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Mechanical Behaviour of Rocklike Material with an Open Flaw under Triaxial Loading

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Abstract. The study of flaw effect on the strength and failure of rock mass is important to predict the unstable failure in the rock mass. A series of conventional triaxial compression tests were conducted on the rocklike specimens to study the cracking behaviour. The triaxial compressive strength was investigated by increasing the confining pressure from 25 kg/cm^2 to 75 kg/cm^2 and five angles of the flaw from 0° to 90°. The cracking pattern under triaxial compression was explored. An open flaw penetrating through the depth of the prismatic specimens of size 100 mm x 45 mm x 45 mm was prepared using a mould. Metal strips were inserted in the prefabricated groove in the mould before casting and removed after a fixed time to obtain the specimens with an open flaw. A pumping unit is used to apply confining pressure for the triaxial tests. A data acquisition system attached to the data logger was used to record the vertical load and deformation of flawed specimens. The experimental results provide an understanding of the triaxial compressive strength and failure characteristics of rocklike specimens with an open flaw. The results revealed that the strength of flawed specimens increases with the increase in the confining stress for a constant angle of inclination of the flaw. It was also found that the flawed specimens mainly failed due to the development of anti-tensile wing and secondary shear cracks in triaxial compression.

Keywords: Open flaw; confining pressure; triaxial compression; rocklike specimens; anti-tensile wing crack.

1 Introduction

Rocks are heterogeneous, discontinuous, and anisotropic, consisting of joints, faults, and flaws. One such anisotropy can be due to the presence of flaws. Flaws and microcracks are common to rock masses identified based on macroscopic and microscopic observation. Also, due to the stress concentration, unstable failure always starts from the tip of the flaw. These flaws can be 2D or 3D, depending upon the geometry of the flaw. Comprehensive studies have been carried out on the 2D flaws and their effect on the mechanical behaviour of rock and rocklike specimens, along with the crack coalescence under uniaxial ([1]; [2]) and biaxial compression[3].

Further, studies on 3D flaws have been performed using different modelling materials since it is difficult to create 3D flaws in actual rock specimens. Several numerical studies have also been carried out on rocklike specimens with pre-existing flaws to study the crack initiation, crack coalescence and crack propagation of rock and rocklike specimens under uniaxial [4], biaxial ([5]; [6]) and triaxial compression [7]. Due to the difficulty in conducting triaxial compression experiments on fissured rock, especially with open fissures, few studies have been conducted for 3D fissured rock. Triaxial compression experiments on sandstone samples with two pre-existing closed non-overlapping flaws [8], granite samples with a single flaw [9] and two coplanar flaws [10] were performed. It was found that the flaws significantly affect the mechanical behaviour and failure pattern of the rock mass. Since it is not always possible to obtain fissured samples, researchers have artificially fabricated the flaw in rocklike specimens. The researchers [11] investigated the effect of crack opening on the cracking behaviour of rocklike specimens under uniaxial compression. Most flaw openings in the previously mentioned studies have an aperture up to 1 mm, which can be considered a small crack compared to its specimen size.

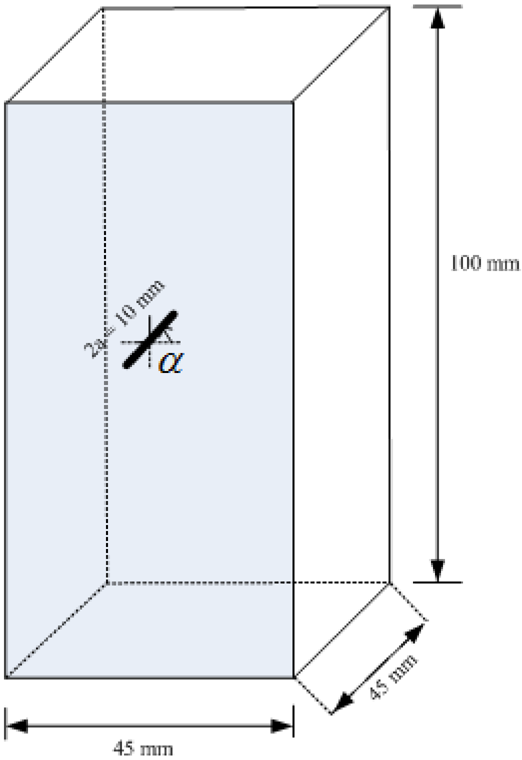
In summary, limited experimental studies are performed on flawed rock or rocklike specimens in triaxial compression. This experimental study aims to investigate the effect of the angle of inclination and confining pressure on the strength and crack propagation of rocklike specimens with a single open flaw in triaxial compression. The open flaw is fully penetrating through the depth of the rocklike specimens. Also, failure characteristics of the rocklike specimens under triaxial compression were studied on the macroscopic scale.

2 Experimental study

The rocklike specimens were tested under conventional triaxial compression as per Indian Standards [12] to investigate the effect of the angle of inclination of an open flaw on the strength and the failure characteristics. Cuboidal specimens with dimensions of 100 mm x 45 mm x 45 mm were prepared (see Fig. 1), and they contained an open pre-existing flaw of 1 mm aperture penetrating fully through the depth of the specimen. All the rocklike specimens had pre-existing flaws with the same flaw length of 10 mm but with different inclination angles, such as 0°, 30°, 45°, 60°, and 90°. The term ‘flaw’ refers to the artificially generated crack, whereas the ‘crack’ is a newly generated crack due to the application of external loads to the rock or rocklike specimens.

2.1 Preparation of rocklike specimens

It is difficult to fabricate the flaw in actual rock specimens, due to which laboratory model rocks consisting of gypsum, resin, glass, and cement mortar have been used to study the crack initiation, crack coalescence, and macro-failure of rock masses. Every material has its limitation in simulating the behaviour of actual rock masses. For example, gypsum can simulate the frictional characteristic but lacks enough bond



(a)

(b)

Fig. 1. (a) Geometry of the specimen (b) Prepared rock like specimens

strength and undergoes high deformation, whereas glass and resin have a weak friction effect. Hence, cement mortar ([13];[14]) has been used to model the rocklike material, which has good frictional properties and sufficient bond strength. The mass ratio of the cement mortar varies, as reported in the literature. The rocklike specimens are prepared by using sand, cement, and water in the mass ratio of 1: 0.80: 0.4. The laboratory tests, including uniaxial and triaxial tests, are conducted on cylindrical specimens of diameter 54 mm and length 108 mm to obtain the mechanical properties for this rocklike material as shown in Table 1. The mechanical properties of the rock-like material are found to be consistent with the actual rock, mainly sandstone, as mentioned in the literature.

The specimens with an open flaw are prepared by casting method using a mould with a groove cut at the preferred orientation and metal strips placed inside the prefabricated groove. The geometric parameter includes the length (2a) of the open flaw, which is 10 mm, the aperture (width) of the open flaw, 1mm and varying angles of inclination (0°,30°,45°,60° & 90°). An open flaw can be made by pre-inserting a thin metal sheet inside the prefabricated groove in the mould and pulling the sheet outwards after the initial solidification of the specimen. The sample is kept for 28 days in the curing chamber, and the testing is done after drying.

Table 1. Mechanical properties of rocklike specimens

Properties	Value
Density (kg/m^3)	2210
UCS (MPa)	42.6
Elastic modulus (GPa)	3.85
Φ (degrees)	36.54
c (MPa)	8.34

2.2 Testing Apparatus

Triaxial tests were conducted in a rock triaxial testing machine (maximum capacity of 70 MPa). As shown in Fig. 2a, this machine consists of a loading unit, pumping unit, and data acquisition system (data logger as in Fig. 2b). The loading unit consists of a loading frame made of steel (see Fig. 2a). The base carries a fine-finished hydraulic ram and a lower platen. During the test, the load and deformation of the rocklike specimens were recorded concurrently at an interval of 3s.

The actual rock condition for the rock masses can vary depending on the state of stress surrounding the rock masses. This laboratory study has been performed assuming the typical state of stress to be in the triaxial condition in the field. However, no such field investigation is done to obtain the actual state of stress for the rock. The typical confining pressures selected for this study are based on the assumption that the range of confining pressure should be such that it should not exceed 50 per cent of the uniaxial axial compressive strength of flawed specimens. However, various confining pressures have been applied to the flawed specimens. However, only three different confining pressures (25 kg/cm^2, 50 kg/cm^2, 75 kg/cm^2) to the tested rock specimens have been reported here.

The pumping unit (see Fig. 2a) is a multi-plunger pump submersed in the tank and is powered by a 1.5 kW electric motor. This unit is used to apply pressure for triaxial strength tests. The power pack gives a non-pulsating flow to the hydraulic ram. A data acquisition system is attached to the machine to record the load (see Fig. 2b). Prismatic-shaped loading platens were put on top and bottom of the specimen. Teflon sheets between the specimen and prismatic platen were used to minimize end friction. The strain rate was adjusted to 0.1 mm/min such that the failure occurred within about 25 to 30 mins from starting of the experiment.

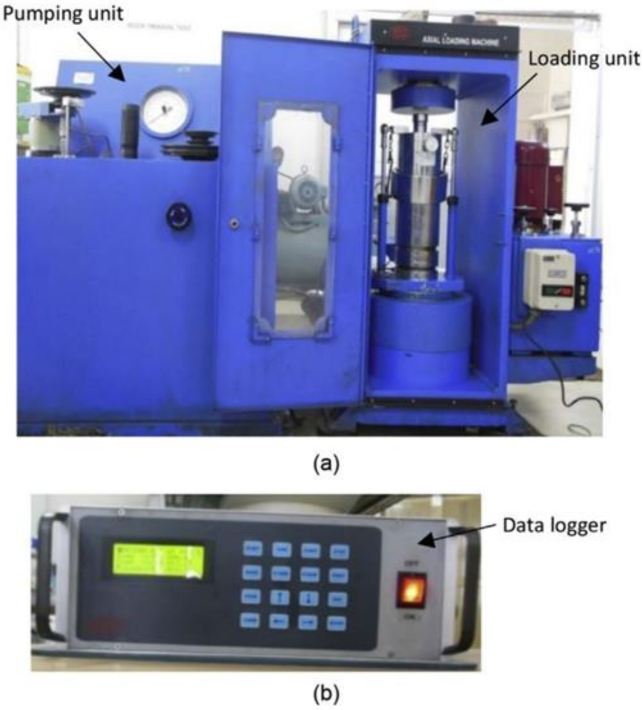


Fig. 2. (a) Triaxial testing equipment used in the experimental study (b) Data logger for recording load and deformation

3 Results and Discussion

3.1 Stress strain behavior of open flawed rocklike specimens under triaxial compression

Specimens are numbered by the Group name-angle of inclination of flaw (α°)-serial number for that angle of inclination of flaw. ‘A-90-7’ indicates that it is the seventh specimen having an angle of inclination of flaw (α= 90°), which belongs to Group-A. For the specimens with a flaw angle of 60° and 90° (see Fig. 3 and Fig. 4), the stress-strain behaviour was different and had higher peak strength than those with relatively lower flaw angles. The strengths of flawed rocklike specimens under triaxial compression depended on the orientation of the flaw. It can be seen from (see Fig. 3 and Fig. 4) with the increase in flaw angle from 45° to 90°, the triaxial compressive strength increased.

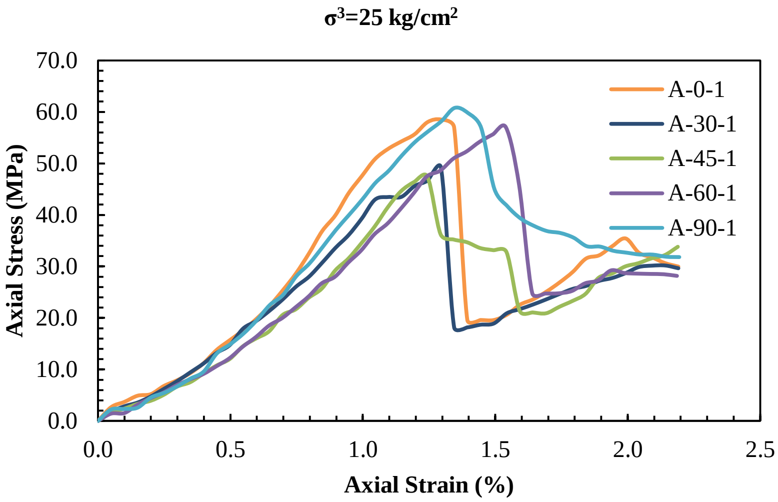


Fig. 3. Stress–strain curves of flawed rocklike specimens with different angle of inclination of flaw (α°) under triaxial compression (σ_3= 25 kg/cm^2)

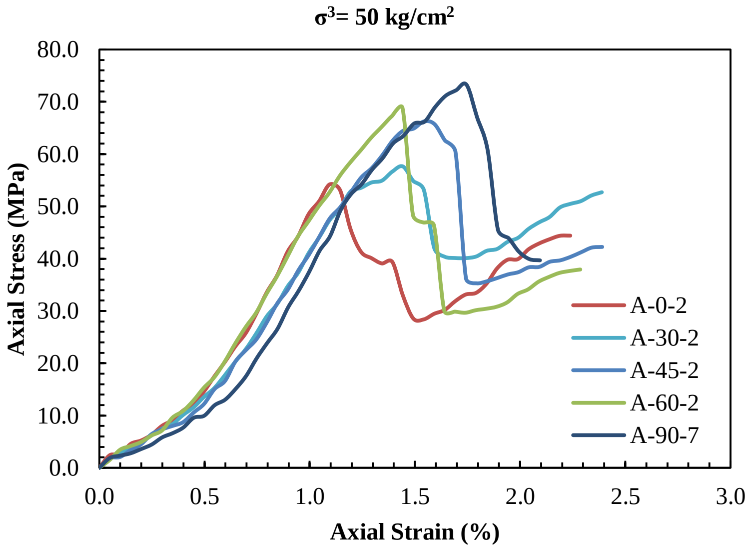


Fig. 4. Stress–strain curves of flawed rocklike specimens with different angle of inclination of flaw (α°) under triaxial compression (σ_3= 50 kg/cm^2)

3.2 Influence of confining pressure on triaxial strength of open flawed rocklike specimens

For the flawed rocklike specimens of a particular flaw angle as shown in (see Fig. 5) the compressive strength increases linearly with the increase in the confining pressure under triaxial state of stress.

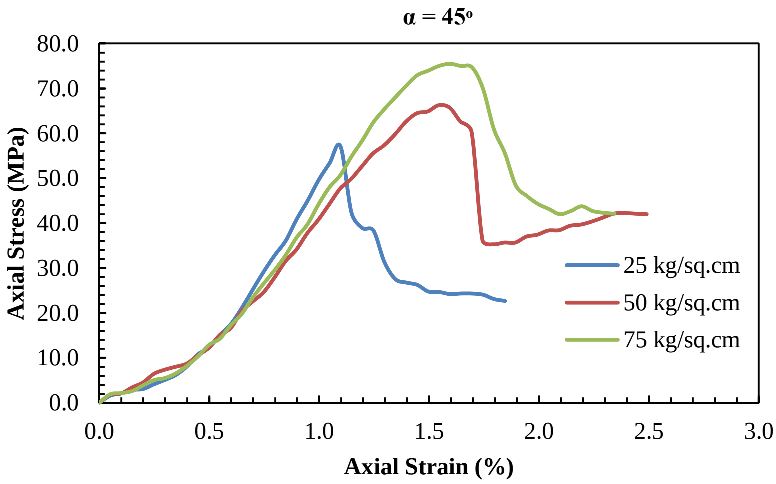


Fig. 5. Stress–strain curves of flawed rocklike specimens with different angle of inclination of flaw (α= 45°) at different confining pressure under triaxial compression.

3.3 Failure of open flawed rocklike specimens under triaxial compression

The cracking pattern for single flawed rocklike specimens under triaxial compression is presented in Fig. 6. Most commonly, the flawed specimens failed due to anti-tensile wing cracks. For flaw angles 30° and 45°, the cracking pattern was similar regardless of the confining pressure.

4 Conclusions

The strength and failure processes of a rocklike material containing a single penetrating flaw are investigated under triaxial compression. The cracking pattern and strength of the flawed specimens are researched by experimentation. From this current study, the following conclusions can be drawn:

- The stress-strain curve of flawed specimens shows an abrupt change of slope under various confining pressures. However, the axial strain at failure usually increases with increasing confining pressure for the same angle of flaw inclination.
- The peak axial strength and axial failure strain increase with the increase in confining pressure. Also, peak axial strength and axial failure strain for flaw inclinations of 60° and 90° specimens are higher than other flaw inclinations for a given confining pressure.

- Two main types of shear and tensile cracks are observed in specimens containing a pre-existing flaw opening of 1mm. The failure of these flawed specimens is mainly caused by the propagation of secondary shear cracks initiated after anti-tensile wing cracks.

(a). α =0°, σ_3 = 75 kg/cm^2

(b). α = 30°, σ_3= 50 kg/cm^2

(c). α =45°, σ_3= 75 kg/cm^2

(d). α =60°, σ_3= 75 kg/cm^2

(e). α =90°, σ_3= 50 kg/cm^2

Fig. 6. Typical failure of open flawed rocklike specimens under triaxial compression

References

1. Wong, L.N.Y., Einstein, H.H.: Systematic evaluation of cracking behavior in specimens containing single flaws under uniaxial compression. International Journal of Rock Mechanics & Mining Sciences 46, 239-249 (2009).

2. Lee, H., Jeon, S.: An experimental and numerical study of fracture coalescence in pre-cracked specimens under uniaxial compression. International Journal of Solids and Structures 48, 979-999 (2011).
3. Bobet, A., Einstein, H. H.: Fracture coalescence in rock-type materials under uniaxial and biaxial compression. International Journal of Rock Mechanics and Mining Sciences35(7), 863-888 (1998).
4. Li, H., Wong, L. N. Y.: Influence of flaw inclination angle and loading condition on crack initiation and propagation. International Journal of Solids and Structures49(18), 2482-2499 (2012).
5. Manouchehrian, A., Marji, M. F.: Numerical analysis of confinement effect on crack propagation mechanism from a flaw in a pre-cracked rock under compression. Acta MechanicaSinica 28(5), 1389–1397 (2012).
6. Bi, J., Zhou, X.P., Qian, Q.H.: The 3D numerical simulation for the propagation process of multiple pre-existing flaws in rock-like materials subjected to biaxial compressive loads. Rock Mechanics and Rock Engineering 49, 1611-1627 (2016).
7. Huang, Y., Yang, S., Zhao, J.: Three-dimensional numerical simulation on triaxial failure mechanical behavior of rock-like specimen containing two unparallel fissures. Rock Mechanics and Rock Engineering 49, 4711-4729 (2016).
8. Huang, D., Gu, D., Yang, C., Huang, R., Fu, G.: Investigation on mechanical behaviors of sandstone with two preexisting flaws under triaxial compression. Rock Mechanics and Rock Engineering 49, 375-399 (2016).
9. Yang, S.Q., Huang, Y.H.: An experimental study on deformation and failure mechanical behavior of granite containing a single fissure under different confining pressures. Environ Earth Sci 76, 364 (2017).
10. Huang, Y., Yang, S.: Mechanical and cracking behavior of granite containing two coplanar flaws under conventional triaxial compression. International Journal of Damage Mechanics 28(4), 590-610 (2019).
11. Cheng, H., Zhou, X., Zhu, J., Qian, Q.: The effects of crack openings on crack initiation, propagation and coalescence behavior in rock-like materials under uniaxial compression. Rock Mechanics and Rock Engineering 49, 3481-3494 (2016).
12. IS 13047: Method for determination of strength of rock materials in triaxial compression, Bureau of Indian Standards, New Delhi (1991).
13. Cao, P., Liu, T., Pu, C., & Lin, H.: Crack propagation and coalescence of brittle rock-like specimens with pre-existing cracks in compression. Engineering geology 187, 113-121(2015).
14. Zhao, Y., Zhang, L., Wang, W., Pu, C., Wan, W., & Tang, J.: Cracking and stress–strain behavior of rock-like material containing two flaws under uniaxial compression. Rock Mechanics and Rock Engineering49(7), 2665-2687(2016).