

Scale Effect on Mode of Failure and Strength of Offset Rock Joints

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Abstract. As a sustainable construction material, the use of rock has increased significantly. In this experimental study, the scale effect on failure mechanisms and compressive strength of rock blocks was investigated. Samples of rock with non-persistent offset joints were subjected to uniaxial loading. The angle of orientation of the rock bridge with respect to the applied axial load and the size of the block were studied. Two different block sizes, having dimensions of (63.5 x 28 x 20.3) cm and (30.5 x 15.24 x 10) cm, were tested. The joint inclination angle was maintained at 22.5° in both cases. Also, degree of persistence was kept constant at 0.3 for all tested blocks. However, the offset angle which connects the inner tips of the joints was changed from 30°-90° with an increment of 15°. The results showed a reduction in strength with increasing the size of the sample. This reduction is becoming more significant as the bridge inclination angle increases. This behavior is due to the fact that as the bridge inclination angle increases the mode of failure shifted from shear to tension mode which is more dependent on the size of sample due to the presence of more micro flaws. No effect of block size was noticed on mode of failure for the tested blocks.

1 Introduction

The use of rock in the built-environment has increased significantly as rocks emerge as sustainable construction material. This trend requires engineers to carefully examine the behaviour of rock under loading. Specifically, factors affecting the strength of rock and contributing to failure need to be evaluated and quantified for design/application purposes. The scale effect on strength of rock mass with persistent rock joints has been studied previously by many researchers [1, 2] and they indicated the existent of size effect on the strength of rock mass

The exact behavior of non-persistent rock joints at failure under uniaxial or biaxial loading condition is not well understood due to the interaction between the intact rock segments and the joint segments. The interaction between the intact rock and the joints depends on many parameters such as the geometry of the joint and bridge segments, the slope of the joint segment, the stiffness of the rock among others [3-10].

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Generally, the process of failure begins with the initiation of cracks perpendicular to the joint segment which then becomes parallel to the principal loading axis. These cracks are called wing cracks. Wing cracks are followed by another type of cracks called secondary cracks that initiate from the inner joint segment tips and propagate toward each other and meet across the intact rock segment causing the coalescence of the joint segments leading eventually to failure of the rock. Propagation and coalescence of the secondary cracks are very quick compared to that of the wing cracks.

This current work is a continuation to the previous work that has been done by the first author and his co-workers. Mughieda and Alzoubi [11] have studied the mode of failure of offset non-persistent rock joints while the joint inclination angle was kept at 45° in all blocks tested and Mughieda and Khawaldeh [12, 13] have studied the scale effect on fracture mechanisms and strength of blocks with non offset (planar) rock joints with bridge inclination angles of 67.5° and 45 . It is the first time to investigate the behaviour of offset non-persistent rock joints with joint inclination angle of 22.5° .

2 Specimen preparation and testing

2.1 Specimen preparation

In this study the model material used was made of mixing silica sand, ordinary Portland cement type I and water in 72%, 16%, and 12% proportion by weight respectively. In order to obtain grain to grain contact that cause low tensile strength and high friction angle, high sand content and low cement content were used.

The friction angle of the model material determined from direct shear tests was 33° . The ratio of unconfined compressive strength to the tensile strength for material was 12 and the ratio of secant modulus to the unconfined compressive strength was 1100.

The procedure developed by Jamil [4] for preparing open non-persistent joints was used in this research with some modification. The sample preparation mold and set-up is shown in Fig. 1. Each sample was cured for 28 days prior to testing. It is important to note that wooden boards were placed on all sides of the sample and secured during handling of the samples to avoid splitting of the jointed sample. A typical sample dimensions are shown in Fig. 2.

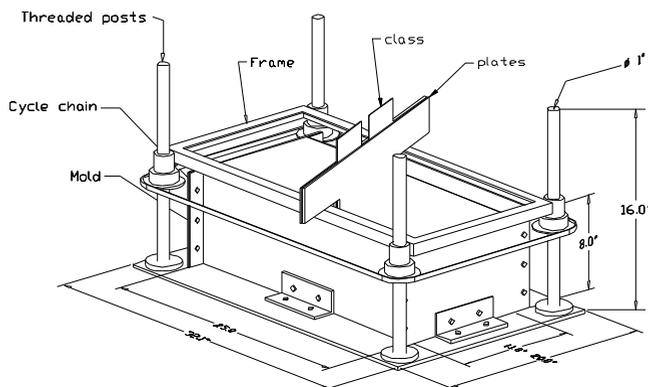


Fig. 1. Sample preparation mold and set-up for making open joints

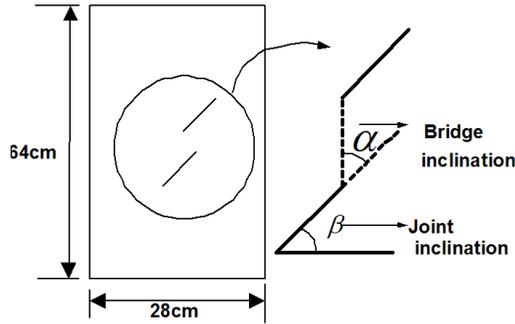


Fig. 2. Geometry of the specimens and pre-existing cracks

2.2 Test machine, instrumentation and recording

The tests were performed using a 2000kN universal compression machine. The load applied on the sample was measured by load cells installed on the testing machine. The total deformation and the displacements in the vicinity of the joint, were measured by Linear Variable Differential Transducers (LVDT) with a maximum range $\pm 5\text{mm}$ (sensitivity $\pm 0.001\text{mm}$). Readings of the Load cells and LVDTs were recorded and collected by using a Hewlett Packard data acquisition system.

3 Results and discussion

3.1 Mode of failure

3.1.1 Slightly offset joints ($\beta=22.5^\circ$, $\alpha=30^\circ$)

The failure started with the initiation and propagation of the wing crack the wing first and then the secondary cracks initiated at the tips of the joints and propagated to coalesce at a point in the bridge causing sample failure. Crushed and pulverized materials have been noticed on the failure surface. Shear displacement was noticed at the tips of the ligament between the joints. No scale effect was noticed on mode failure. The failed specimen and sketch of the wing and secondary cracks are shown in Fig. 3.

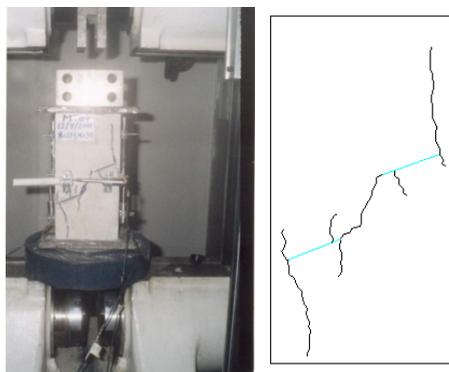


Fig. 3. Crack growth in 22.5° - 30° flaws

3.1.2 Offset joints ($\beta= 22.5^\circ, \alpha= 45^\circ$)

In these blocks wing cracks propagated from the external flaw tips only and kept growing till the boundary of the block. Coalescence occurred through the growth of secondary crack matching through the flaws. The mode of failure in both sizes was identical. However size shows slight effect on the strength of the joint. The failed specimen and sketch of the wing and secondary cracks are shown in Fig. 4.

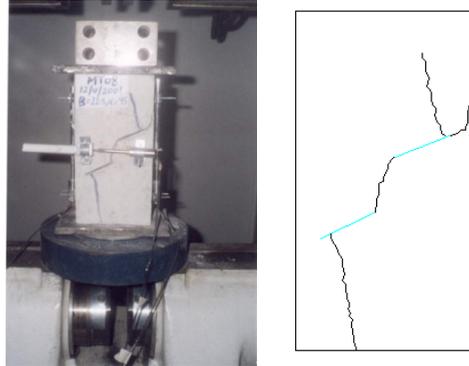


Fig. 4. Crack growth in 22.5° - 45° flaws

3.1.3 Offset joints ($\beta= 22.5^\circ, \alpha= 60^\circ$)

In both block sizes the failure initiated by wing cracks propagated from the external flaw tips only, extended to a certain distance from the tips of the joints and opened. Coalescence occurred through the growth of secondary crack matching through the flaws. No scale effect was noticed on mode of failure while strength has affected by the block size. The failed specimen and sketch of the wing and secondary cracks are shown in Fig. 5.

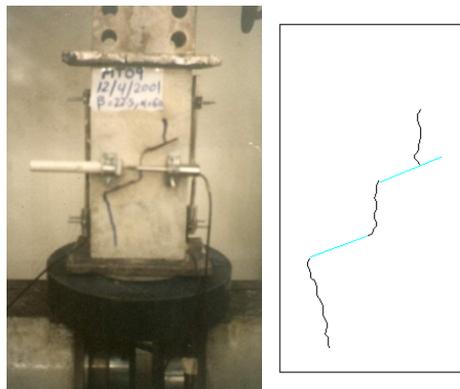


Fig. 5. Crack growth in 22.5° - 60° flaws

3.1.4 Overlapped joints ($\beta= 22.5^\circ, \alpha= 90^\circ$)

In these blocks failure started as wing cracks propagated from the external and internal flaw tips, they extended and opened. Coalescence occurred through two wing cracks matching through the flaws. The failed specimen and sketch of the wing and secondary cracks are

shown in Fig. 6. The results of mode of failure of all tested samples are summarized in Table 1.

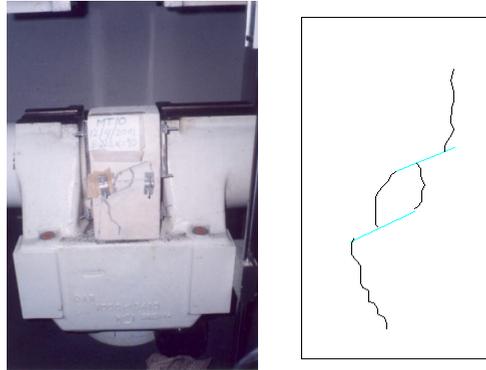


Fig. 6. Crack growth in 22.5°-90° flaws

Table 1. Mode of block failure with different bridge inclinations

	30°	45°	60°	90°
Large sample	Tensile + Shear failure	Tensile + Shear failure	Tensile failure	Tensile failure
Small sample	Tensile + Shear failure	Tensile + Shear failure	Tensile failure	Tensile failure

3.2 Effect of scale on strength

The current research showed that the scale has slight effect on the strength on the offset non persistent rock joints. Also, the results showed that this effect increased as the bridge inclination angle increases. This behaviour is understood as the mode of failure changes from shear to tension failure as bridge inclination angle increases. As the size of the block increases the intensity of micro flaws also increases which resulted in decreasing the tensile strength of the rock. To eliminate the effect of variation in curing time for the samples, variation in mixes for the samples, and material sources, strength of each sample was normalized by dividing it by the average unconfined compressive strength (f'_c) of the cylinders for each sample. The results of normalized uniaxial compressive strength of the large samples and small samples tested are shown in Table 2 and Table 3 respectively.

Table 2. Uniaxial compressive strength (MPa) of large samples

Large sample	30°	45°	60°	90°
σ_{lf} (MPa)	11	5	6	7
σ_{lf} / f'_c	0.92	0.68	0.66	0.58

Table 3. Uniaxial compressive strength (MPa) of small samples

Small Sample	30°	45°	60°	90°
σ_{lf} (MPa)	13.76	7.46	12.52	12.4
σ_{lf} / f_c'	0.98	0.918	0.84	0.81

4 Conclusions

The following conclusions may be drawn from the presented research:

- i) Mode of failure of Rock Bridge varies from shear to tensile failure as the bridge inclination increases. For slightly offset joint ($\alpha = 30^\circ$ or 45°) the failure was due to combined shear and tension failure while it was purely tension for overlapped joints ($\alpha = 90^\circ$).
- ii) Wing cracks (Tensile cracks) grew first, and were followed by secondary cracks (Shear cracks) for all the geometries tested, and for both sizes.
- iii) Size has small or no effect on the mode of bridge failure.
- iv) Strength is a scale dependent property. As the size of sample increases the strength decreases. The influence of scale becomes more significant as the bridge inclination angle increases.

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