Laboratory Study for Determining Long-term Shear Strength of Rock

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Abstract

This research determines long-term shear strength of intact rock indirectly through shear creep test. The shear creep test is applied to sandstone rock sample taking from south pit Tutupan mine site of PT. Adaro Indonesia. There are two sizes of sandstone sample which are tested, first, drill core sample with 45 mm diameter that sheared through existing bedding plane, and second, square block sample that sheared through shear plane of 250 mm x 250 mm. During testing, the samples are given constant stresses, which are normal stress about 12.5% of its unconfined compressive strength, while shear stress about 81% of its shear strength under normal stress mentioned before. The shear displacement occurred during loading process is recorded as an input for creep behavior analysis. The creep behavior analysis is carried out using two approaching method which are empirical equation and rheological model. Based on the result of shear creep test the large sample has been obviously fitted to the Burger rheology model. The long-term shear strength of rock sample is then determined based on burger rheology model.

Keyword: Shear creep test, long-term shear strength, large sample.

INTRODUCTION

Tutupan mine site is one of coal mining of PT. Adaro Indonesia located in south Kalimantan province. The site consists of four pits such as PAMA pit, SIS pit, BUMA pit and RA pit. The PAMA pit will be developed down to RL -204m and formed the low wall slope with overall height of 300 m. Lithology in the low wall slope is dominated by sandstone. By this condition, the awareness to slope stability becomes necessary.

One of the parameter which need to be noticed in slope stability of the coal open pit mining is physical and mechanical properties of rock materials that form the slope. The rock material near slope surface will suffer disturbance due to stress distribution changing and weathering process which will decrease its strength. This condition can be known by observing the appearing of deformation and sametimes tension crack.

Creep phenomenon can occur on a slope as slowly deformation process that happens continuously. The phenomenon is caused by deformation due to stressing on rock material in subsurface of slope resulted by at advancing the excavation. The slope behavior can then be understood through the deformation monitoring, however, it is not so easy, taking time and costly. Provide that the stressing in the slope body is relatively shearing process, the creep process in the slope body can be observed by shearing test in the laboratory using constant load.

The rock mass is not so homogeneous like intact rock, so the usual shear test using drill core rock sample becomes unsuitable, therefore, in this research the direct shear creep test using large scale sample is developed.

LITERATURE REVIEW

Time Dependent Behavior

Determination of Safety Factor (SF) for slope stability analysis by using limit equilibrium method is based upon the ratio of resistance force against moving force at a failure plane. Thus, failure criteria which include shear strength is the most appropriate method to be used for slope stability analysis and Mohr-Coulomb criteria is the most well accepted. Despite of criticism on the accuracy of this criterion in predicting rock strength, the Mohr-Coulomb failure criterion has been widely uses both for soil and rock stability analysis (Schofield, 1998; Swan & Seo, 1999). The Mohr-Coulomb failure suggests that shear strength (τ) is a function of cohesion (C), normal stress (σ_n), and internal friction angle (ϕ).

From time dependent strength can be defined as the maximum stress sustained by geo-materials at which failure has been applied. The strength has been described by various terms namely fundamental strength, true strength time safe stress, and long term strength.

Regarding the time dependent behaviour of geo-materials this may be approach by a combination of two fundamental rheological models.

Time-dependent behaviour in claystone and mudstone of Indonesia coal mine has been studied both in the laboratory under shear stress constant (Kramadibrata et.al. 2007). In spite of the extensive work done in this field under a variety of test conditions, the results are more qualitative than quantitative; it is only in a few instances that the elastic and viscous constants have been determined.

Rheological Model

It is important to determine the stress-strain curve for the rocks and the time-dependent strain so that the mechanical behaviour of rocks can be predicted. Several mechanical models have been suggested that may have direct or indirect application to the description of the behaviour of rock. Goodman (1989) concluded that for many practical purposes for rocks, the Burgers creep model is preferable and will suffice for the description of most rock creep behaviour if proper parameters were selected.

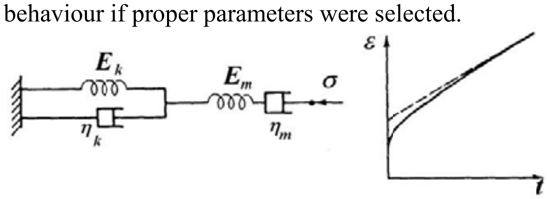

Fig. 1 – Burger's Model (after Goodman, 1989)

When such a model is subjected to a constant stress σ_o maintained for a time *t*, the strain produced will be the sum of the strains in the Maxwell and Kelvin units and can be given:

$$\varepsilon(t) = \varepsilon_m + \varepsilon_k \tag{1}$$

Where $\varepsilon(t)$ = strain in Burger's Model
ε_m = strain in Maxwell unit and
ε_k = strain in Kelvin Unit.

or

$$\varepsilon(t) = \frac{\sigma}{E_m} + \frac{\sigma}{E_k}\left[1 - e\left(\frac{E_k.t}{3.\eta_k}\right)\right] + \frac{\sigma.t}{3.\eta_m} \tag{2}$$

Where E_m and η_m = Parameters for Maxwell unit
E_k and η_k = Parameters for Kelvin unit

Long-term Strength

Based on Bieniawski's research (1970) for uniaxial compression test on sandstone with several different strain rates, it can be concluded when strain rate is decreasing, lower compression strength, lower modulus elasticity, and bigger deformation can be gained (Figure 2). Therefore, it can be assumed that the longer testing duration, the smaller difference for modulus of deformation. In other words, constant modulus of deformation can be gained for a long testing duration.

Using Burger rheological model equation (2) and modulus deformation equation (3) and (4) ,

$$\varepsilon(t) = \frac{\tau}{K(t)} \tag{3}$$

$$\frac{\tau}{K(t)} = \frac{\tau}{K_m} + \frac{\tau}{K_k}\left[1 - e^{\wedge}\left(\frac{K_k.t}{\eta_k}\right)\right] + \frac{\tau.t}{\eta_m} \tag{4}$$

K(t) can be formulated as follow

$$K(t) = \frac{K_m.K_k.\eta_m}{K_k.K_m + (K_k.\eta_k\left[1 - e^{\left(-\frac{K_k.t}{\eta_k}\right)}\right] + K_m K_k.t} \tag{5}$$

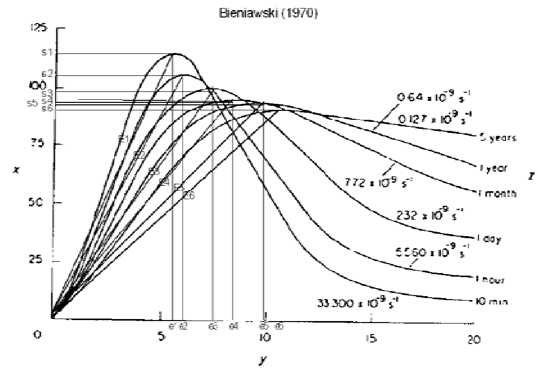

Figure 2 - Stress-strain curve in sandstone under variation constant stress (after Bieniawski,1970)

Based on equation 5, the relationship between time and long term modulus of deformation can be depicted with a graph (Figure 3).

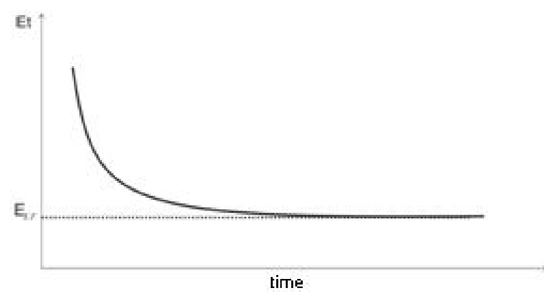

Figure 3 – Modulus deformation-time curve

If it is assumed that long-term rock strain is bigger than short term rock strain, the relationship (Figure 3) can be expressed as follow

$$\varepsilon_{LT} > \varepsilon_m \tag{6}$$

Furthermore, if it is assumed that the rock is acted under elastic behavior, equation (6) can be formulated as follow

$$\frac{\sigma_{LT}}{E_{LT}} > \frac{\sigma_m}{E_m} \tag{7}$$

$$\sigma_{LT} > \frac{\sigma_m}{E_m}.E_{LT} \tag{8}$$

$$\sigma_{LT} = \frac{\sigma_m}{E_m}.E_{LT}.\psi \tag{9}$$

Where,
σ_{LT} = long term compressive strength (MPa)
σ_m = empirical compressive strength (MPa)
E_{LT} = long term compressive stiffness (MPa/mm)
E_m = instant compressive stiffness (MPa/mm)
$\Psi > 1$ (constant)

TESTING AND RESULT

Material Description

The sandstone is described as predominantly fine to medium sand, interspersed irregularly with pebbly layers. According to the ISRM, 1979 classification, the strength (UCS) of low strength sandstone is likely to be in the range of 2.44 to 22.4 MPa, whilst moderate strength sandstone is in the range of 26.8 to 46.4 MPa. Poory cementation can be observed within the sandstone layer (UCS = 0.13 – 0.27 MPa) so that the sandstone layer is defined as uncemented sand and very friable.

Equipment and Modification

Direct shear creep test instrument has been successfully developed using uniaxial creep test with hanger loading through several modification up to 60 mm core sample (Kramadibrata et.al, 2007). Based on direct shear creep test previous, Kramadibrata, in 2010, has several modifications with the rock sample size and loading system. Normal and shear loading applied on this instrument is a combination of hydraulic jack and spring system. Direct shear creep test (Figure 4 and 5) for sandstone on this research used 3 tons hydraulic jack for normal stress and 5 tons hydraulic jack for the shear stress. The magnitude of the normal and shear force was observed using load cell, 600 kN capacity load cell for normal force and 2000 kN capacity load cell for shear force. Maximum shear force can be applied using this instrument is 50 kN. The last instrument used to measure the lateral and axial deformation is dial gauge with accuracy 0.001 mm is placed at the side and top of shear box (Kramadibrata, 2010).

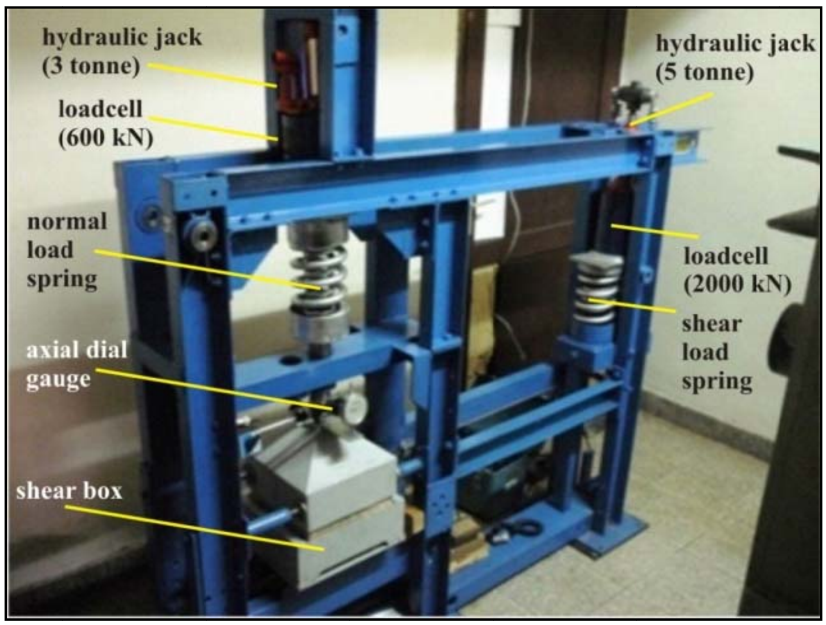

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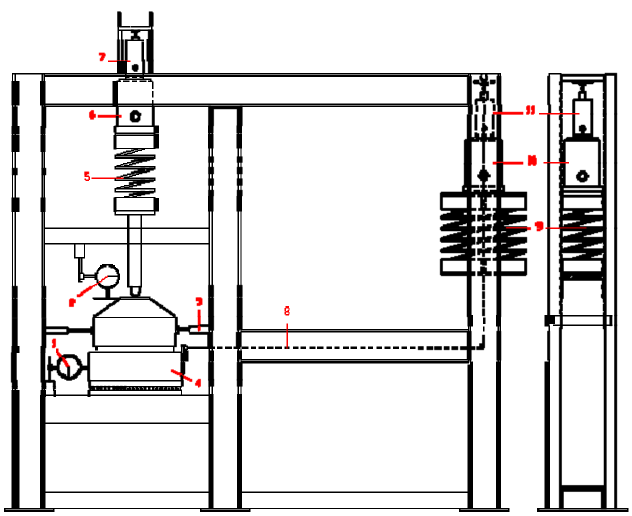
Figure 4 - Direct shear creep test instrument (Kramadibrata, 2010)



Where:
1. Lateral dial gauge
2. Axial dial gauge
3. Horizontal counter rod
4. Shear box
5. Normal load spring
6. Load cell (600 kN capacity)
7. Hydraulic Jack (3 tonne capacity)
8. Wire rope
9. Shear load spring
10. Load cell (2000 kN capacity)
11. Hydraulic Jack (5 tonne capacity)

Figure 5 - Schematic of direct shear creep test instrument (Kramadibrata, 2010)

Results

Before the direct shear creep test is conducted, the unconfined compressive strength test and the direct shear test must be carried out. The result of those tests will be used for determining the value of normal load and shear load in the direct shear creep test (Figure 4 and 5). The drilled core sample with diameter of 45 mm has the average value of UCS of 12.99 MPa and the shear strength parameters, i.e. cohesion and internal friction angle, are 0.106 MPa and 57.25°, respectively. Based on this, the Normal load that had been applied to the sample is 0.42 kN (will give normal stress about 2% of UCS) and a shear load of 0.65 kN (will give shear stress about 81% from the shear strength under that normal stress). The result revealed by this test is shown in Figure 6.

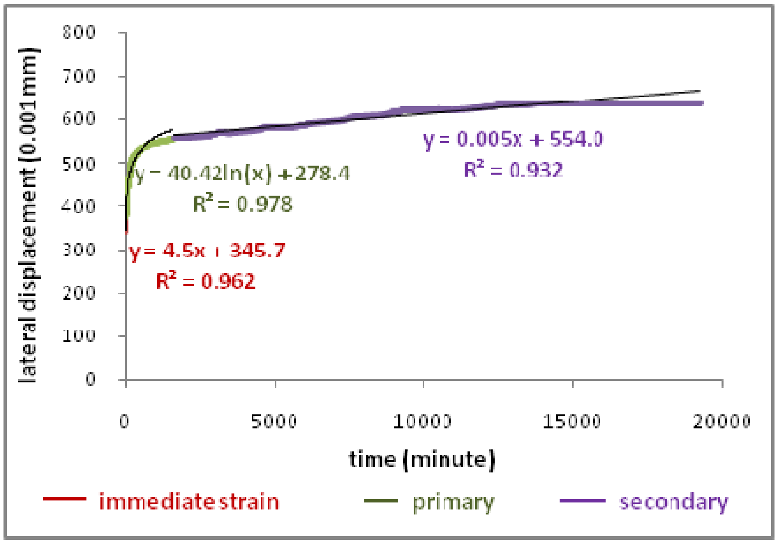


Figure 6 - Creep and empirical equation of 45 mm diameter of sample

Through the Burger's rheological equation, and by adopting equation (9), it is found that long term shear strength decrease around 66% from the peak shear strength. By this value cohesion and internal friction angle are then calculated. The results are given in table 3. From the table it can be seen that the long term cohesion decrease in to 66% of the C_p value while the internal friction angle decrease in to 79 % of ϕ_p and73% of ϕ_r.

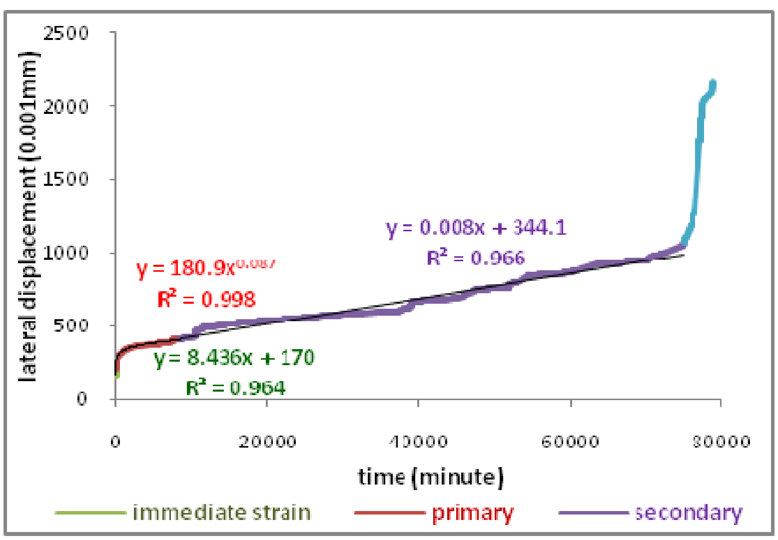


Figure 7- Creep and empirical equation of the sample with shear plane of 250 mm x 250 mm

The large sample with 250 mm x 250 mm of the shear plane has the range value of UCS about 3.3 – 5.2 MPa and the shear strength parameters, i.e. cohesion and internal friction angle are 0.6 MPa and 45°., respectively. The applied normal load and shear load are 4.1 kN (will give normal stress about 2% of UCS) and 31.2 kN (will give shear stress about 81% from the shear strength under that normal stress), respectively. The result revealed by this test is shown in Figure 7.

Through the Burger's rheological equation, and by adopting equation (9), it is found that long term shear strength decrease around 45% from the peak shear strength. By this value cohesion and internal friction angle are then calculated. The results are given in table 3. From the table it can be seen that the long term cohesion decrease in to 36% from the Cp value and 42% from the Cr value. Internal friction angle decline in to 71% from the value of ϕp and 55% from the value of ϕr.

DISCUSSION

The result of the experiment shows that Burger rheological model can be used to approximate sandstone creep behaviour following Goodman's statement (Goodman,1989). Burger rheological equation of the two samples are given in Table 2 while Table 1 shows the constants obtained from this experiment. It can be seen that there is relationship between scale effect and the constants obtained from this research.

The result given in Figure 6 and 7 showed that the samples have plastic behavior. Nevertheless, the deformability constans are difference between one and another. It can be seen that η_m (the rate of viscous flow) of drill core 45 mm is higher than large sample. Meanwhile, the other parameter i.e. η_k (rate of delayed viscous flow), K_m (shear modulus) and K_k (amount of delayed shear modulus) of drill core 45 mm are lower than large sample. Therefore, this condition proves that the small sample is stiffer than the large sample.

Tabel 1 - Burger's rheological model constants

*) Samp.	Burger's rheological model constants			
	η_m (MPa.min/mm)	η_k (MPa.min/mm)	K_m (MPa/mm)	K_k (MPa/mm)
1	75,792	470.4	0.903	2.82
2	62,382	1951.7	2.143	4.489

**) shear plane of rock sample, 1 is Core (D = 45 mm), 2 is Square Plane (250 mm x 250 mm)*

Tabel 2 - Burger's rheological model equation

*) Samp.	Burger's rheological model equation
1	$U(t) = 0.4914 + 0.1345\left[1 - e^{-0.006.t}\right] + 0.000005t$
2	$U(t) = 0.2329 + 0.11118\left[1 - e^{-0.0023t}\right] + 0.000008t$

**) shear plane of rock sample, 1 is Core (D = 45 mm), 2 is Square Plane (250 mm x 250 mm)*

Eventhough the sandstone rock samples are taken from similar location, however, there are variance of rock shear strength (Table 3). It is also found that the result of creep shear test indicates that there is a tendency getting decline on cohesion and friction angle regard to the increasing size. The cohesion of long term strength are decreased about 36% to 66% from cohesion short term and 55% to 75% of friction angle short term. It can be understood that the large sample will contain more defect compare to small sample.

In the previous creep shear test applied on claystone and mudstone in drill core sample, the decreasing of long term strength are about 40% to 50% from their short term (Kramadibrata, et al., 2007). Comparing with this condition, sandstone sample will give the decreasing rate greater than claystone and mudstone.

Tabel 3 - Shear strength parameters

*) Samp.	Shear strength parameters	Period of Time		
		Short term	Long term	Percents
1	C_p (MPa)	0.106	0.070	66.09%
	ϕ_p (°)	57.25	45.76	79.93%
	C_r (MPa)	0	0	-
	ϕ_r (°)	45.23	33.43	73.30%
2	C_p (MPa)	0.552	0.197	36%
	ϕ_p (°)	45.29	32.37	71%
	C_r (MPa)	0.393	0.166	42%
	ϕ_r (°)	30.28	16.75	55%

**) shear plane of rock sample, 1 is Core (D = 45 mm), 2 is Square Plane (250 mm x 250 mm)*

Table 4 is summerizing the long-term shear strength and parameters. Based on Table 4, the long-term shear strength reduction is equivalent with increasing of the rock sample size. Therefore it can be concluded that there is a relationship between the scale effect with the rock long term strength value determination.

Tabel 4 – Long term shear strength and parameters

*) Samp.	Long-term shear strength	Long-term shear strength parameters			
		C_p (MPa)	ϕ_p (°)	C_r (MPa)	ϕ_r (°)
1	66.09 %	66,09%	79,93%	-	73.30%
2	45.04 %	36%	71%	42%	55%

**) shear plane of rock sample, 1 is Core (D = 45 mm), 2 is Square Plane (250 mm x 250 mm)*

CONLUSIONS

a. Shear strength time dependent behaviour of coal bearing strata measures, especially sandstone large scale had been obviously fitted to the Burger rheological model. The sample test with 250 mm x 250 mm of the shear plane showed a decreasing of shear strength greater than core sample test with the diameter of 45 mm.
b. Long-term shear strength of sandstone can be determined based on the laboratory test result, and it is obtained that there is a relationship

between the scale effect and the rock long term strength.

c. In the next research, more scale variation of shear plane is needed to be done to get more detailed of result.

ACKNOWLEDGEMENT

The authors wish to extend their gratitude to all the final year students who participated in conducting to shear and shear creep studies of the mentioned coal bearing strata, and laboratory technician and mechanics (Mr. Sudibyo and Mr. Suparman) without whom the research work would have not possibly been well performed. Our sincere thanks are also due to the Management of PT. Adaro Indonesia who has provided invaluable support to these studies.

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