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Residual shear strength of shales from the Gemas Formation based on ring shear tests

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Abstract: Fresh, dark grey to black, shales with minor sandstones of the Triassic Gemas Formation outcrop at the slope cut between Km 81.30 and 81.05 (southbound) of the North-South Expressway near Ayer Hitam in Johore State. The beds strike 165^o with eastward dips of 35^o to 43^o and have thickness of between 0.2 and 1.5 m. Over-lying the fresh bedrock along an irregular boundary is a bleached zone, some 14 to 18 m thick, comprising light grey to white, *in situ* oxidized shales and sandstones. Three samples were collected from a thick shale bed; fresh samples A and B at 18 m and 15 m depth, respectively, and a bleached shale sample C at 11 m depth. All samples were air dried, finely ground, and then passed through a wire mesh sieve with 180 µm aperture sieve. The remoulded samples were tested with the Bromhead ring shear apparatus, employing the pre-shearing test procedure with multi-stage loading. Plots of shear stress versus cumulative horizontal shear displacement under low normal stresses (<150 kPa) yield failure envelopes with residual friction angles of 27.4^o, 27.4^o and 27.9^o for samples A, B, and C, respectively. Under moderate to large normal stresses (150-350 kPa), plots of shear stress versus linear displacement sometimes slope upward due to increased friction as a result of sample extrusion and settlement of the top platen. It is concluded that the pre-shearing test procedure with multi-stage loading is best suited for low to moderate, effective normal stresses (<250 kPa). Based on the test results, the residual friction angle for shales from the Gemas Formation is between 27^o and 28^o.

Keywords: Gemas Formation, shale, ring shear tests, residual friction angle

INTRODUCTION

In the case of most landslides, the formation of a shear zone or shear surface involves disruption of an existing fabric and its replacement by a fabric dominated by the effects of shear (Bromhead, 1986). This alteration of the fabric results in a decrease in the strength properties of earth materials. The shear strength with the original material fabric is known as the "peak strength", and the strength under large shear deformation is known as the "residual strength" (or also sometimes called the ultimate or large deformation strength) (Bromhead, 1986).

The shear box has been widely used to obtain the peak shear strength parameters of soil and, has in more recent years been modified to determine the residual strength by continual forward and reverse shearing of a sample. The ring shear apparatus developed by Bishop *et al.* (1971) allows a continuous shearing of sample in one direction as does the less sophisticated Bromhead ring shear apparatus which has become more widespread in use for it is relatively easier to operate. Test results obtained using the Bromhead apparatus, however, have been treated with some reservation by practicing engineers on the grounds that the determined residual friction angles are under-estimates of the true values (Hawkins & Privett, 1985). Hawkins & Privett (1985) have shown that for remoulded samples, similar results can be obtained using the Bromhead apparatus as that obtained using the conventional reversal shear box.

The Bromhead ring shear apparatus allows testing of an annular sample, some 5 mm thick with inner and outer diameters of 70 and 100 mm, respectively that is confined radially between concentric rings (Bromhead, 1979). The sample is compressed vertically between porous bronze loading platens by means of a counter balanced 10:1 ratio lever loading system. A rotation is then imparted to the base plate and lower platen by means of a variable speed motor and gearbox driving through a worm drive. This causes the sample to shear close to the upper platen which is artificially roughened to prevent slip at the platen/soil interface (Wykeham Farrance, 1988). Settlement of the upper platen during consolidation or shear can be monitored using dial gauge mounted on top of the load hanger.

In a comprehensive literature review, Rigo *et al.* (2006) noted that the residual strength of transported soils and soils resulting from weathering of sedimentary rocks is extensively described in the geotechnical literature with well-known examples being the over-consolidated clays, clays and clay shales of northern Europe and North

America. Rigo *et al.* (2006) also noted that there is a significant lack of published data on the residual strength of soils in tropical areas.

In Peninsular Malaysia, there is limited published data on the residual shear strength of both fresh and weathered sedimentary and metamorphic rocks. The shear strength of mudstones from the Triassic Semanggol Formation at the Muda Dam in Kedah State was reported to be close to the residual value with a good correlation between field and laboratory determined residual friction angles (φ_r) of 17.5° to 19° (James, 1969). Field and laboratory shear tests on undisturbed and remoulded samples of sheared mudstones from the Muda Dam were also reported to yield a residual friction angle of 18°, whilst peak shear strengths were more variable (Clarke *et al.*, 1970). In Singapore, a basic friction angle (φ_b) of 32° has been determined from portable shear box tests on rough sawn, sandstone blocks from the Triassic Jurong Formation (Pitts, 1988).

Soil shear box tests along a pre-cut surface in weathered graphitic-quartz-mica schist under low normal stresses (<10 kPa) and limited displacements have yielded a residual friction angle of 26.5° (Raj, 1988). Bromhead ring shear tests on the weathered graphitic-quartz-mica schist furthermore, have been shown to be only reliable for low normal stresses (<150 kPa), yielding residual friction angles of 24.7° to 25.8° (Raj, 2019).

In this short note are presented the results of laboratory tests carried out with the Bromhead ring shear apparatus to determine the residual shear strength of fresh and bleached shale exposed at a slope cut close to Air Hitam in Johore state.

METHODOLOGY

Slope cuts for the construction of the North-South Expressway in Peninsular Malaysia have led to several exposures of completely to slightly weathered, and fresh bedrock. One of these cuts is between Yong Peng and Ayer Hitam in Johore State, where fresh (unaltered) and bleached sedimentary strata of the Gemas Formation are exposed (Figure 1). Three samples were collected at different depths along a single thick shale bed at the cut to determine the residual shear strength of fresh and bleached shale. Samples A and B of fresh, dark grey shale were collected at 18 m and 15 m depths, whilst sample C of bleached shale was collected at a depth of 11 m (Plate 1).

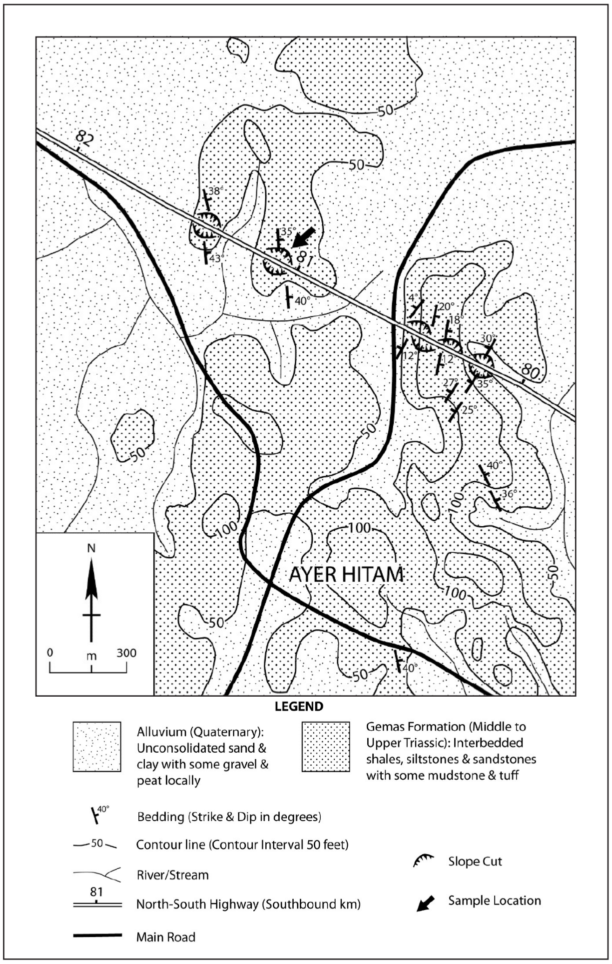

Figure 1: Geology map of the Air Hitam area, Johore. (After Sanisah binti Ahmad, 1992; Wahid Abdul Rahman, 1983)

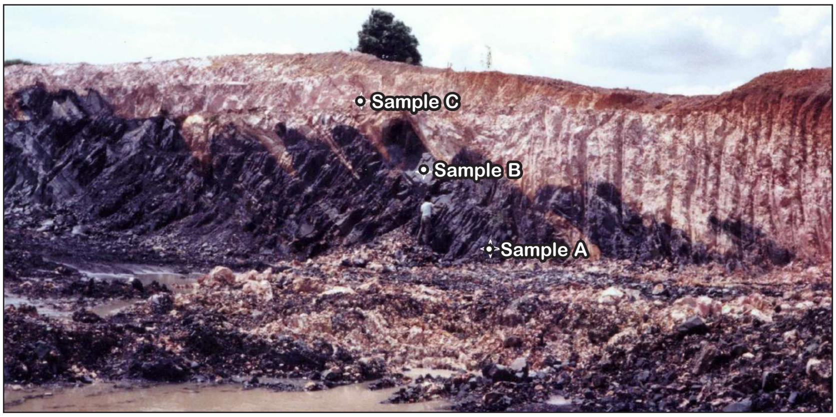

Plate 1: Outcrop showing bleached (pallid) zone over fresh bedrock and location of samples A, B and C.

The samples were first air dried, and then finely ground with a mortar and pestle before being passed through a 180 µm wire mesh sieve. Densities, unit weights and apparent porosities of representative specimens of the three shale samples were also determined employing the saturation and bouyancy technique described in ISRM (2007).

Several test procedures have been proposed for the Bromhead ring shear apparatus; the first being the single stage procedure which provides a good estimate of the residual strength at effective normal stresses below 200 kPa (Stark & Vettel, 1992). The pre-shearing procedure facilitates creation of a shear plane and reduces the length of horizontal displacement needed to reach the residual condition, though there is often extrusion of a substantial amount of soil during the shearing (Wykeham Farrance, 1988; Anayi *et al.*, 1988). In the multi-stage procedure, an additional strength often develops during consolidation and shearing, probably due to wall friction as the top platen settles into the specimen container (Stark & Vettel, 1992). The flush procedure has also been proposed where increasing the thickness of the specimen prior to shear reduces the wall friction and thus gives a more reliable results (Stark & Vettel, 1992).

The pre-shearing test procedure with multi-stage loading was adopted for this study as this is the procedure recommended by the manufacturer of the Bromhead ring shear apparatus (Model WF36859) (Wykeham Farrance, 1988). A displacement rate of 0.048 mm/min was adopted for shearing of the samples. The average effective shear stress acting on the pre-formed slip surface was calculated from the recorded values of two load gauges and this plotted against the corrected average linear displacement calculated from the recorded values of angular displacement. The effective shear stress at maximum corrected linear displacement plotted against the effective normal stress then defined the "complete failure envelope" which actually represents the Mohr-Coulomb failure envelope (Lambe & Whitman, 1973; Hawkins & Privett, 1985).

GEOLOGICAL SETTING OF SAMPLING SITE

The sampling site is located between km 81.30 and 81.05 (southbound) of the North-South Expressway where a slope cut exposes fresh and unaltered, dark grey to black, shales and fine-grained sandstones (Figure 1). The shales are the predominant lithology with individual bed thickness between 0.5 and 1.5 m whilst the sandstone beds are 0.2 to 1.0 m thick. Joints of variable orientations and lengths are present in the beds which strike about 165^o, and dip eastwards at 35^o to 43^o.

In the top three benches of the slope cut, the shales and sandstones are white to light grey in color and form a distinct bleached or pallid zone, some 14 to 18 m thick (Plate 1). The bleached zone overlies the fresh (unaltered) bedrock along an irregular boundary controlled by the overlying topography and inherent bedding (Plate 1). Seepage has been observed and indicates the presence of an unconfined groundwater table located at the bottom of the bleached zone. The bleached zone has thus developed from *in situ* alteration of the strata due to lowering of the groundwater table and aeration of bedrock. Bleaching (i.e. loss of original dark grey to black colors) is thus considered to result from oxidation of organic materials originally present in the bedrock.

Correlation with surrounding areas shows the bedrock to be part of the Gemas Formation which mainly consists of rapidly alternating inter-beds of shale, sandstone, tuff, and tuffaceous sandstone and shale, with minor lenticular bodies of conglomerate and limestone (Wahid Abdul Rahman, 1983). Several fossil locations have been found with faunal assemblages of shell imprints of pelecypods and ammonites yielding a reliable Middle to Upper Triassic age (Lum, 1982).

RESULTS

Physical properties of shale samples

Physical properties of the three shale samples show slight variations with the fresh samples A and B having an almost similar dry density and unit weight of 2,536 and 2,533 kg/m^3, and 24.87 and 24.91 kN/m^3, respectively (Table 1). The bleached shale sample C however, shows dry density of 2,231 kg/m^3 and dry unit weight of 21.88 kN/m^3. Some variations of apparent porosities have been observed, with the fresh shale samples A and B having values of 6.4%, and 7.1%, respectively, while the bleached shale sample C has a porosity of 11.4% (Table 1).

Linear effective shear stress versus corrected linear displacement

Plots of effective shear stress versus cumulative corrected horizontal displacement for low normal stresses (0-150 kPa) for sample A are shown in Figure 2. Plots for low to moderate normal stresses (<250 kPa) of samples B and C are shown in Figures 3 and 4. The plots indicate smooth sliding surfaces with little resistance to displacement due to the parallel alignment of the silt-, and clay-, sized particles during shearing. This feature is similar to that reported by Vaughan (1988) for sedimentary soils, where there is increasing orientation of the low-friction, platy shaped clay particles along slip surfaces with increasing shear displacement.

For moderate normal stresses (150-250 kPa) for sample A (Figure 2), and high normal stresses (250-350 kPa) for samples B and C (Figures 3 and 4) however, the plots appear to slope upward, indicating an increase of resistance with respect to the shear displacement. Observations during testing show that there was extrusion of sample from the sample container during the consolidation and shearing stage under moderate to high normal stresses (>150 kPa). This observation may

Table 1: Physical properties of shale samples from the Gemas Formation.

Sample Number	Lithology (Vertical Depth)	Dry Density (kg/m³)	Saturated Density (kg/m³)	Apparent Porosity (%)	Dry Unit Weight (kN/m³)	Saturated Unit Weight (kN/m³)
A1	Fresh Shale (18 m depth)	2,588	2,649	6.1	25.38	25.98
A2		2,480	2,541	6.2	24.32	24.92
A3		2,547	2,611	6.4	24.98	25.60
A4		2,530	2,599	6.9	24.81	25.49
Average		2,536	2,600	6.4	24.87	25.56
B1	Fresh Shale (15 m depth)	2,581	2,653	7.2	25.31	26.02
B2		2,502	2,577	7.5	24.80	25.44
B3		2,560	2,624	6.4	25.10	25.73
B4		2,490	2,563	7.2	24.42	25.13
Average		2,533	2,604	7.1	24.91	25.58
C1	Bleached Shale (11 m depth)	2,305	2,432	12.7	22.60	23.85
C2		2,157	2,258	10.1	21.15	22.14
Average		2,231	2,345	11.4	21.88	23.00

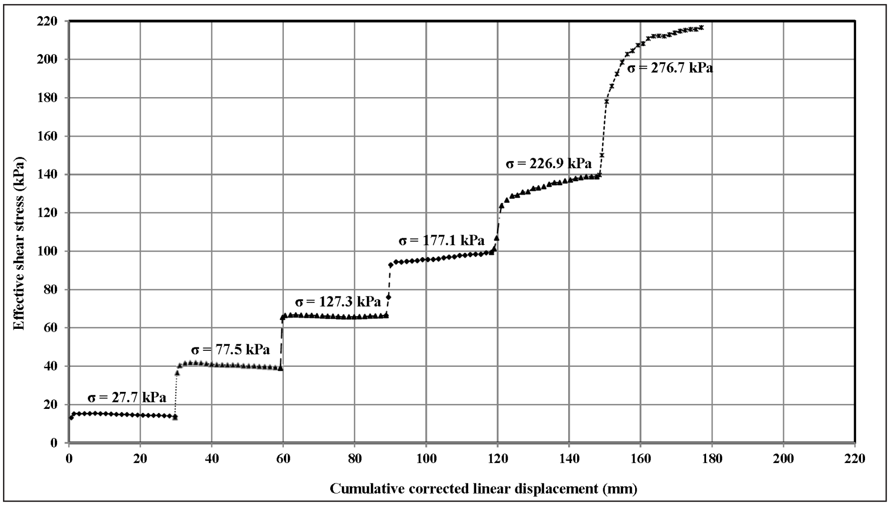

Figure 2: Effective shear stress versus cumulative corrected linear displacement - Shale sample A.

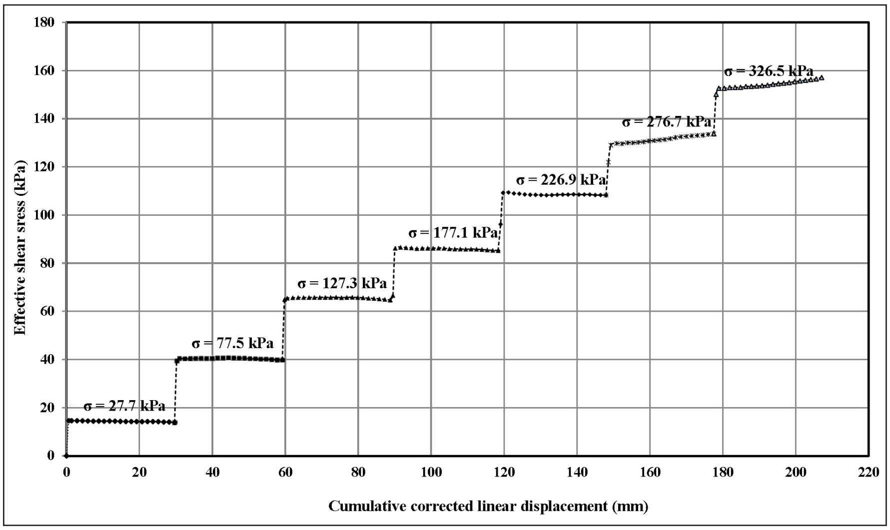

Figure 3: Effective shear stress versus cumulative corrected linear displacement - Shale sample B.

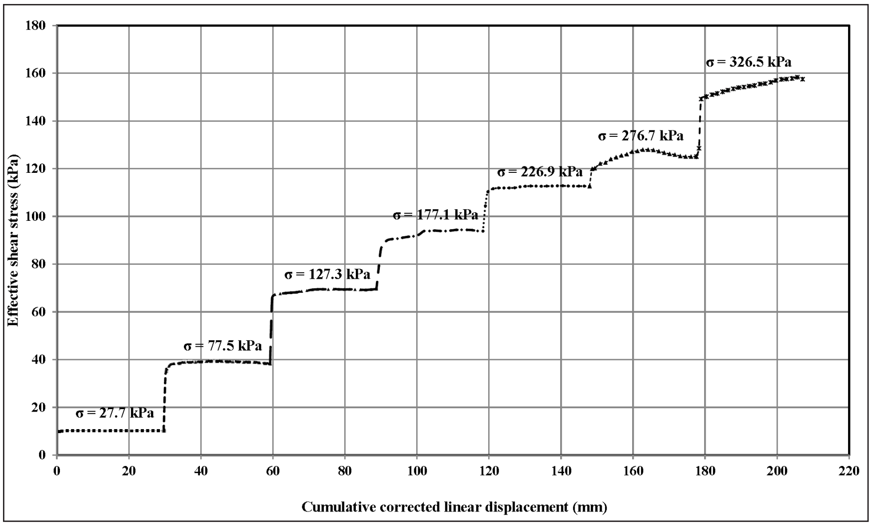

Figure 4: Effective shear stress versus cumulative corrected linear displacement - Shale sample C.

Table 2: Analyses of results of Bromhead ring shear tests in terms of Mohr-Coulomb failure envlope.

Linear Equation	Normal Stress (kPa)	Residual Friction Angle (φ°)	R^2
Sample A: y = 0.5175x kPa	0 - 150	27.4	1.0000
Sample B: y = 0.5192x kPa	0 - 150	27.4	0.9997
Sample C: y = 0.5292x kPa	0 - 150	27.9	0.9840
Sample B: y = 0.4909x kPa	0 - 250	26.1	0.9952
Sample C: y = 0.5147x kPa	0 - 250	27.2	0.9913

Note: R^2 = Correlation coefficient

imply the limitation of the multi-stage loading procedure for there is an increased wall friction due to sample extrusion and settlement of the upper platen into the specimen container during shearing (Stark & Vettel, 1992; Raj, 2019). Extrusion of sample during pre-shearing may also contribute to the increased wall friction (Wykeham Farrance, 1988; Anayi *et al.*, 1988).

Failure envelope

Analysis of Bromhead ring shear tests involves determination of the residual friction angle from the gradient of the linear relationship between the average effective shear stress and effective normal stress, i.e. the plot which defines the "complete failure envelope" (Hawkins & Privett, 1985). This plot represents the Mohr-Coulomb failure envelope which is a line drawn tangent to the Mohr circles plotted to represent the state-of-stress at the peak points of stress-strain curves of soil shear strength tests (Lambe & Whitman, 1973). The "complete failure envelope" has been shown to be a curve in many Bromhead ring shear tests, and it was suggested by Hawkins & Privett (1985) that the residual friction angle is dependent upon the effective normal stresses acting along the sliding plane.

For the tested samples, distinctive linear failure envelopes are obtained for low effective normal stresses (<150 kPa); the gradients yielding residual friction angles of 27.4°, 27.4° and 27.9° with correlation coefficients exceeding 0.98 for samples A, B and C, respectively (Table 2). For samples B, and C furthermore, linear failure envelopes are obtained for low to moderate effective normal stresses (0-250 kPa). The gradients yield residual friction angles of 26.1° and 27.2°, with correlation coefficients exceeding 0.99 (Table 2). A failure envelope for sample A under moderate effective normal stress (150-250 kPa), however, was not considered due to erroneous test results resulting from sample extrusion. Exclusion of test results for samples B and C under large effective normal stress (250-350 kPa) is also due to the same reason.

DISCUSSION

The results clearly show that the pre-shearing test procedure with multi-stage loading is only applicable to determining the residual shear strength of the fresh and bleached shale under low to moderate effective normal stresses (<250 kPa). Tests at greater effective normal stress may lead to extrusion of sample during consolidation and shearing and result in higher friction in the sample.

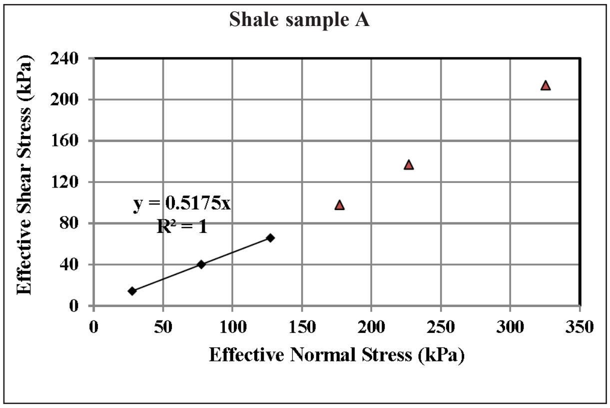

Figure 5: Effective shear stress versus effective normal stress (complete failure envelope) - Shale sample A.

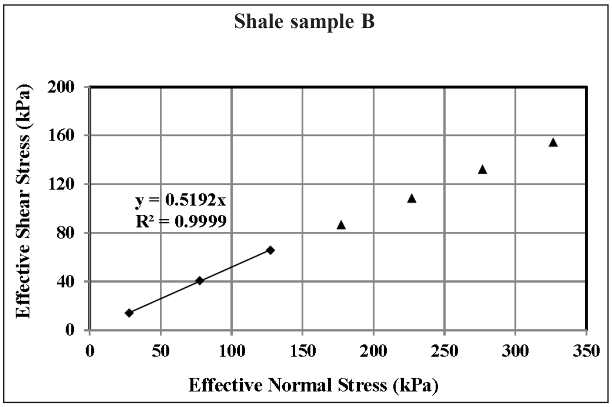

Figure 6: Effective shear stress versus effective normal stress (complete failure envelope) - Shale sample B.

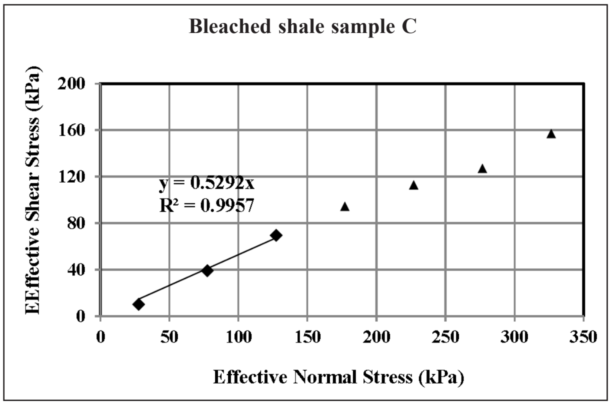

Figure 7: Effective shear stress versus effective normal stress (complete failure envelope) - Shale sample C.

The results also show that under low to moderate, effective normal stresses (<250 kPa), there is very little difference in the value of the residual friction angle (φ_r) for both the fresh (unaltered) and bleached shale samples (Table 2). Bleaching of the shales thus has little effect on its' residual shear strength.

CONCLUSION

It is concluded that bleaching has had little effect on the residual shear strength of shakes from the Gemas Formation; fresh shale having a residual friction angle of 27.4^{o,} and bleached shale, an angle of 27.9^{o}. It is further concluded that the pre-shearing test procedure with multi-stage loading is ideally only applicable to determination of the residual shear strength of the shales under low to moderate, effective normal stresses (<250 kPa).

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