Characterization of Mobilized Cohesion, Friction and Dilation Angles of Brittle Rock During Plastic Deformation

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ABSTRACT: The behavior of basalt rock in plastic region is investigated by tri-axial compression tests. Four sets of basalt rocks are tested using a servo-controlled universal testing machine (UTM) under three confining stress 2, 4, 6 MPa. This study generates valuable information of post-yielding parameters like cohesion, friction and dilation angles of brittle rocks and shows their behavior during plastic deformation. The analysis results show that in post peak region, the basalt rock is brittle in nature. It exhibits a negative exponential relationship of cohesion and dilation angle with plastic shear strain. However, the friction angle remains almost constant with increase of plastic shear strain. The existing dilation angle models of (Zhao & Cai 2010) and (Pourhosseini & Shabanimashcool 2014) are used for estimating the model parameters for basalt rock. It is found that (Zhao & Cai 2010) is more aptly fitted for basalt rock.

Keywords: Brittle rock, cohesion, peak dilation angle, plastic shear strain.

1 INTRODUCTION

The understanding of mechanical behavior of intact rock and rockmass is important in designing of any mining and civil excavations. Various research conducted in laboratories and in the field has demonstrated that the failure behavior of the rocks is nonlinear, so that elastic analysis alone cannot describe the complete stress-strain behavior. Therefore, it is very important to understand the full stress-strain curve of the rock, especially the post-peak region of the curve. The nonlinear behavior of rock like material is caused by the initiation of cracks, their propagation and correlation of the newly formed cracks. This results in the expansion of certain existing voids or the creation of new voids. Consequently, as a result of plastic deformation, the volume of the rock rises. This is known as the dilation.

Reynolds (1885) highlighted granular material's shear dilatancy. Dilatancy can be demonstrated as the volume change due to shear distortion of a material's component. A convenient parameter for defining a dilatant material is the dilatancy angle (ψ). Dilation is measured by dilation angle (ψ) that may be determined by plastic axial strain and volumetric strain from tri-axial testing of rock (Vermeer & De Borst 1984). Hansen (1958) first proposed dilation angle, which expressed the proportion of plastic volume change to plastic shear strain. Cook (1970) established that the dilation at the time of compression failure is a volumetric characteristic universal to rock and it is not a superficial phenomenon. It is understood that when a rock is loaded above the yield point, a phenomenon known as dilation occurs that is linked to microcrack initiation, propagation, and growth in void space. Dilation is an accurate representation of the volumetric behavior of rocks and is an element of the rock failure procedure.

The novel way of computing volumetric strain reckons on the computation of the linear axial and radial strains with resistance strain gauges pasted on cylindrical samples. This process is restricted to minor strain, and the volumetric strain of a rock after peak load cannot be calculated objectively using this procedure because of the impact of localized failure and large deformation. For this, a new technique was developed by (Crouch 1970) to evade the effects of localized failure and calculated the volumetric strain as an average over the total specimen by immersing samples in a fluid-filled vessel and witnessing fluid level changes in a standpipe. Several other authors [Wawersik (1975); Cipullo et al. (1985); Singh (1997); Medhurst & Brown (1998)] have modified and used this method to measure volumetric strain.

The dilatancy angle is presumed to be zero in the non-associated flow rule and equal to the friction angle in the associated flow rule. Zhao & Cai (2010) has done pioneer work on dilation and proposed mobilized dilation angle model in view of the effect of the confining stress and plastic shear strain. Arzúa & Alejano (2013) did the experimental work using three different types of granitic rocks and fitted (Zhao & Cai 2010) model. A constitutive model was presented by Pourhosseini & Shabanimashcool (2014) to explain the nonlinear behavior of rocks under static loading. With fewer independent parameters, Walton & Diederichs (2015) offered an improved model for the dilation of rocks. Rahjoo & Eberhardt (2016) suggested a novel dilation model with fewer parameters based on the work of Zhao & Cai (2010). Zhao & Li (2022) proposed another new model for dilation angle model for rocks whose accuracy is better than the widely used model of (Zhao & Cai 2010) and (Walton & Diederichs 2015).

In this study, stress-strain and volumetric strain-axial strain curve of basalt rock under three confining stress 2, 4, 6 MPa is discussed. Further, behavior of dilation and cohesion with increase of plastic shear strain is studied. Finally, the experimental data is compared with the existing models of dilation angle and cohesion.

2 EXPERIMENTAL INVESTIGATION

2.1 Sample preparation

In this study, twelve basalt samples of 60 mm diameter are collected and tested in the Rock Mechanics laboratory, Department of Mining Engineering of IIT, Kharagpur. The physico-mechanical properties of the rocks are determined as per ISRM standard and reported in Table 1. The Poisson's ratio (ν) of basalt rock is 0.2.

Table 1. Physico-mechanical properties of basalt rock.

Set No.	UCS (MPa)	E (GPa)
Set 1	52.52	12
Set 2	80.71	11.5
Set 3	42	9.5
Set 4	71.52	11

2.2 Experimental setup

Tri-axial tests are done in WILLE tri-axial cum shear apparatus. During the tests, change of volume of sample is estimated by measuring the change of hydraulic oil entering and exiting the tri-axial chamber. The elastic component of strains at that stress level are subtracted from the total strains to estimate the plastic shear strain (γ_p). Total four sets of basalts are tested varying three different confining pressure i.e., 2 MPa, 4 MPa and 6 MPa using displacement rate 0.1mm/min.

3 RESULT AND DISCUSSIONS

3.1 *Stress-strain curves and volumetric strain-axial strain curves*

Stress–strain curves of the basalt for different confining stresses are showed in Figure 1a. It is clear that in pre-peak region stress-strain curves overlap very well demonstrating the uniformity of rock specimen chosen for testing. Additionally, under different confining pressures patterns of the stress-strain curves in the pre-peak and residual deformation stages are similar. It is also observed that as confining pressure increases, the peak strength and residual strength also increases. Figure 1b shows the contraction and dilation behavior of basalt with increase of axial strain for set 2. The condition of basalt rock before and after the test is shown in Figure 1c.

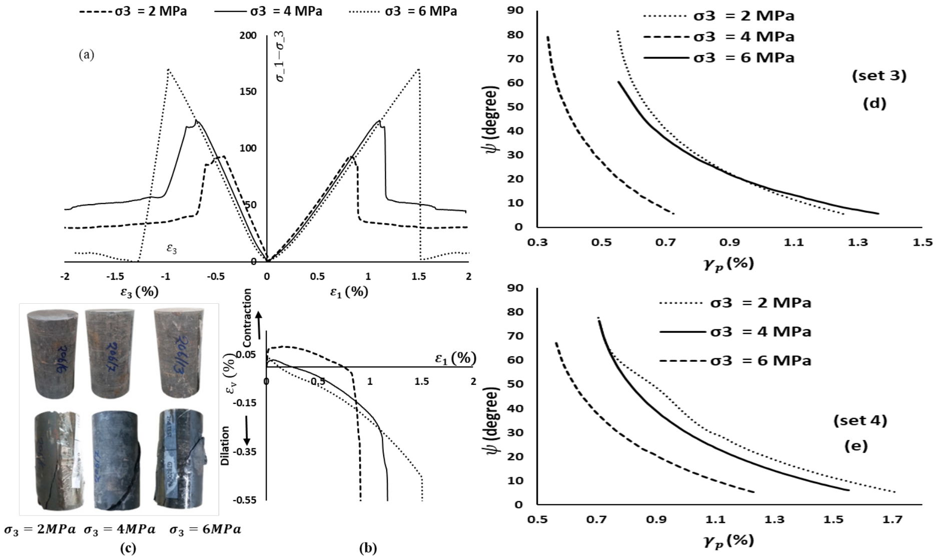

Figure 1. (a) Stress-strain curve (b) Volumetric strain-axial strain curve (c) Before and after test samples (d and e) Dilation angle versus Plastic shear strain.

3.2 *Relation of dilation with plastic parameters*

The change in dilation angle with plastic shear strain and confining pressure is shown in Figure 1d and 1e. It is found that dilation angle is dependent on the confining pressure and the plastic shear strain. It is clear that when γ_p increases, the dilation angle gradually decreases in form of negative exponentially. It is evident that low confining pressure causes high peak dilation angle as the confining pressure increases the peak dilation angle decreases and become almost constant at high confining pressure.

3.3 *Relation between cohesion and friction angle with plastic shear strain*

The Mohr-Coulomb (MC) could be written as the criterion in the principal stress system:

$$f = \sigma_1 - \frac{2c\ cos\phi}{1 - sin\phi} - \sigma_3 \frac{1 + sin\phi}{1 - sin\phi} \tag{1}$$

Where c= cohesion and ϕ= friction angle. The plastic strain affects the aspects of cohesion and friction. Propagation of crack is a c-losing procedure. At the time of strain softening phenomena, the frictional section of the strength shouldn't change, because strain softening has no consequence on the mechanical state of the crack surface. It is presumed, at the highest strength of rocks the c is at its maximum magnitude. The MC failure criteria can be rewritten as using softening parameter (η).

$$f = \sigma_1 - \frac{2c(\eta)\ cos\phi}{1 - sin\phi} - \sigma_3 \frac{1 + sin\phi}{1 - sin\phi} \tag{2}$$

The softening parameter (η) is identical to zero in the elastic region and η >0 from the peak point to the residual strength. It is well acknowledged that η is an incremental function of the shear plastic strain.

$$\eta = \gamma_p = \varepsilon_1^p \text{ - } \varepsilon_3^p \tag{3}$$

Where, ε_1^p= plastic axial strain and ε_3^p= plastic lateral strain. The post-peak behavior of the c with γ_p is showed (Figure 2a). At different γ_p the graph is plotted between σ_1 and σ_3 and the post-peak values of c and ϕ is determined. (Figure 2b). It is evident that when the γ_p increases, the c diminishes negative exponentially, but the ϕ remains almost constant. The empirical equation to foresee the loss of c of the rocks with increase of γ_p is given by (Pourhosseini & Shabanimashcool 2014) as follows:

$$C = C_0 \left(1 - \frac{\tanh(100\gamma_p)}{\tan(10)} + 0.001\right)^n \tag{4}$$

Where, C_0= cohesion at peak strength of the rock, and n= fitting parameter depends upon rock type. In this study the value of n for four sets of basalt rocks is found to be in between 0.05 to 0.1.

3.4 Comparison with existing dilation angle model

The experimental data of ψ and γ_p is fitted in dilation model (Eq. 5) of (Zhao & Cai 2010) and fitting coefficient a, b, c are determined at different confining pressure and reported in Table 2.

$$\psi = ab\left[\exp(-b\gamma_p) - \exp(-c\gamma_p)\right]/(c - b) \tag{5}$$

Where, a, b, c are fit coefficients. Pourhosseini & Shabanimashcool (2014) also proposed an empirical equation for predicting the peak dilation angle (Eq. 6).

$$\psi_{max} = A \ln\left(\frac{\phi\sigma_{ci}}{\sigma_3 + 0.10}\right) - B \tag{6}$$

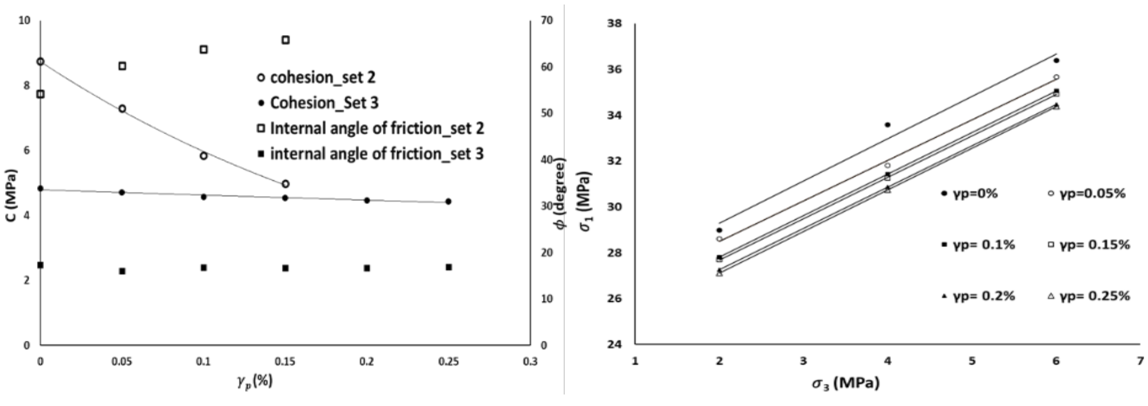

Figure 2. (a) Post-peak behavior of cohesion with plastic shear strain and post-peak behavior of friction angle with plastic shear stain 2. (b) M-C envelop at different plastic shear strain for set 3.

Table 2. Zhao & Cai (2010) coefficients a, b, and c and Pourhosseini & Shabanimashcool (2014) coefficients A, B, m for basalt rock.

			Zhao and Cai (2010)			Pourhosseini & Shabanimashcool (2014)		
Set No.	σ_3(MPa)	ψ_{peak}	a	b	c	A	B	m
1	2	80.88	96.13	37.17	0.099	22.259	77.696	0.16
	4	66.59	139.13	16.20	1.449			0.59
	6	57.03	82.65	23.49	0.050			0.25
2	2	54.60	76.31	54.58	9.700	9.867	22.598	6.70
	4	48.00	87.54	20.00	2.974			0.98
	6	44.08	71.02	17.11	4.986			17.97
3	2	81.51	438.58	23.45	3.553	18.104	40.423	0.96
	4	79.11	440.98	26.55	6.155			1.73
	6	60.40	214.32	16.83	2.723			0.75
4	2	77.62	331.72	3.41	3.362	12.899	18.928	0.71
	4	76.32	354.70	8.23	2.880			0.70
	6	67.31	335.52	11.70	3.578			0.91

Where, A and B are model parameters which are reliant on the rock type. The values of A and B for different sets are presented in Table 2. They also proposed a function (Eq. 7) for mobilized dilation angle (Eq. 7) which is as follows:

$$\psi = \psi_{max}\left(1 - \frac{\tanh(100\gamma_p)}{\tan(10)} + 0.001\right)^m \tag{7}$$

Where, m= model parameter, which is depended on rock types. The values of m of different sets are presented in Table 2. There are two values 6.70 and 17.97 for set 2 in the dataset that are identified as exception. The possible reason for excepotion is not clear so far. More testing data is required for the same.

Further, the existing dilation models of Zhao & Cai (2010) and Pourhosseini & Shabanimashcool (2014) is compared with experimental data (Figure 3) and found that Zhao & Cai (2010) fits more accurately for basalt rock.

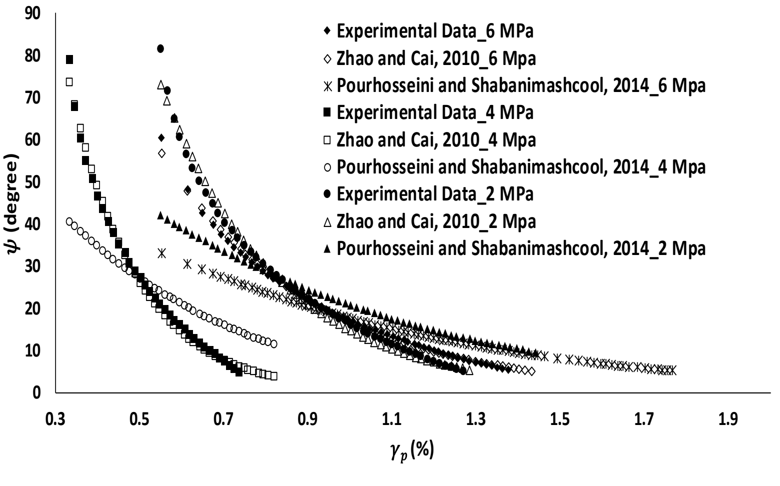

Figure 3. Comparison of experimental data of basalt with (Zhao & Cai 2010) and (Pourhosseini & Shabanimashcool 2014) for Set 3.

4 CONCLUSIONS

In this study, tri-axial test is done on four sets of basalt rock under confining stress of 2, 4, 6 MPa. The study depicts characterization of the dilation, cohesion, and internal angle of friction with increase of plastic shear strain. The findings show that basalt rock is brittle in post peak region. The dilation angle and cohesion show a negative exponential relationship with increase of plastic shear strain. However, ϕ remains constant with increase of γ_p. The average peak dilation angle found to be 73.65 degrees for σ_3= 2 MPa, 67.50 degrees for σ_3= 4 MPa, 57.20 degrees for σ_3= 6 MPa. Zhao & Cai (2010) and Pourhosseini & Shabanimashcool (2014) dilation angle model compared with experimental data and it is found that Zhao & Cai (2010) is more fitted for basalt rock. Further experimental test data are needed at wider range of confining stress to characterize the dilation angle and cohesion with plastic shear strain more accurately.

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