Davies and Morgan (2001) lava caves are tunnels or tubes in lava formed when the outer surface of a lava flow cools and hardens while the molten lava within continues to flow and eventually drains out through the newly formed tube. Tubular or "soda straw" grow in this way; most are fragile and have the diameter of a drop of water, but some reach a length of perhaps a yard or more. The large cone-shaped features begin as this fragile tube, and then enlarge to cones when enough water accumulates to flow along the outside of the soda straws. Raufarhóll ehf. Shareholders (2020) also noted that tubular cavities can be very large, which was confirmed by Google search U tube (2021) presenting limestone cave formations.

Photos of tubular lime stone collected from the internet (Google search) are shown in Figure (1).

Figure (1) Tubular joints in limestone

2- Rock - Like materials

Rock masses are generally composed of cavities, joints, faults, fractures, and bedding planes. The investigation of failure mechanisms by using specimens of natural rock containing cavities is complicated due to the large number of variables, including: cavity size, and shape, anisotropy of specimens, normal boundary conditions, and specimen size. Furthermore, due to the natural variability of rock materials, the failure mechanisms of rock containing cavities can be investigated in laboratory by using specimens made of Rock - Like Materials.

Several studies had used such materials to aid in the study of the different aspects of discontinuities, e.g. Bandis et al., 1981; Lam and Johnston, 1989; Fishman, 1990; Handanyan et al., 1990; Aydan et al., 1990; Pereira and Freitas, 1993; Shen et al. ,1995; Wong and Chau ,1998; Yang and Chiang, 2000; Wong et al. ,2001; Huang et al., 2002; Ko et al. ,2006; Suknev, 2008; Ghazvinian et al., 2012; Haeri et al., 2014; Tatone et al., 2014; and Zhang et al., 2016.

2. Experimental Work

2.1 Materials and specimens preparation

The rock-like material was a mix of gypsum, fine sand and Portland cement, as a binder. Conventional laboratory tests were carried out satisfying the necessary requirements. The mix was prepared in different proportions. A number of trial specimens were prepared to find out the compressive strength and density of rock-like material. Typical cubes with side length 15 cm were used in casting the specimens. All of samples were cured at a constant temperature and humidity in a chamber for 28 days. The maximum (UCS) of the tested cubes was found to be 42.71 KN/m^2. The results of the unconfined compressive strength (UCS) for randomly distributed discontinuities on 8 groups of tubular discontinuities in the rock-like mass are analyzed. The samples were tested to obtain the UCS. The discontinuity tubes were placed into the mass in a random orientation. Carrying out different tests on different groups, a significant variance was observed and no trend of the results was noticed. This is common in limestone at shallow depths which is exposed to climatic variation and different environmental factors. This necessitated that the present work included tubular discontinuities at regular patterns, which is common in nature for rock at greater depths. Tests are divided into three main groups, group A, group B and group C. The orientations of discontinuity axes were perpendicular for (Group A), parallel for (Group B) and diagonal for (Group C) with respect to direction of compression load

Several variables are concerned including discontinuity tube size (D, L), cavity depth(H), cavity location (S1, S2), and number of discontinuity tubes (N1, N2).

The failure processes are denoted for the different factors contributed to the test

2.2 Placing Discontinuities in Specimens

Before carry out the casting process and after several trials, the discontinuities were selected the as following:

2.2.1 Discontinuity shape:

The induced continuity shape was done by using ordinary straw (thin tube typically for drinking). These Discontinuities were placed vertically, or horizontally, or diagonally with reference to compression load direction.

2.2.2 Discontinuity size:

The sizes of cylindrical discontinuities were 4, 6, 8, 10 and 12 mm diameter, with heights 10, 30, 50 and 100 mm.

2.2.3 Discontinuity depth:

Discontinuities are placed at different depths inside test blocks by using stamps in regular orientations of tubular discontinuities test. The depth of cavity (H) is the same in single block, as shown in Figure (2).

2.2.4 Discontinuity location:

Discontinuities were placed at different locations inside blocks in regular orientations using stamps. Single cavity was located at centerline inside block, multiple cavities were positioned inside blocks at distances between tubes (S1) at section elevation, and distances between tubes (S2) at section side view, and horizontal spaces were equal, as shown in Figure (2).

Figure (2) Stamps for discontinuities depth and locations inside the block

2.3 Test Procedure

2.3.1 Compression Testing of Rock-like Specimens

Unconfined compressive strength testing (UCS) was performed on all prepared specimens (intact and jointed ones). Each specimen was placed between the two loading platforms in the servo-controlled uniaxial loading machine. The top and bottom boundaries were fixed in the horizontal direction. The specimens were loaded under compression till failure. Figure (3), shows the compression testing equipment during loading on a sample. The applied load at the point of failure was recorded. The load is divided by the bearing surface of the specimen which gives the uniaxial compressive strength of the specimen.

Figure (3) UCS test

2.4 Test Parameters

The discontinuity geometry was defined by four parameters. Discontinuity geometry parameters discontinuity tube size (D, L), cavity depth (H), cavity location (S1, S2), and discontinuities ratio (V_t/V_c). As shown in Figure (4) and Table (1).

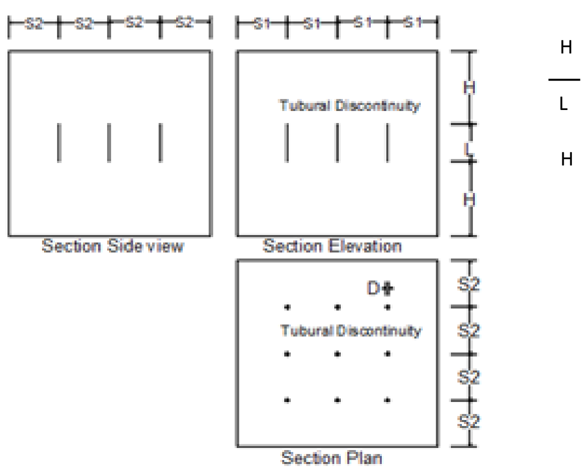

Figure 4 Geometry of joints

Table 1 Discontinuity geometry parameters

D (cm)	0.4	0.6	0.8	1	1.2	-	-	-
L (cm)	1	3	5	10	-	-	-	-
H (cm)	2.5	3	3.75	5	6	7.5	-	-
(V_t/V_c)	1/300	1/250	1/200	1/150	1/100	1/75	1/50	1/25

2.5 Random and regular orientations of tubular discontinuities

2.5.1 Random discontinuities

Each group of discontinuities (1 to 8), contains three main test conditions. The effect of isolated cavities in rock on strength of rock was studied under uniaxial compressive conditions. Several variables were investigated. These variables are discontinuity tube discontinuity tube size (D, L) and discontinuities ratio (V_t/V_c). As shown in Table (2).

Table 2 Discontinuity geometries

of specimen of random groups

Group	Vt/Vc at UCS	Diameter D (cm)	Length L (cm)
1	1/300 to 1/25	0.4	1
2	1/300 to 1/25	0.4	3
3	1/300 to 1/25	0.6	1
4	1/300 to 1/25	0.6	3
5	1/300 to 1/25	0.6	5
6	1/300 to 1/25	0.8	3
7	1/300 to 1/25	0.8	3
8	1/300 to 1/25	1	5

2.5.2 Regular discontinuities

Each group of discontinuities A, B and C, contains four main test conditions. The effect of isolated cavities in rock on strength of rock was studied under uniaxial compressive conditions. Several variables were investigated. These variables are discontinuity tube direction, discontinuity tube size (D, L), cavity depth (H) and discontinuities ratio (V_t/V_c). As shown in Table (3)

Table 3 Discontinuity geometries of specimen of regular groups

Group	A										
(V_t/V_c)	1/250	1/250	1/200	1/200	1/150	1/150	1/150	1/150	1/100	1/75	1/25
D (cm)	0.6	0.8	0.6	1	0.6	0.8	1.2	1	1	1.2	1.2
L (cm)	3	3	5	5	5	5	5	5	5	10	10
H (cm)	3	3.75	3	7.5	3	3.75	7.5	3.75	3.75	7.5	3
UCS (MN/m^2)	29.56	38.09	32.09	42.18	35.69	27.47	38.18	37.33	33.07	37.64	24.44

Group	B										
(V_t/V_c)	1/250	1/250	1/200	1/200	1/150	1/150	1/150	1/150	1/100	1/75	1/25
D (cm)	0.6	0.8	0.6	1	0.6	0.8	1.2	1	1	1.2	1.2
L (cm)	3	3	5	5	5	5	5	5	5	10	10
H (cm)	6	6	5	5	5	5	5	5	5	2.5	2.5
UCS (MN/m^2)	31.87	33.91	39.47	39.82	39.6	38.67	37.16	42.44	34.09	36.67	35.42

Group	C		
(V_t/V_c)	1/200	1/150	1/75
D (cm)	1	1.2	1.2
L (cm)	5	5	10
H (cm)	5	5	2.5
UCS (MN/m^2)	33.73	32	28.44

3. Results and Analyses

3.1 Comparisons between rock without discontinuities and rock with discontinuities for all groups for regular discontinuities and random discontinuities with respect to UCS

Tables 4, 5 and Figure 5 clarify the different between the UCS of rock without discontinuities and UCS of rock with random and regular discontinuities.

Table 4 Properties of cubes without and with discontinuities for all groups rock with random and regular discontinuities

UCS without discontinuities MN/m2	(Vt/Vc) at UCS	UCS average for random discontinuities MN/m2	Reduction of UCS for random groups %	UCS average for regular discontinuities MN/m2	Reduction of UCS for regular groups %
42.71	1/300	28	34.44	————	————
	1/250	29.36	31.26	33.36	21.89
	1/200	28.52	33.22	37.46	12.29
	1/150	28.02	34.39	36.50	14.54
	1/100	28.98	32.15	33.58	21.38
	1/75	27.54	35.52	34.25	19.81
	1/50	26.88	37.06	————	————
	1/25	22.26	47.88	29.93	29.92

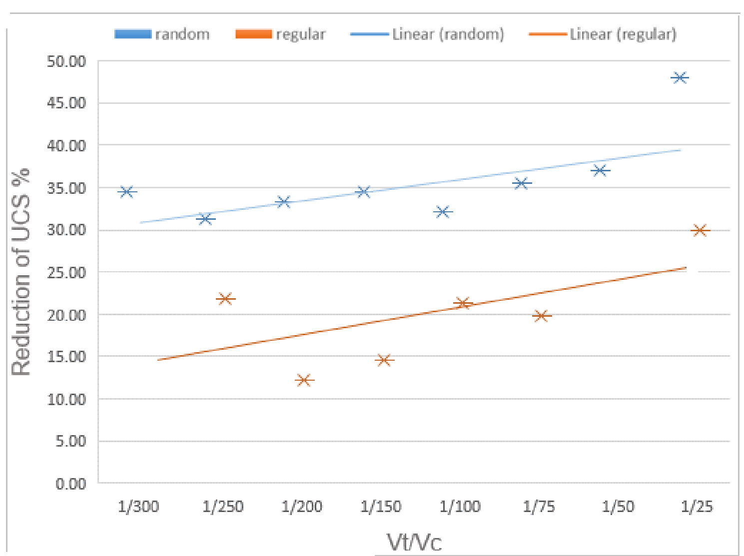

Figure 5 Relation between V_c/V_t and the reduction ratio of UCS of rock with random and regular discontinuities

From Table 4 and Figure 5 show that incase random discontinuities, whenever (V_t/V_c) inside the rock increased the reduction UCS value of rock decrease. Except two cases, (V_t/V_c) = 1/300, 1/100. In case (V_t/V_c) = 1/300, the reduction of UCS is 34.44%, it could be because there are some tubular discontinuities inside critical region that assist to weaken the rock. In case (V_t/V_c) = 1/100, the reduction of UCS is 32.15%. The reduction of UCS in case (V_t/V_c) = 1/100 is less than (V_t/V_c) = 1/150, it could be because there are some tubular discontinuities far from critical region that assist to strong the rock. In case regular discontinuities, whenever (V_t/V_c) inside the rock increased the UCS value of rock decrease. Except two cases, (V_t/V_c) = 1/250, 1/175. In case (V_t/V_c) = 1/250, the reduction of UCS is 21.89%, it could be because there are some tubular discontinuities inside critical region that assist to weaken the rock. In case (V_t/V_c) = 1/75, the reduction of UCS is 19.81%. The reduction of UCS in case (V_t/V_c) = 1/75 is less than (V_t/V_c) = 1/100, it could be because there are some tubular discontinuities far from critical region that assist to strong the rock. When comparing between the random discontinuities inside rock and its counterpart the regular discontinuities inside rock. It found the slope of reduction of UCS in case of the random discontinuities is increase by 13.5% and the slope of reduction of UCS in case of the regular discontinuities is increase by 17.5%. Its results are close. This is because the UCS depend on the mass of the rock and spacing between the discontinuities and the critical region. The reduction of USC increased when the (V_t/V_c) increased.

Table 5 Properties of cubes without and with discontinuities for group (A, B, C)

UCS without discontinuities MN/m^2	(V_t/V_c) at UCS	UCS average for group (A) MN/m^2	Reduction of UCS for group (A) %	UCS average for group (B) MN/m^2	Reduction of UCS for group (A) %	UCS average for group (C) MN/m^2	Reduction of UCS for group (A) %
42.71	1/250	33.82	20.81	32.89	22.99	————	————
	1/200	37.13	13.06	39.64	7.19	33.73	21.03
	1/150	34.67	18.82	39.47	7.59	————	————
	1/100	33.07	22.57	34.09	20.18	————	————
	1/75	37.64	11.87	36.67	14.14	32.00	25.08
	1/25	24.44	42.78	35.42	17.07	28.44	33.41

From Table 5 it is found that the UCS values of group (A) are lower than those of group (B), except in two cases, when (V_t/V_c) equal (1/250, 1/75). It is expected that the reduction of UCS increased when the (V_t/V_c) increased and discontinuities in same load direction group (B) have weakness strength, but it doesn't happen in all cases. This is because the rock mass thickness below the surface of cube is thick and can hold more shearing resistance before failure; and there is a critical region below the surface of cube and axis of cube. This agrees with Terzaghi's work (1943). It means that the critical failure mechanisms are formed through the weakest region, regardless the number of cavities and the configuration of cavities. This agrees with Kiyosumi et al (2007) and Sabouni (2013). It can be noticed that the effect of discontinuity on UCS is high in the shallow depths and decreases with increasing discontinuity depth below surface of cube.

3.2 Comparisons between rock without discontinuities and rock with discontinuities for all groups

Table 6 and Figure 6 clarify the different between the UCS of rock without discontinuities and UCS for all groups. When setting regular groups (A, B, C) together produce the same behavior of random groups (1 to 8).

Table 6 Properties of cubes without and with discontinuities for all groups

UCS without discontinuities MN/m^2	(V_t/V_c) at UCS	UCS average for all groups of discontinuities MN/m^2	Reduction of UCS for all groups %
42.71	1/300	28.00	34.44
	1/250	31.36	26.57
	1/200	32.99	22.76
	1/150	32.26	24.47
	1/100	31.28	26.76
	1/75	30.90	27.66
	1/50	26.88	37.06
	1/25	26.10	38.90

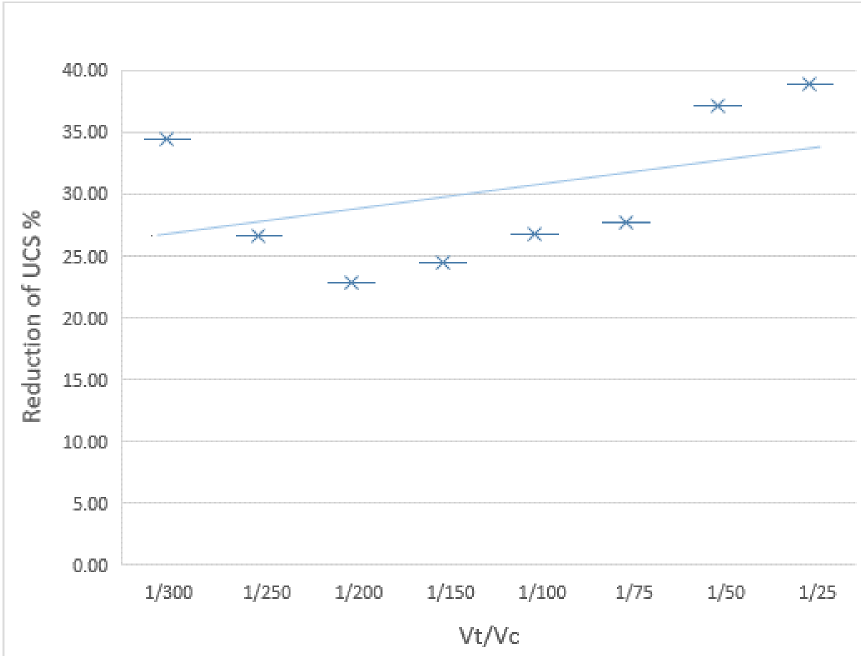

Figure 6 Relation between Vc/Vt and the reduction ratio of UCS for all groups

From Table 6 and Figure 6 The slope reduction is increase by 13.1%. whenever (V_t/V_c) inside the rock increased the reduction UCS value of rock decrease. Except two cases, (V_t/V_c) = 1/300, 1/250. In case (V_t/V_c) = 1/300, the reduction of UCS is 34.44%, it could be because there are some tubular discontinuities inside critical region that assist to weaken the rock. In case (V_t/V_c) = 1/250, the reduction of UCS is 26.57%. The reduction of UCS in case (V_t/V_c) = 1/250 is less than (V_t/V_c) = 1/300, it could be because there are some tubular discontinuities far from critical region that assist to strong the rock, but the reduction of UCS more than (V_t/V_c) = 1/250. It could be because there are some tubular discontinuities closer from critical region than (V_t/V_c) = 1/250.

4. Conclusions

1. The strength of the discontinuities rocks (intermittent systematic and random discontinuities) is significantly smaller than that of the intact rock.
2. The orthogonal experimental method is used to analyze the influence of geometric factors D, L, (V_t/V_c) on the UCS in random orientation of discontinuities in rock (groups from 1 to 8) and variables D, L, (V_t/V_c), S, H in irregular orientation of discontinuities in rock (groups A, B and C).

3. For all test results for random patters of discontinuities with respect to load direction for different discontinuity parameters, it is generally noticed that trend of results indicates

reduction of USC values with increase of (V_t/V_c). It found the slope of reduction of UCS is increase by 13.5%.

4. Presence of discontinuity may effect on both of stability of rock and its failure mechanism. There is a critical region below the foundation, when the cavity is located inside this critical region, the stability of foundation will be affected. The area of critical region depends on cavity size (D/B) and cavity depth (H).

5. The presence of multiple discontinuities in rock was affected on rock stability. The UCS decreases with decreasing of radial distance from cavities centers to cube axis, for all cavities sizes, but this effect disappears gradually with increasing the radial distance, and with increasing the depth.

6. The presence of many multiple discontinuities with parallel, perpendicular and diagonal with respect to load direction cause very small change of UCS. There is a critical region below the surface of cube and axis of cube. The critical failure mechanism is formed through the weakest region, regardless of the number of cavities and the configuration of cavities. This agrees with Kiyosumi et al. (2007) and Reem Sabouni (2013).

7. For all test results for regular patters of discontinuities parallel, perpendicular and diagonal with respect to load direction for different discontinuity parameters, it is generally noticed that trend of results indicates reduction of USC values with increase of (V_t/V_c). It found the slope of reduction of UCS is increase by 17.5%.

8. The reduction of USC increased when the (V_t/V_c) increased.

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