Mechanical anisotropy of jointed rock mass under uniaxial compression and tensile loading

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Abstract. Anisotropic in a rock mass are the properties which have directional mechanical behaviours. These anisotropic characteristics are originated from foliation of minerals in metamorphic rock, stratification in sedimentary rocks and discontinuities in the rock mass. The strength and deformability of rock mass are influenced by the orientation and distribution of fractured networks and the failure mode is varies significantly with the variation of fracture orientation. Therefore, the mechanical behaviour of rock mass becomes one of the most crucial topics in rock engineering fields. In this paper, stratified and jointed limestone samples from two different quarries of Ipoh areas (LafargeHolcim and Hume Cement) were studied to determine the mechanical strength and failure patterns under uniaxial compression and tensile loading. The results showed that the failure pattern and maximum strength of was correlated with relative layer orientations. It was observed that the higher the inclination angle the lower the failure strength. The maximum tensile strength also observed at 0° with 16.77 MPa and the lowest occurred at 75° which are 5.68 MPa. The highest compression loaded at 0° which to break at 104.81 MPa and the lowest occurred at 75° which are 40.38 MPa. It is suggested that the failure pattern analysis should be considered in mechanical study of jointed rock mass.

1. Introduction

Rock mass is a geological body consists of discontinuities, ranging from large scale fractures such as faults and bedding planes to small scales of joints and schistosity to create complex natures of rock like heterogeneous and anisotropic properties. Considering the geological history and repeated events of deformation experienced, a rock is considered to be an anisotropic. Rocks which to have properties that vary with direction are said as an anisotropic. It is also refer to the properties of a material that is dependent on the direction. In general, anisotropic is defined as the presence of different properties in different directions [1]. These anisotropic characteristics are originated from mineral foliation in metamorphic rock, discontinuities in any of rock mass and stratification in sedimentary rocks.

The anisotropic created by the discontinuities will have much greater engineering significance [2]. Anisotropy in rocks significantly affects many engineering aspects such as in civil and mining engineering where the stability of deeper foundation, underground and surface excavations can be questioned [3]. It also affects drilling, blasting and rock cutting in mining and quarrying activities [4]. Rock anisotropy is also a critical factor in petroleum engineering as in controlling the deviation,
stability, deformation and failure of boreholes [5]. It also influences the propagation and fraction of cracks in shale gas extraction activities [6]. Therefore, the degree of mechanical behaviour of anisotropic rock masses need to be aware in order to decide whether it is relevant or not to consider the anisotropy before start any certain operations [7].

This paper focuses on the anisotropic strength and fracture pattern of laminated limestones. In order to understand the effects of the layer orientation on the strength and the fracture pattern, the anisotropic rocks were studied.

2. Methods

Intact laminated limestone blocks were collected from two limestone quarries in Kinta Valley areas, QA and QB (Fig. 1). For this purpose, 15 block samples were collected from each quarry to later be cored into different lengths with the same 54 mm diameter. The length varied with the ratio of thickness to diameter as it is two (2) in UCS and one (1) in Brazilian. The rock were cored at different direction with respect to the inclination angles ($\beta$) of 0, 30, 60, 75 and 90°. In this study, the inclination angle ($\beta$) is the angle between the loading direction and lamination plane. The visual inspection of the inclination was indicated during the loading of force applied by the Universal Testing Machine (UTM) used. The UCS test on cored limestones was carried out in accordance with the test methods suggested by ISRM (1981). The stress rate was kept at constant value of 1kN/s so that the failure could occurred within 5 – 10 min of loading applied. The layer is adjusting based on the required inclination angle before the load is applied. When the load is applied, the sample fail and the fracture pattern occurred is observed and determine if it is a layer activation fracture, central fracture or non-central fracture.

Fig. 1. (a) Part of Keramat Pulai industrial area; (b) Geology of Keramat Pulai area, Perak.

3. Results and discussion

3.1 Uniaxial Compressive Strength (UCS) Test

A total of 20 cored samples (10 from QA and 10 from QB) were tested under the uniaxial compression strength (UCS) test. For this test, five inclination angles were chosen, 0, 30, 60, 75 and 90°. Fig. 2 and Table 1 show the physical properties of samples, the failure pattern and ranges of uniaxial compressive strength with respect to the anisotropy orientations. Fig. 3 shows the variations of the UCS values (MPa) ranging from 15 MPa to 106 MPa as a function of inclination angle. The results indicate the maximum UCS is in the inclination angle of 60° for QA at 51.18 MPa and 0° for
QB at 105.94 MPa. In contrast, the least strength recorded at 15.42 MPa of 90° angle of inclination for QA and at 31.79 MPa at 75° inclination for QB.

| Samples and fracture patterns of QA | Samples and fracture patterns of QB |
|------------------------------------|------------------------------------|
| ![Sample Image](Image1)            | ![Sample Image](Image2)            |
| ![Sample Image](Image3)            | ![Sample Image](Image4)            |
| ![Sample Image](Image5)            | ![Sample Image](Image6)            |

Figure 2. The observed condition of limestone samples of before and after the failure under different lamination-loading angles of UCS test.

Generally, the variant strength of intact rock in uniaxial and triaxial loading conditions with respect to the anisotropy orientation is defined as the “strength anisotropy” and its magnitude is representing the degree of anisotropy

\[ R_c = \frac{\sigma_c(90)}{\sigma_c(min)} \]

where \( R_c \) is the degree of anisotropy, \( \sigma_c(90) \) or can use \( \sigma_c(max) \) is UCS perpendicular to the planes of anisotropy which is maximum value \( \sigma_c \) of and \( \sigma_c(min) \) is the minimum value of \( \sigma_c \) commonly at \( \beta = 30°–45° \). The strength anisotropy classification depends on the degree of anisotropy \( (R_c) \), which is the ratio of the maximum to the minimum values of uniaxial compressive strength (UCS) of anisotropic intact rock samples. The lower the value of \( R_c \), the closer the rock nature to be isotropic. The higher value of \( R_c \) the higher anisotropy of rock class. Table 1 shows relationship between value of \( R_c \) and degree of anisotropy. In this case of QA and QB, both of limestones are valued at 3.32 and 3.33 respectively, thus to classify as medium anisotropy rock.

In reference to the previous studies, the minimum strength of laminated rock is at an orientation angle of \( \beta = 30° \) and the maximum failure strength is either at \( \beta = 0° \) or \( \beta = 90° \). This is because at \( \beta = 30° \), the weak plane is in the orientation in relation to major loading direction. The tests were carried out at orientation angles, \( \beta \) (the angle between the major principal stress direction and weakness plane), of 0°, 30°, 60°, 75° and 90°. So for QB, it was noted that it was in accordance to the theory as the maximum value of UCS (MPa) is at 0°. For QA, it does not follow the theory of 90° to record as the weakest angle measured from loading direction. The results are believed due to the moisture content of the specimens, and it thus should be noted. The UCS value of rock is highly dependent on the effective porosity, which in other term is the existence of water and applicable to the reduction of strength in the specimen. The inclined fissures, intrusions, and other anomalies will often cause premature failures on those planes.
Table 1. Anisotropic strength and failure patterns of Kinta Limestone samples in UCS test

| No | Sample no | Inclination angle (β) | UCS (MPa) | Failure pattern      |
|----|-----------|-----------------------|-----------|---------------------|
| 1  | QA0°      | 0°                    | 22.83     | Axial splitting     |
| 2  | QA0°      | 0°                    | 33.39     | Shearing along single plane |
| 3  | QA30°     | 30°                   | 35.25     | Along foliation     |
| 4  | QA30°     | 30°                   | 26.12     | Axial splitting     |
| 5  | QA60°     | 60°                   | 30.77     | Axial splitting     |
| 6  | QA60°     | 60°                   | 51.18     | Along foliation     |
| 7  | QA75°     | 75°                   | 33.26     | Shearing along single plane |
| 8  | QA75°     | 75°                   | 28.29     | Along foliation     |
| 9  | QA90°     | 90°                   | 33.28     | Shearing along single plane |
| 10 | QA90°     | 90°                   | 15.42     | Shearing along single plane |
| 11 | QB0°      | 0°                    | 104.81    | Along foliation     |
| 12 | QB0°      | 0°                    | 105.94    | Along foliation     |
| 13 | QB30°     | 30°                   | 71.51     | Shearing along single plane |
| 14 | QB30°     | 30°                   | 61.34     | Shearing along single plane |
| 15 | QB60°     | 60°                   | 40.38     | Axial splitting     |
| 16 | QB60°     | 60°                   | 49.11     | Axial splitting     |
| 17 | QB75°     | 75°                   | 65.08     | Axial splitting     |
| 18 | QB75°     | 75°                   | 31.79     | Shearing along single plane |
| 19 | QB90°     | 90°                   | 46.54     | Shearing along single plane |
| 20 | QB90°     | 90°                   | 33.32     | Axial splitting     |

3.2 Indirect Tensile test

A total of 25 cores were tested for Brazilian test, 15 for QA and 10 for QB. Based on Fig. 3 and Table 2, the maximum tensile strength for QA occurred at or near $\beta = 0^\circ$, at 13.23 MPa and the minimum tensile strength occurred at $\beta = 90^\circ$, at 2.35 MPa. Theoretically, the tensile strength should decrease when the inclination angle increase. However, when the average of tensile strength is calculated, it was observed that the tensile strength decreased from $0^\circ$ to $60^\circ$, suddenly increased at $75^\circ$ and later dropped at $90^\circ$. As in Tab. 2, the tensile strength for the inclination angle of $75^\circ$ is quite high compared to the sample of inclination angle of $60^\circ$.

For QB, the results are in contrast to the theory stated (Tab. 2). The maximum tensile strength is near or equal to $\beta = 0^\circ$ which is 16.77 MPa and the minimum tensile strength was at $\beta = 75^\circ$ which is 5.68 MPa. This may cause by certain factors that influence the fracture pattern. The existence of tight cracks can be observed in QB-75 in comparison to much intact core of QB-90. In general, the strength decreases from QB-0 to QB-75 and increase in QB-90. If there are no other factors that influence the crack, it can be concluding that the values of tensile strength are inversely proportional to the inclination angle. The lower the inclination angle, the higher the tensile strength.
Figure 3. The observed condition of limestone samples from QA and QB after the failure under different lamination-loading angles of Brazilian test.

Table 2. Anisotropic strength and failure patterns of Kinta Limestone samples in Brazilian test

| No | Sample no | UCS (MPa) | Failure pattern |
|----|-----------|-----------|-----------------|
| 1  | QA0°      | 11.92     | Central fracture|
| 2  | QA30°     | 8.26      | Central fracture|
| 3  | QA60°     | 6.62      | Central fracture|
| 4  | QA75°     | 9.22      | Central fracture|
| 5  | QA90°     | 6.42      | Central fracture|
| 6  | QB0°      | 16.77     | Central fracture|
| 7  | QB30°     | 8.48      | Central fracture|
| 8  | QB60°     | 9.77      | Central fracture|
| 9  | QB75°     | 5.68      | Central fracture|
| 10 | QB90°     | 10.01     | Central fracture|

The different strength can be observed in these two sites. As in both tables, the highest tensile strength is from QA site. Even though the rock from QA is more stratified compared to the QB, it is much stronger than QA. Compared the maximum compressive load between QA and QB for every inclination angle, it can be seen that the samples of QA is easily to break compare to the samples from QB.

The fracture pattern occurred are differently for every inclination angle. There are five inclination angle were tested ranging between 0° (perpendicular to loading direction) and 90° (parallel to loading direction). It should be highlighted that the orientation of the layers with respect to loading direction is evaluated. The loading direction in this test is always vertical while the layer orientation become the variable where it always change followed by the layer orientation required. Five different values are considered: 0°, 30°, 60°, 75°, and 90°. There are three types of fracture pattern had occurred (Fig. 3). Normally, in most cases, there is two or three different fracture patterns will occurred in the same experiment. After conduct the test, three fractures are observed: (1) - layer activation occurred if some fractures are parallel to the isotropic layers; (2) - central fractures will occurred if some fracture are roughly parallel to the loading direction and it is located in the central part of the sample between the two loading lines; (3) - non-central fractures occurred if the fractured occurred outside the central and do not correspond to part of layer activation.

4. Conclusion

This paper studied the experimental characterization of the anisotropic behaviours of laminated limestone using UCS and Brazilian test. Observations were made on anisotropic strength and failure
patterns at five different inclination angles of loading, 0°, 30°, 60°, 75° and 90° in respect to lamination planes of limestones collected from two different quarries in Kinta Valley, Ipoh. The results show that the anisotropic strength and failure patterns of laminated limestones depend significantly on the inclination angle of planes and loading direction. From this study, it shows that the failure strength is correlated with the relative layer orientation (Fig. 4). But, nonetheless, due to the condition of rock itself which have crack cause the some failure strength are not correlated with the relatives’ layer orientation as shown in the graph of the comparison between two sites where at 75° of sample QB, it is the lowest tensile strength while for the QA, 0° is the lowest tensile strength that is occurred. The different of this inclination angle cause by the condition of rock itself. From both sites, different fracture patterns were observed based on the inclination test. The fractured sample of QA and QB follow the trend where the fracture occur for the inclination angle of 0°, 30°, 60°, 75°, and 90° starts with the central fracture then followed by the combination of the central fracture and activation layer fracture and finally activation layer respectively. Based on the fracture pattern occurred, it can be conclude that the range between 30° and 60° is the range where the combination of the central fracture and activation layer fracture occurred.

Figure 4. Variation of anisotropic strength (MPa) with the inclination angle (β) for each limestone samples (QA and QB)

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