International Journal of Mining Science and Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Strength behaviour of sandstone subjected to polyaxial state of stress

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ARTICLE INFO

Article history:
Received 28 December 2016
Received in revised form 26 February 2017
Accepted 2 April 2017
Available online xxxx

Keywords:
Polyaxial testing
Sandstone
Strength criterion
Modified Mohr-Coulomb criterion
Modified Weibols and Cook criterion

ABSTRACT

The paper presents an experimental investigation on the strength behaviour of natural rock subjected to polyaxial state of stress. The polyaxial tests were conducted on cubical specimens of sandstone obtained from the Shivpuri district in Madhya Pradesh state of India. The specimens having nominal dimensions of 100 mm × 100 mm × 100 mm were tested using a polyaxial testing machine. Twenty-five combinations of intermediate and minor principal stresses were applied and the specimens were loaded till failure occurs. It was observed that the intermediate principal stress has a substantial effect on the strength of the Shivpuri sandstone. A database of rock strength under various combinations of σ_2 and σ_3 was obtained for the Shivpuri sandstone. The database was used to study the predictability of five most commonly used strength criterion. Root mean square error (*RMSE*), average absolute relative error percentage (*AAREP*) and coefficient of accordance (*COA*) were used as indices for the measure of goodness of fit. It was observed that the least error in the prediction was shown by modified Mohr Coulomb criterion followed by modified Weibols and Cook criterion. A probability analysis of the error in prediction was also done.

1. Introduction

The state of stresses around deep underground facilities and mines in rockmass is generally polyaxial in nature where all the principal stresses have different magnitude. This polyaxial condition of state of stress near rock structures is more common in the areas of high tectonic activity [1,2]. The behaviour of rock under polyaxial state of stress must be studied so as to have a safe and reliable design. The effect of intermediate principal stress on the strength of intact rock was first estimated on the basis of results obtained from conventional triaxial compression test and conventional triaxial extension test. Murrell analyzed the results of Von Kármán and Böker and concluded that the difference in strength under the two stress conditions (compression and extension) is due to the effect of intermediate principal stress [3–5]. The findings were reaffirmed by Murrell, Handin and Mogi [6–8]. This incited the researchers worldwide to conduct the test where all the three principal stresses could be applied independently. Mogi developed the first of its kind of polyaxial testing machine in Japan and tested various types of rocks from Japan [9]. Beron and Chirkov in Russia developed their own self designed polyaxial testing equipment and tested on number of specimens of different rocks like coal, limestone, shale, sandstone, etc. [10–12]. Since then a number of researchers have tried polyaxial testing on rocks with their indigenously designed machines [13–29]. Every researcher with their experimental results affirmed that intermediate principal stress indeed affect the strength of the rock. Earlier Weibols and Cook stated that the strength of rock (σ_1) increases with the increase in intermediate principal stress (σ_2) for a given minor principal stress (σ_3), reaches a maximum at some intermediate value of σ_2 and then decrease to value greater than the conventional triaxial equivalent value [30]. Mogi's results were similar to this assumption [9], however, Chang and Haimson with their study on KTB amphibolites observed that the strength, σ_1 increased with increasing σ_2 while σ_3 was held constant, reaches a maximum value and then remain almost constant [20]. Few polyaxial unloading tests were also conducted by some researchers to explain the phenomenon of rock burst occurring in the deep underground rock structures [31,32].

Various strength criteria were also presented to predict the value of strength of rock at various combination σ_2 and σ_3. For some criteria presented in [8,33–35], the parameters associated were calculated by optimizing the error in prediction value. The database in term of principal stresses (σ_1, σ_2, σ_3) collected from published data was used to calculate the most optimum value of parameters for each rock type. For other criteria presented in [36–41], the parameters are related to conventional Mohr-Coulomb criterion parameters i.e. cohesion and angle of internal friction. These parameters can be easily obtained by conducting few conventional triaxial tests on cylindrical specimen of rock. Few comparative assessments of these criteria were presented by

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http://dx.doi.org/10.1016/j.ijmst.2017.06.022
2095-2686/© 2017 Published by Elsevier B.V. on behalf of China University of Mining & Technology.

some researchers on the basis of various goodness of fit and published test data [42–44].

The laboratory studies on polyaxial strength of rock are very few. The available database for polyaxial strength test on intact rock is very small and requires more testing. The present article discusses in detail an experimental study wherein cubical specimen of sandstone has been tested under polyaxial stress condition. Effect of intermediate principal stress on strength of rock has been investigated. Applicability of five polyaxial criteria in vogue has been evaluated in the light of test results.

2. Experimental program

An experimental study has been conducted to study the natural rock under polyaxial state of stress. The complete procedure involved in the preparation of rock specimen and testing is discussed here under.

2.1. Rock samples

Present study was conducted on natural sandstone obtained from Shivpuri district located at northern part of the state of Madhya Pradesh, India. The Shivpuri sandstone is characterized by their brownish pink color. The sandstone belongs to the Vindhyan formation. Petrographic study was conducted on the rock samples. The thin section prepared was studied under optical microscope at 200 μm resolution. The rock has almost 80–85% quartz and 15–20% of feldspar. The rock is without any micaceous mineral and is undeformed rock. The thin sections of rock specimen under uncrossed Nicole and cross Nicole condition are shown in Fig. 1.

The samples were quarried from a sandstone mine. The quarrying was done manually such that almost cubical sample of size 150 mm × 150 mm × 150 mm can be extracted. Fig. 2a shows some of the quarried samples. The samples were brought to the Geotechnical Engineering Laboratories of IIT Roorkee. Cubical specimens of size 100 mm × 100 mm × 100 mm were prepared by cutting the specimen on high power hacksaw cutting machine. Fig. 2b shows the cutting of the samples. The specimens were then carefully grounded and lapped with the help of manual polishing machine. Fig. 2c shows the polishing of the specimen. The polishing is done very carefully such that the perfect orthogonality of specimen faces was obtained. Fig. 2d shows the final prepared specimen.

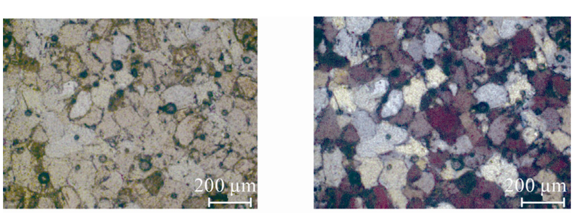
A total of 30 specimens were prepared. Fig. 3 shows the entire prepared specimen used for the present study. The physical and engineering properties of the rock material are presented in Table 1.

2.2. Testing apparatus

Polyaxial testing systems were developed by a number of researches with the aim of applying the intermediate principal stress independently. Takahashi and Mogi have tried to classify the polyaxial testing equipment in three broad categories [45,46]. The categorization was done according to the loading method applied and is the Rigid Platen Types (Type-1), the Flexible medium Type (Type-2), and the Mixed Type or Mogi Type (Type-3).

Details of the three polyaxial type testing equipment citing various merits and demerits have been presented by Li et al. [47]. It has been concluded that none of the three systems is near to perfection however the Mogi type apparatus has a number of advantages. Kwaśniewski collected a database of polyaxial testing conducted on intact rock worldwide [42]. He clearly mentioned the type of testing system used for each test. The maximum of testing were conducted with Mogi type apparatus however some have been conducted on Type-1 and Type-2 apparatus [13-14,17,23,27–29].

For the present study, the polyaxial testing system developed by Wille-Geotechnik Germany has been used. The testing system conforms to Type-1, i.e., rigid Platen Type. The testing system has three basic units as shown in Fig. 4. The units are the specimen holder, the power-pack and the pressure intensifiers. The specimen



(a) Uncrossed nicole (b) Crossed nicole

Fig. 1. Petrographic study of the rock samples by thin section.

Fig. 3. Specimens used for the present study.

Table 1
Properties of the Shivpuri sandstone (Based on test on cubical specimens).

Property	Symbol	Value
Unit weight (kN/m^3)	γ	23.99
Uniaxial compressive strength (MPa)	σ_{ci}	34.62
Tangent modulus (GPa)	E_{t50}	7.23
Cohesion (MPa) (for σ_3=0–10 MPa)	c_i	6.44
Friction angle (°) (for σ_3=0–10 MPa)	φ_i	48.93
Deere-Miller classification		DL

(a) Quarried sample (b) Cutting of sample (c) Grounding and lapping of specimen (d) Final specimen

Fig. 2. Preparation of cubical specimen.