Strength Characteristics of Hollow Specimens from Sedimentary Rocks

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ABSTRACT

Simulation of stress distribution around underground openings leads to safe design of excavations. In many engineering projects involving rock, the failure of rock is of fundamental importance and the aim of laboratory research in rock mechanics. The work described in this paper involves a series of experiments that were performed on hollow thick-walled cylinders of three different types of rock namely: Gypsum, Limestone and Sandstone. Three hole sizes were made in the specimens of the rocks with ratio of hole diameter to specimen diameter of 0.188, 0.235 and 0.277 as well as zero (a solid one). Different loading conditions have been considered including uniaxial compression, triaxial compression as well as Brazilian and ring tests.

The results indicated that both unconfined compressive and tensile strengths decrease with the increasing hole size. A critical hole size ratio, ratio of hole diameter to specimen diameter, beyond which there is no significant reduction in strength, has been defined clearly in uniaxial loading condition of about 0.2 to 0.25, but not for tension condition. Ratio of the unconfined compressive to tensile strengths of solid specimen is more than 6.0, while it becomes less than 3.0 in case of hollow specimen.

Despite the fluctuation in shear strength parameters (c and ϕ) with the hole size, but in general, both parameters show decrease with the increasing hole size while they increase with the confining pressure. All the rocks have shown similar trends of stress-strain behavior. Finally, it can be concluded that the loading type has a pronounced effects on strength characteristics and stresses distribution around the excavation.

Keywords: Rock strength; Hollow cylinders; Underground opening; Sedimentary rocks

1. INTRODUCTION

In many geotechnical, mining and petroleum engineering problems, it is necessary to evaluate the stresses and deformations around underground structures. The stress condition encountered in field cannot be simulated by a conventional strength test such as uniaxial and triaxial tests on solid disc specimens. Hence, a hollow cylinder test system appeared as vital in analysis of such problems.

Hoskins (1969) carried out experiments on thick-walled hollow cylinders of five different types of isotropic rock. The failure of specimens tested with external pressure and axial load, started at inner surface towards the outer one. Thicker walled specimens were the strongest. Rock in hollow cylinder test failed at a tensile stress about 3.7 times greater than its tensile strength obtained from solid disc.

Hudson (1969) performed ring tests on gypsum plaster specimens with small hole sizes. The tensile strength of ring specimen increases as the diameter of the hole is decreased. A constant tensile strength was obtained when the relative hole size is greater than 20% of specimen diameter for the material used. There is a critical hole size beyond which the hole has insignificant effect on the failure load. Hudson et al. (1972) conducted Brazilian tests on disc alongwith ring tests. The failure initiated under the loading points in both Brazilian and ring tests when flat steel platen loading used, while it is initiated at boundary of the hole of ring specimen when distributed load device is employed. A small hole created in disc center affects the distribution of stresses. Different tensile strengths obtained with various ratio of hole diameter to disc diameter.

Gay (1976) simulated the underground mining by using a thick-walled cylinder of sandstone and quartzite with circular, elliptical and rectangular holes. Al-Sayed (2002) used hollow cylinders from spring well sandstone subjected to a combination of internal pressure, external pressure and axial load. Hollow cylinders appear much weaker than solid one, however, the strengths of later were higher when no internal pressure is applied. Also, the tensile strength obtained from ring test was higher than that from the Brazilian disc test. Sharan (2003) suggested a closed form solution to predict the stresses around a circular opening in brittle rock mass. Both tangential and radial stresses vary along the thickness of the hollow ring.

In the present study, the effect of hole size on the compressive and tensile strength characteristics of different types of rock has been examined experimentally. The uniaxial, triaxial, Brazilian and ring tests have been carried out on solid and hollow specimens. The results of the compressive and tensile strengths are presented for various ratios of the hole size to diameter of specimen. Variations of shear strength parameters with confining pressure and hole size are also presented.

2. MATERIALS AND METHODS OF TESTING

2.1 Rock Types

Three types of rocks found in the region of Mosul namely, gypsum, limestone and sandstone have been considered in this study. The index properties of these rocks are presented in Table 1.

The limestone is of medium grained, slightly dolomotic limestone with abundance of fossils which are considered from Miocene age.
The sandstone is located stratigraphically within the upper most part of the lower Fars formation. It was deposited in fluvial dominated delta around major lagoons of various grain sizes ranging from fine to very fine-grained.

The gypsum or hydrous calcium sulphate ($CaSO_4.2H_2O$) classified within the evaporate class which is deposit from the body of sea water.

Table 1 - Index Properties of Rocks

Rock Type	Dry density (gm/cm^3)	Absolute porosity (%)	Specific gravity
Gypsum	2.23	5.5	2.36
Limestone	2.10	18.7	2.68
Sandstone	1.93	24.9	2.62

2.2 Specimen Preparation

The preparation of rock specimens for the testing is one of the tasks in this work. Cylindrical specimens for uniaxial and triaxial compression tests have been prepared taking into account the ratio of diameter to the larger particle size of about 10:1 and not less than 54 mm (ASTM D - 4543). To satisfy the ratio of H/D equal to 2, hence, the 54.2mm diameter by 108mm height has been considered. However, disc specimen with diameter 54.2mm and thickness 23.4mm has been selected for Brazilian test.

Holes with different diameter have been performed with high precision to avoid any crack or disturbance in the specimens during the drilling process. Because of the sensitivity of sandstone to be broken, since its specimens have been warped thoroughly during the preparation.

Three sizes of openings, namely, 1.02, 1.27 and 1.50 cm have been adopted. These openings give ratios of hole diameter to the specimen diameter ($\acute{r} = D_i / D_o$) of 0.188, 0.235 and 0.277 respectively (Fig. 1).

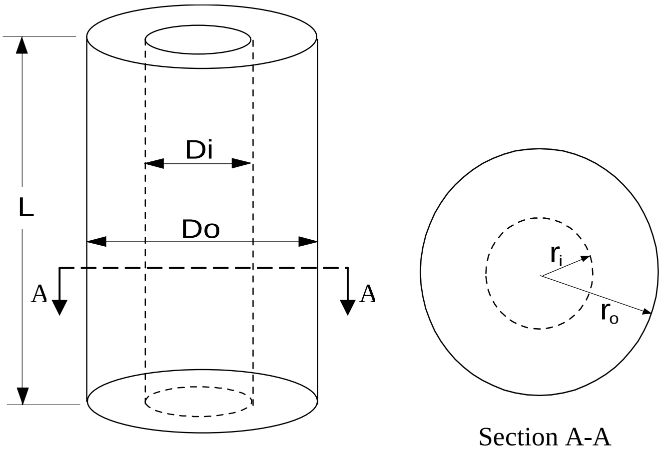


Fig. 1- Geometry of specimen

2.3 Tests Procedure

In order to examine the effect of the hole size on the compressive and tensile strengths of the rocks, many types of test have been carried out. The compression test has been performed including uniaxial and triaxial compression tests. The tensile strength has been found through Brazilian and ring tests.

2.3.1 Uniaxial compression test

The uniaxial compression test has been carried out on hollow cylindrical specimens with different hole sizes as well as solid one. The specimens of 54.2 mm in diameter and 108mm in height have been prepared for testing. The rate of test has been adapted as 0.7 MPa/sec to ensure failure within 5-10 minutes in compression machine of 150 Ton capacity, following the procedure given by ASTM (D-2938).

2.3.2 Triaxial compression test

All the tests in this category are carried out using Hoek triaxial cell developed by Hoek and Franklin (1968) at the Rock Mechanics Center, Imperial College, London and illustrated in Fig. 2. Many specimen groups have been considered including hollow cylindrical specimens of different hole sizes as well as solid cylinder. Three cylindrical specimens of 54.2mm in diameter and 108mm in height were prepared for each group. The specimens were sealed by a durable synthetic rubber sleeve with threaded end caps to sustain confinement by hydraulic oil using hydraulic machine. Axial stress, σ_1 was applied using digital hydraulic compression machine (2000 kN capacity) at a rate of 0.5mm/min to ensure the failure of specimens within 5 - 10 min (ASTM D-2664).

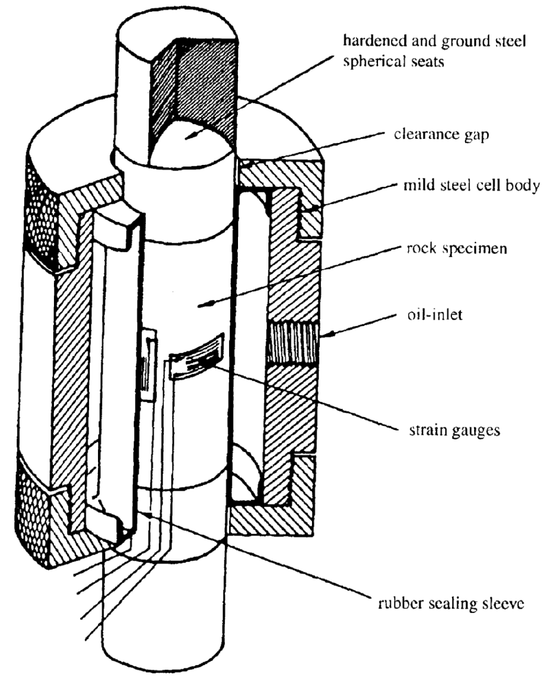


Fig. 2 – Hoek triaxial cell (Hoek and Franklin, 1968)

2.3.3 Brazilian test

The Brazilian test consists of diametrally compressed disc rock specimen loaded by diametral compression (ASTM D-3967) as illustrated in Fig. 3a. With the assumption of the uniform tensile stress generated across the loading diameter, the tensile strength was calculated by the formula:

$$\sigma_t = \frac{2P}{\pi D t} \quad (1)$$

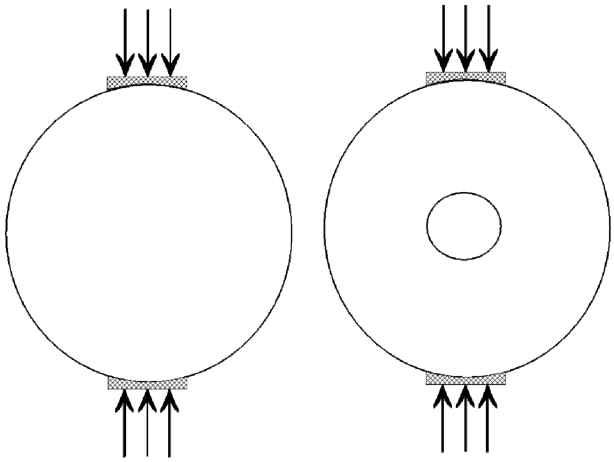
where, σ_t is the tensile strength normal to the loaded diameter, P is amount of the applied load at failure, D represents the diameter (=54.2mm) of disc and t is the thickness of disc (23.4mm).

2.3.4 Ring test

In the ring test, discs with a central hole are diametrally loaded in the same manner as in Brazilian test as shown in Fig. 3b. It has been developed to overcome the development of high shear stresses close to the loading platens in Brazilian test. The critical tensile stress at the intersection of the loading diameter with the hole is given by:

$$\sigma_t = \frac{2PK}{\pi D t} \quad (2)$$

where K is a stress concentration factor which depends on the ratio $r' = r_i/r_o$, r_i being the inside radius of the ring and r_o is the outer radius (Ripperger and Davids, 1947; Hoskins, 1966).



(a) Brazilian test (b) Ring test

Fig. 3 – Load configuration of Brazilian and ring tests

3. RESULTS AND DISCUSSIONS

3.1 Uniaxial Compressive Strength

The results of uniaxial compression tests are presented in Table 2. A reduction in the compressive strength has been noticed directly after the holes were performed in specimens. Figure 4 shows that the compressive strength decreases with the hole size upto 1.27cm hole diameter, thereafter it is increased. Maximum reductions of 31.2%, 45.5% and 37.5% have been reported for gypsum, limestone and sandstone rocks respectively. For all rock types studied herein, it appears that within the range of hole sizes considered, minimum strength has been obtained at ŕ ranging from0.2 to 0.25. Such hole size can be referred as the critical hole size in concern of compressive strength values. It is not clear why such trend occurs, but probably due to the amount of curvature of the hole surface or due to the variation in the stress concentration along the thickness of the specimen wall as hole size changes.

Table 2 - Unconfined compressive strength (N/mm^2)

Hole size ratio (D_i/D_o)	Rock Type		
	Gypsum	Limestone	Sandstone
0.0	20.28	18.40	10.10
0.188	16.14	14.18	8.81
0.235	13.94	10.02	6.31
0.277	17.15	12.06	9.16

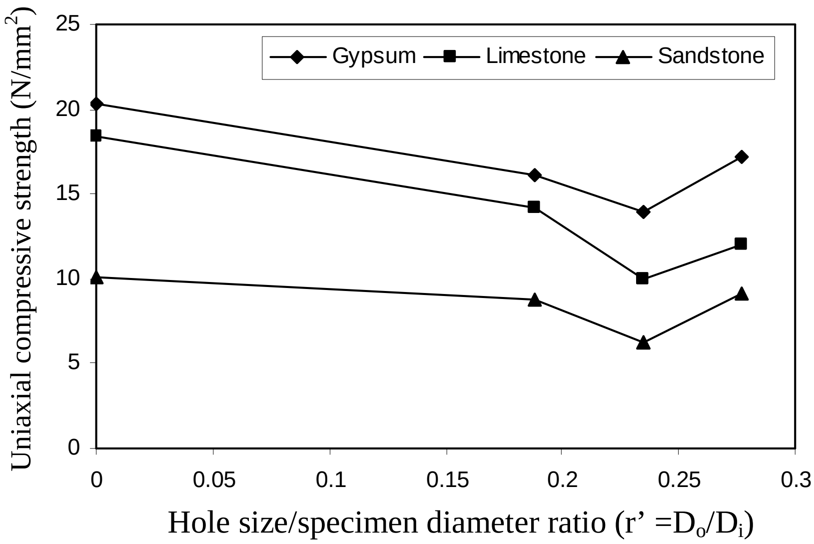


Fig. 4 – Variation of compressive strength with the hole size

For all the ratios of (r'), the sandstone exhibited a minimum compressive strength of order 6 to 10 N/mm^2 due to its high porosity and weak bonds. Maximum compressive strengths obtained in solid specimens are 20, 18 and 10 N/mm^2 for gypsum, limestone and sandstone respectively. However, higher rate of reduction has been noticed in the compressive strength of gypsum and limestone rocks compared with the sandstone rock. This may be due to the presence of weakening spots in gypsum and limestone rock specimens that increases the probability of local failure condition with the hole size while uniform stress distribution condition has been achieved in sandstone type rock.

3.2 Shear Strength Parameters

Results of triaxial compression tests have been listed in Table 3 alongwith Mohr's envelope presented in Figs. 5 to 7. In conjunction with Fig. 8, the shear strength parameters (c and ϕ) show variation with the hole size expressed as ratio of the hole diameter to specimen diameter (r'). Generally, the angle of internal friction ϕ shows a reduction beyond the hole size of 1.02cm created in the specimens as shown in Fig. 8a. Thereafter, increase in the value of ϕ has been obtained followed by reduction. The fluctuation in the value of friction angle with the hole size has been clearly seen in limestone and sandstone rocks while it is less pronounced in gypsum rock specimen. Gypsum rock shows higher values of the angle of internal friction ranging from 35.5^o to 31^o as hole size increases. This may be due to the nature of crystal structure of gypsum.

Table 3 - Shear strength parameters

Hole size ratio (D_i/D_o)	Rock type					
	Gypsum		Limestone		Sandstone	
	c (N/mm^2)	ϕ (deg.)	c (N/mm^2)	ϕ (deg.)	c (N/mm^2)	ϕ (deg.)
0.0	7.5	35.5	7.0	27.0	4.3	34.1
0.188	8.1	35.0	5.2	20.5	6.5	18.4
0.235	6.0	36.1	4.1	30.2	5.8	26.6
0.277	5.8	31.0	3.8	27.6	5.5	17.5

No clear correlation between the cohesion and the size of the holes can be predicted from Fig. 8b. However, reduction in cohesion of the rocks has been noticed with the hole size. As expected, the solid specimens of gypsum give higher values of cohesion which is more than 7.5 N/mm^2 due to the nature of the strong bonding between its grains. On the other hand, the lower values of cohesion, less than 4.35 N/mm^2, have been associated with the sandstone rock which is attributed to the weak bonds between its grains. However, this trend of cohesion deviate when holes create in the specimen. Except for the sandstone rock, the cohesion of solid specimens of the gypsum and limestone rocks show higher value than their hollow specimens. The authors believe that variation of the stress distribution along the wall thickness of the specimens caused such discrepancy in shear strength parameters.

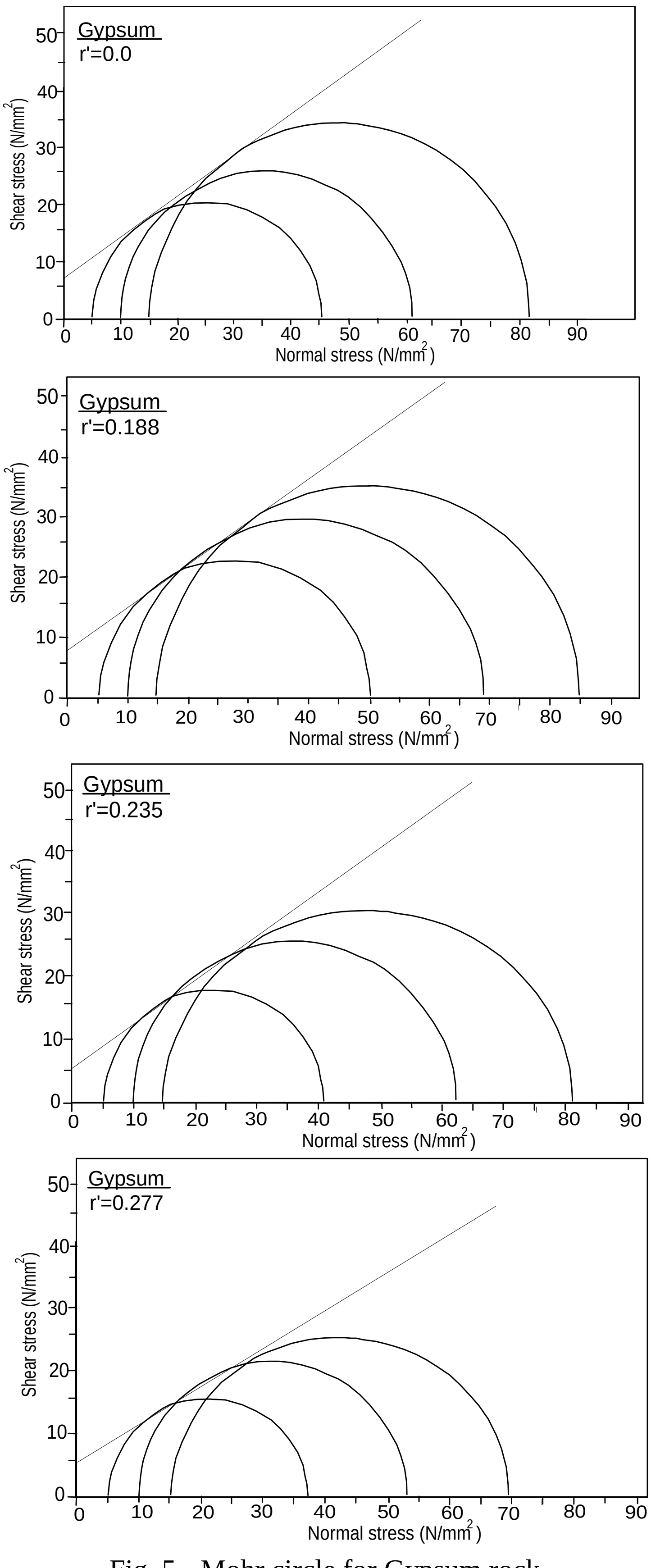


Fig. 5 - Mohr circle for Gypsum rock

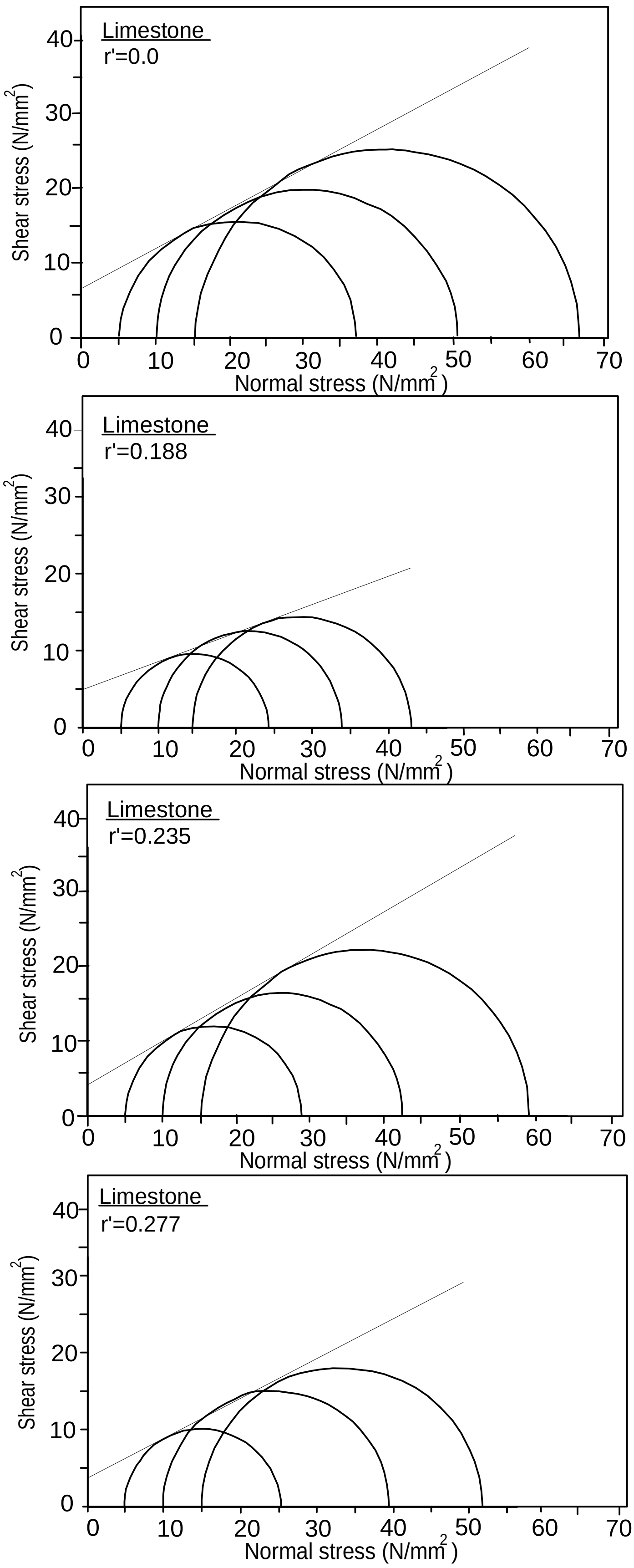


Fig. 6 - Mohr circle for limestone rock

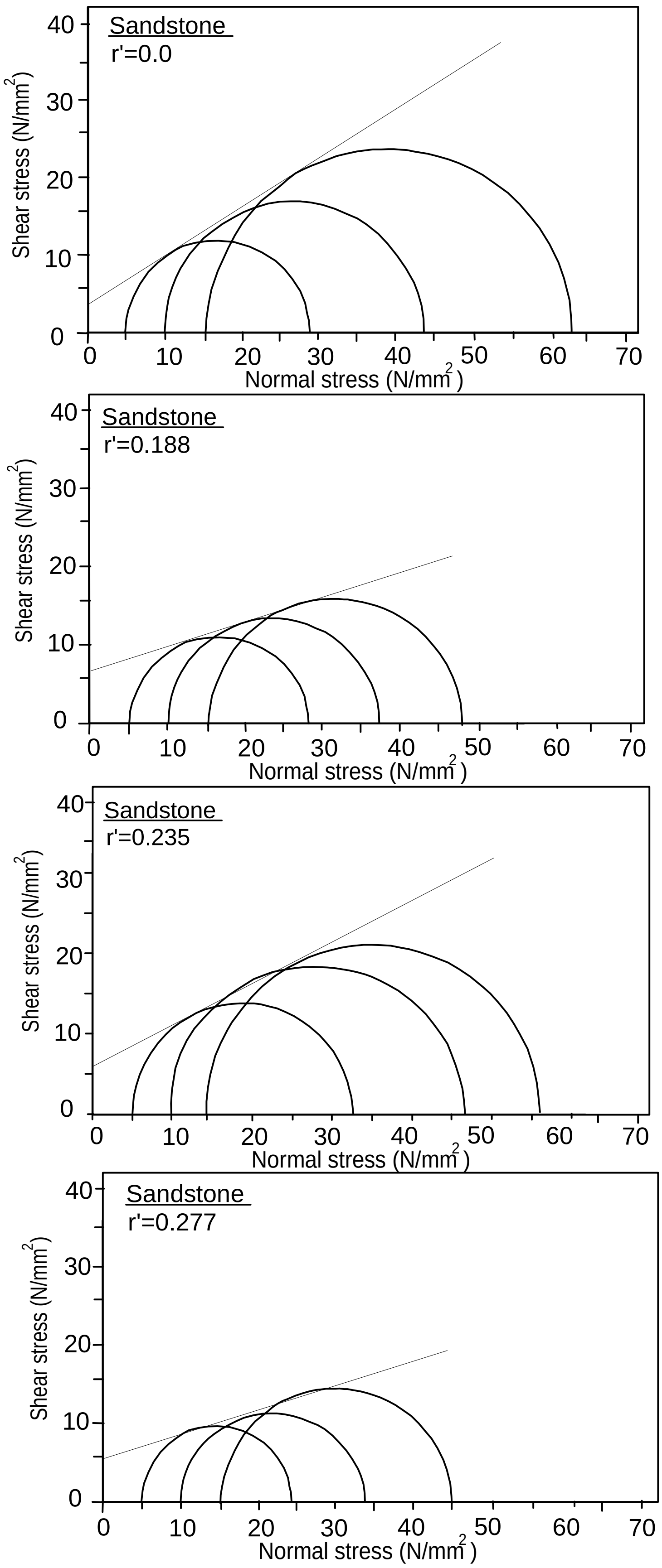
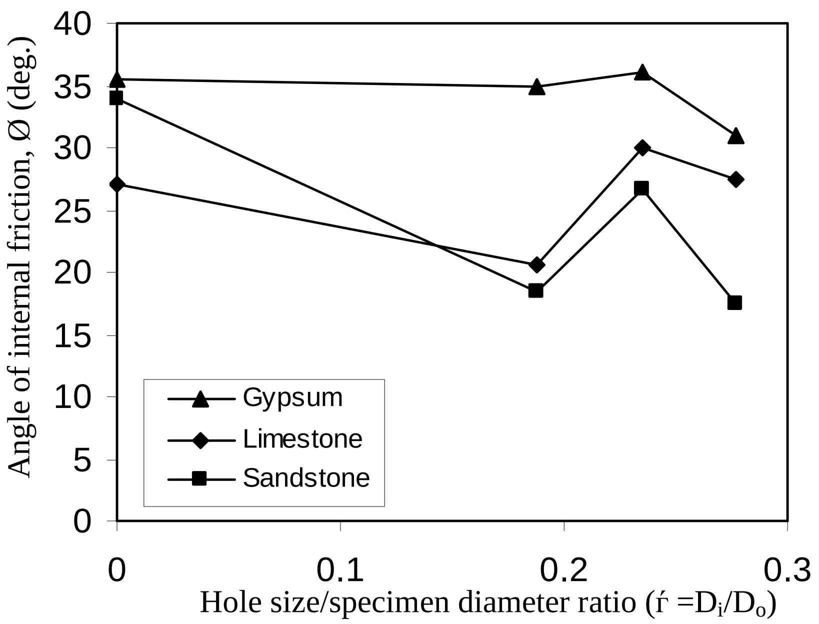
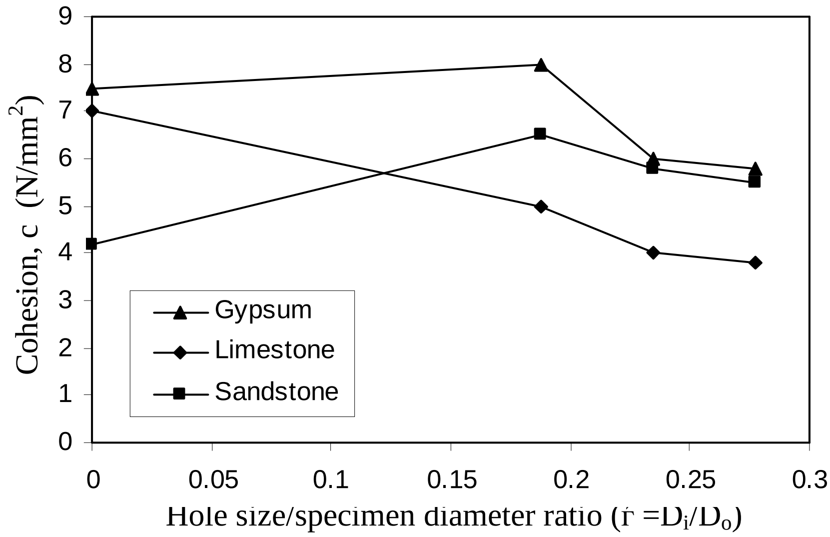


Fig. 7 - Mohr circle for sandstone rock



(a) Angle of friction, Ø (deg.)



(b) Cohesion, c (N/mm^2)

Fig. 8 - Shear strength parameters of the rocks

Figure 9 alongwith Table 4 show variation of the deviator stress at failure ($\Delta\sigma = \sigma_1 - \sigma_3$) with the hole size ratio (ŕ). One may note that the $\Delta\sigma$ in this figure, in general, reduces upon the increase of the hole size in the specimens. Similar trends have been obtained in limestone and sandstone rocks while gypsum rock deviate from that. Such variations in deviator stress may be due to interaction in major and minor factors such as micro structure of rock, presence of fissure or spots, thickness of the specimen wall, stress history of specimens and many other factors. Inspite of such variation in the results, the overall influence of the confining pressure σ_3 is sufficiently clear. As the confining pressure increased the deviator stress also increased in all rock types (Fig. 9). In addition, it is shown that the rate of deviator stress $\Delta\sigma$ increases with increasing confining pressure for solid rock specimens, while for hollow specimens the results are scattered.

Table 4 - Deviator stress at failure (N/mm^2)

Hole size ratio (D_i/D_o)	σ_3 (N/mm^2)	Rock type		
		Gypsum	Limestone	Sandstone
0.0	5	41.4	33.5	24.9
	10	51.5	41.9	33.2
	15	66.0	53.1	47.6
0.188	5	45.3	19.2	23.1
	10	59.4	23.8	26.9
	15	75.0	28.0	33.0
0.235	5	35.8	24.2	27.4
	10	53.1	32.5	36.8
	15	67.1	44.0	43.0
0.277	5	33.2	20.0	19.5
	10	42.0	29.5	24.0
	15	53.3	37.1	30.2

The amount of deviator stress at failure of the gypsum rock under all circumstances of hole sizes and confining pressures, shows higher values than those depicted from limestone and sandstone rocks. This is confirmed with the results that are obtained from unconfined compression test.

3.3 Tensile Strength of Rocks

The tensile strength or modulus of rupture of a material is defined as the value of the maximum tensile stress at failure of material. Table 5 presents the results of indirect tensile Brazilian and ring tests for the three types of rock.

The failure in solid disc specimens under Brazilian test ($r'=0$) is contributed by induced tensile stress at the center of disc. Gypsum rock shows a higher tensile strength, while the lower value has been associated with the sandstone rock. This again can be attributed to the strong bonds between crystals of gypsum and higher porosity of sandstone.

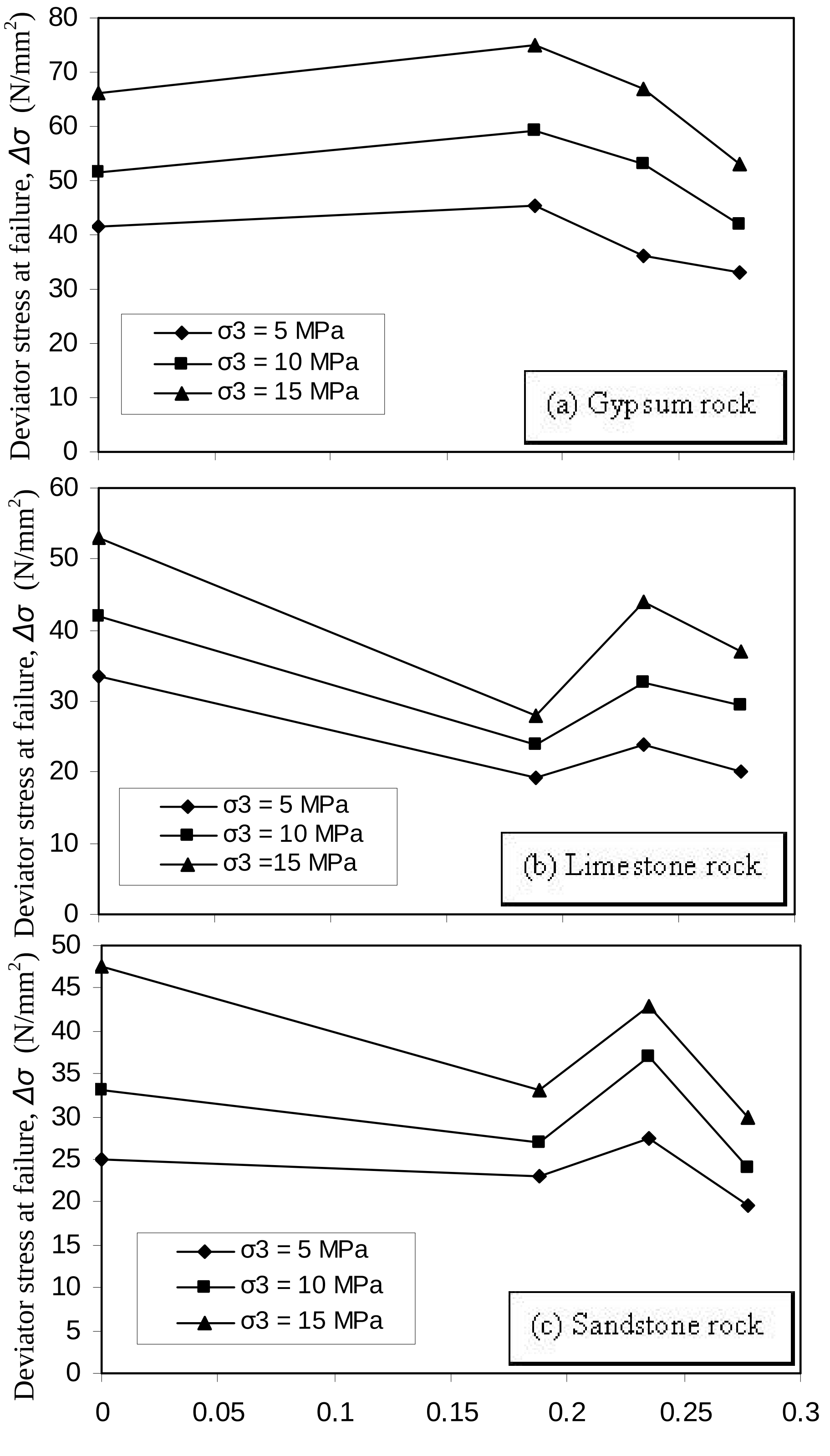


Fig. 9 - Relationship between deviator stress and hole size ratio

Table 5 - Tensile strength values (N/mm^2)

Hole size ratio (D_i/D_o)	Rock Type		
	Gypsum	Limestone	Sandstone
0.0	3.21	2.64	0.84
0.188	18.53	18.72	3.00
0.235	10.52	12.84	2.94
0.277	7.61	9.30	3.17

On the other hand, Fig. 10 shows the variation of the tensile strengths with size of the hole expressed as ratio to diameter of the specimens (ŕ). Both gypsum and limestone show decrease in their tensile strength with the hole size while the tensile strength of sandstone remains almost constant. The mechanical composition of sandstone may be a factor which reduces the effect of the hole on its tensile strength. Accordingly, the critical hole size, which refers to the size of the hole where there is no further reduction in the tensile strength, can be defined clearly in sandstone. At r'=0.2 the recorded σ_t of the sandstone rock is equal to 3.0 N/mm^2. Such phenomena does not exist in the case of gypsum and limestone within the range of hole sizes considered herein. This belongs to the homogeneity of distribution of the pores in sandstone rock. It is also evident that there is generally a considerable difference of about six times less in tensile strength of sandstone compared with the either gypsum or limestone at ŕ=0.188. This difference decreases with the increasing hole sizes. Based on the calculations of Eqs.1 and 2, hollow disc specimens from gypsum and limestone have tensile strength respectively, of about five and seven times higher than the solid one, but it reduces with the hole size ratio beyond r'=0.188 (Fig. 10). The hollow disc from sandstone rock gives three times higher tensile strength than that of the solid one.

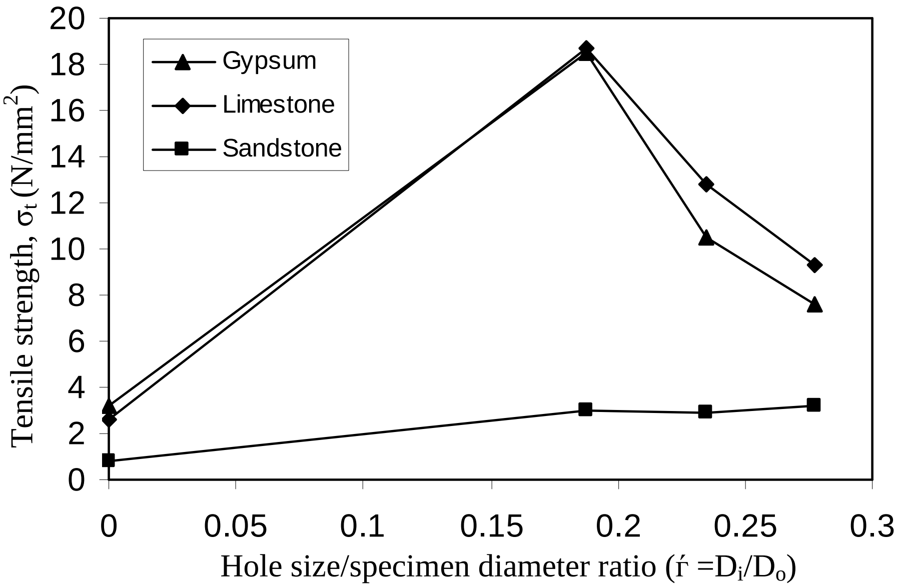


Fig. 10 - Relationship between tensile strengths and hole size ratio

In conjunction with Fig. (11), this would indicate that the hole in the disc tends to reduce the amount of tensile failure load. Such trend is obvious in gypsum and limestone but less significant in sandstone rock. Maximum reductions obtained are of the order of 75.1%, 66.7% and 61.8% for gypsum, limestone and sandstone respectively.

The mode of failure in solid disc specimen (Brazilian test) is caused by induced tensile stress at the center of disc. In the hollow specimen (ring test), the failure has been initiated at the interior of the disc and propagates towards the surface. However, the ratio (r') has a pronounced effect on the mode of failure.

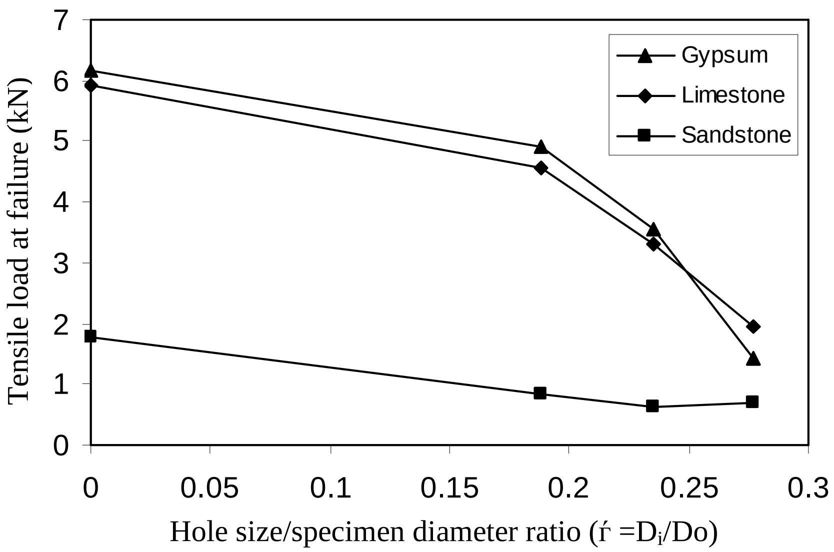


Fig. 11 - Variation of the tensile failure load with the hole size ratio

Tensile strength of rocks is considerably lower than its compressive strength. Ratios of compressive to tensile strengths (σ_c/σ_t) can be drawn from the results shown in Tables 2 and 4. For solid specimens of gypsum, limestone and sandstone the ratios are 6.3, 7.0 and 12.0 respectively. Based on calculations of hollow specimen (Eq. 2), the ratios become less than 2.0 for gypsum and limestone rocks while it is higher in case of sandstone rock.

3.4 Stress-Strain Behavior

Figure 12 shows typical selected stress-strain curves at different confining pressures of gypsum rock with 1.27cm hole size. Young's modulus E, are interpreted from such curves for the three type of rocks and listed in Table 6 as well as plotted in Fig. 13 for different hole size ratios (r'). In general, the experimental stress-strain results of all rock types appeared to exhibit about similar features (Fig. 12). There is sometimes evidence of a concave curve at the beginning which represents the closure of pores and fissures followed by a linear relationship upto yield or failure point. Specimens at failure often seem to develop separate extension and shear fractures simultaneously, particularly in gypsum and limestone rocks. Accordingly, they exhibit exceptionally brittle behavior with some ductility.

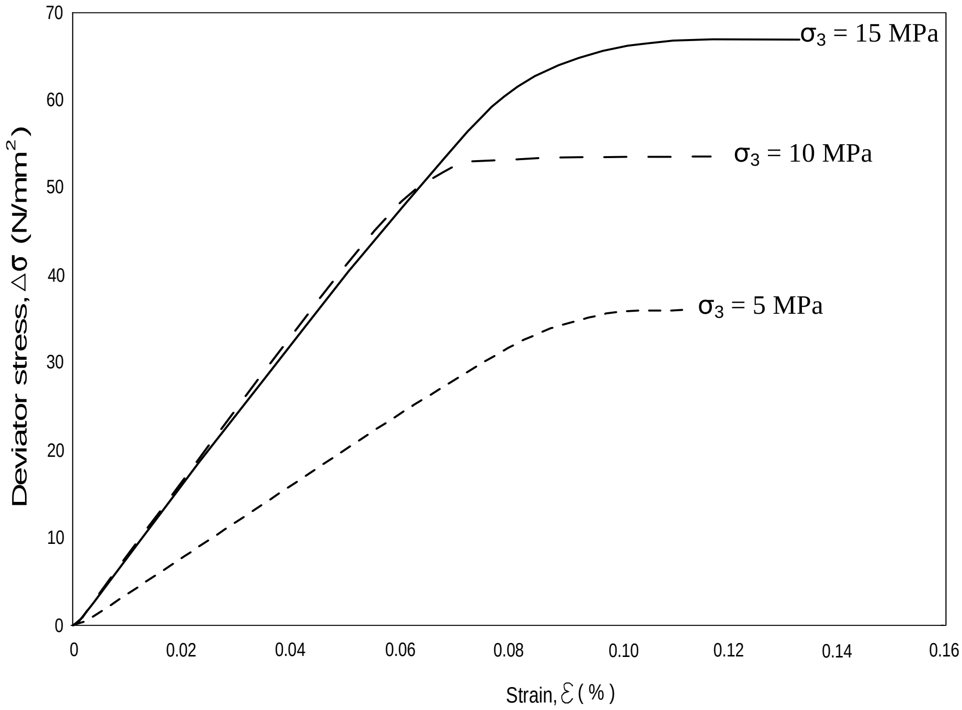


Fig. 12 – Typical stress-strain behavior of gypsum rock with hole size ratio ŕ = 0.277

Table 6 - Values of modulus of elasticity (N/mm^2)

Hole size ratio (D_i/D_o)	σ_3 (N/mm^2)	Rock type		
		Gypsum	Limestone	Sandstone
0.0	5	667	320	228
	10	750	402	510
	15	800	630	645
0.188	5	566	284	148
	10	730	334	420
	15	750	400	520
0.235	5	400	600	138
	10	820	833	200
	15	780	850	220
0.277	5	500	400	120
	10	610	550	161
	15	630	480	200

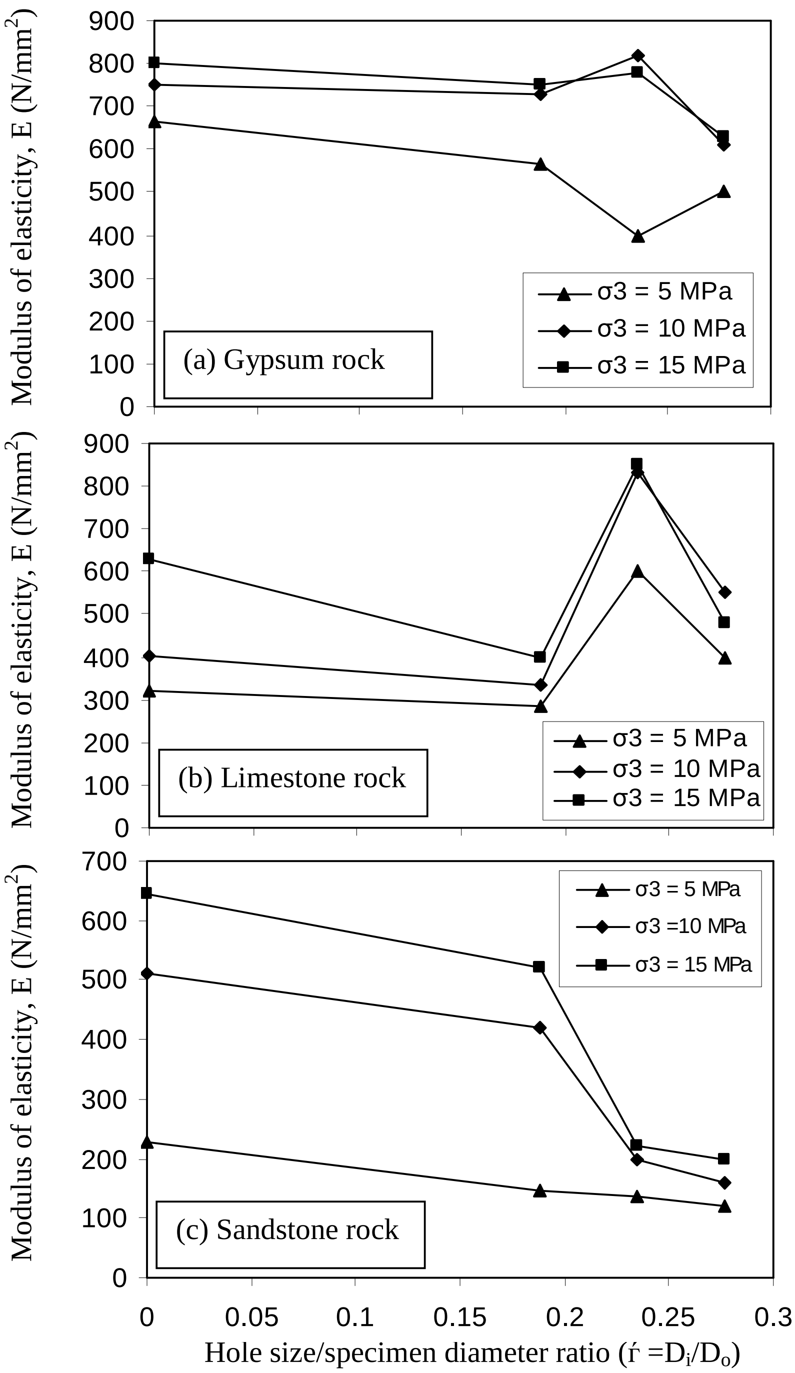


Fig. 13 - Variation of the modulus of elasticity with the hole size ratio

The Young's modulus appears to increase with the increasing confining pressure as shown in Fig. 13, but it is noted that the results are scattered for each type of rocks. However, the gypsum rock under different hole sizes and confining pressures gives greater Young's modulus.

With some exception of E-values of the limestone rock, generally, the increase in the hole sizes causes a reduction in the Young's modulus. For gypsum and sandstone rocks, the E-values at σ_3=15 N/mm^2 reduces from about 805 N/mm^2 and 645 N/mm^2 in solid state (r'=0) to 780 N/mm^2 and 220 N/mm^2 respectively at r'=0.235. Limestone, on the other hand, exhibited more reductions in E-value from solid state (r'=0) of order 630 N/mm^2 at σ_3=15 N/mm^2 to 400 N/mm^2 when r'=0.188, with about 36% reduction.

4. CONCLUSIONS

For simulation of stress distribution around underground openings, hollow cylinders of rock specimens can be adopted. Effect of variations in hole size on the strength characteristics has been examined under different types of testing conditions.

Rock exhibits a reduction in the unconfined compressive strength with the hole size. The critical ratio of the hole size to specimen diameter is of range 0.2 to 0.25. Sandstone gives lower compressive strengths than gypsum and limestone.

Shear strength parameters (c and ϕ) obtained from triaxial compression test decreases with the increasing hole size. However, both c and ϕ fluctuates with the hole sizes.

The deviator stress ($\Delta\sigma = \sigma_1 - \sigma_3$) decreases with increasing of hole size of rock specimens, while increases with the confining pressures. Under all circumstances the gypsum gives the higher values of deviator stress at failure.

The Young's modulus increases with the confining pressures, but generally, it decreases with the increasing hole sizes. All rocks exhibited about similar stress-strain feature.

The gypsum and limestone rocks exhibited a reduction in the tensile strength with increase of the hole size, while the tensile strength of sandstone show insignificant changes. A critical hole size with respect to the tensile strength of sandstone rock seems to be at r'=0.2, while it is not definite for gypsum and limestone. Tensile strength of the hollow cylinder specimens is order of six times of that solid one. The solid specimens show ratios of compressive to tensile strengths (σ_c/σ_t) more than 6.0 and it is reduced to less than 3.0 in case of hollow specimen.

Finally, it can be concluded that the certain type of testing has a pronounced effect on the stress distribution around underground openings and hence the need for safe design for such structure.

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