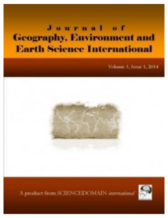

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The Schist Enclaves of Oban Massif, Southeastern Nigeria: Consistency of Dihedral Angle and Other Natural Physical and Mechanical Properties

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Authors' contributions

This work was carried out in collaboration between all authors. Author MIO designed and wrote the protocol of the study. Author AEA managed the literature searches, wrote the first draft of the manuscript and analyzed the data. Author EU managed the data analysis process and appraised data quality. All authors read and approved the final manuscript.

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ABSTRACT

The schist enclaves of Oban massif, southeastern Nigeria were deformed predominantly by brittle deformation and contain a plethora of fractures such as joints and conjugate shear fractures. Analysis of the conjugate shear fractures using stereographic projection technique and statistical methods reveal a consistency in dihedral angle (2θ) in the different schist enclaves studied, irrespective of location. The most frequently occurring (2θ) values range from 55°-60° in this basement terrain and this indicates that the schists were deformed mainly by brittle deformation under similar depth of burial, confining pressure and metamorphic level. The natural angle of internal friction (ϕ) range from 20°-40° while the coefficient of internal friction (μ) range from 0.3 - 0.8. These values lend credence to the dihedral angle (2θ) by being consistent in all the schist enclaves. The natural earth pressure coefficient (K) mostly ranges from 2.0 to 4.0 and this implies that the schists of Oban massif even though somewhat variable in mineralogy, have a moderate natural competence. From all indications, natural rock deformation in a quarzo-feldspathic rock mass at the level that schistose grade is produced, may generate dihedral angles mainly in the range of 55°-60°.

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1. INTRODUCTION

The knowledge of the natural mechanical properties of rocks is fundamental to many branches of earth science and engineering. The mechanical properties of a rock depend on its mineral composition, arrangement of its mineral grains and cracks that may have been introduced into it during its long geological history by diagenesis or tectonic forces [1]. Consequently, fractures and discontinuities in rocks play an important role in determining their mechanical properties and their usage to solve foundation and other geotechnical problems. Deformation in rocks is not a random process, rather it is associated with the laws of mechanics and prevailing environmental conditions [2], hence, studying the propagation of structural features such as conjugate shear fractures in rocks is vital to revealing some of the natural mechanical properties of such materials.

Conjugate shear fractures are the results of differential movements of rock masses along different planes that intersect [3]. Sets of fractures that represent complementary intersecting shear pairs whether locally or regionally are referred to as conjugate sets [4]. Fractures constituting a conjugate pair are formed at the same time (co-genetically developed), under the same stress field with a dihedral angle (2Θ) often greater than 45° and usually between 40°-60° [5–6]. The dihedral angle of conjugate shear fractures increases with depth (confining pressure) and varies from one lithology to another and with changes in deformation mechanism and levels of metamorphism [4,7–9].

The schist enclaves of Oban massif contain a plethora of joints and shear fractures which on analysis of the conjugate shear fractures using stereographic projection technique and other statistical tools, revealed a consistent dihedral angle within the region. The natural angle of internal friction (ϕ), coefficient of internal friction (μ) and the natural earth pressure Coefficient (K) lend credence to the dihedral angle (2Θ).

2. LOCATION AND GEOLOGY OF STUDY AREA

Oban massif is one of the basement areas in Cross River State, southeastern Nigeria (Fig. 1).

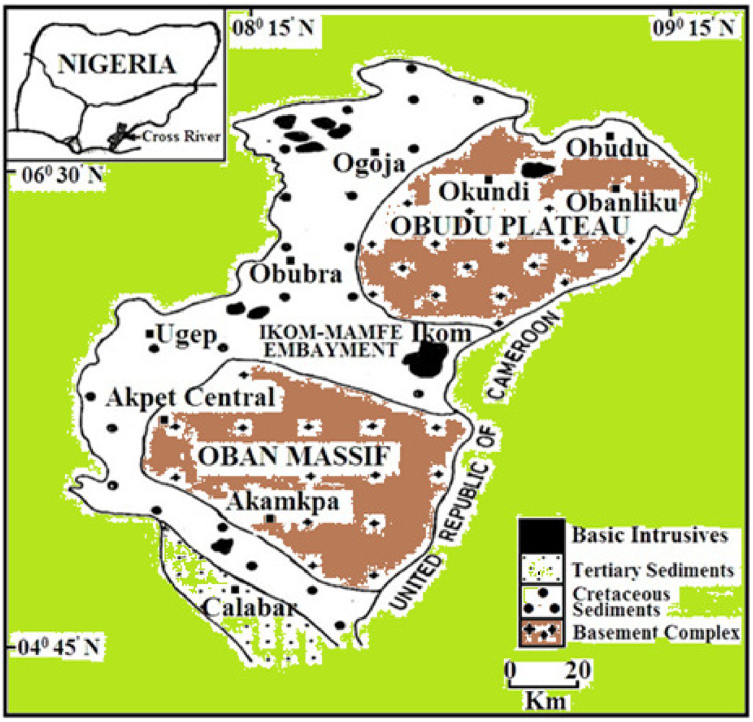

Fig. 1. Map of cross river state showing the basement areas. After [10]

It is a western extension of the Adamawa plateau [10]. This basement complex is bounded between $8°02^{I}$E and $8°54^{I}$ E longitudes and latitudes $5°00^{I}$N and $5°50^{I}$ N.

It covers about 10,000 km^2 and is composed of Precambrian basement, which is overlain in the south by Cretaceous to Tertiary sediments of the Calabar Flank. Metamorphic rock units such as schists, gneisses, phyllites and amphibolites constitute this basement with igneous intrusions such as granites, diorites, granodiorites, tonalites, pegmatites, monzonites, dolerites and charnockites [11–12]. Enclaves of phyllite and schist are more extensive in the western part of Oban massif; however, a syntectonic granitoid (Uwet granodiorite) also dominates this region [13–14]. The eastern part of this basement complex comprises dominantly of migmatite gneiss and granite gneisses [11]. The presence of schists of various grades in Oban massif region of southeastern Nigeria has been reported by [10–11,15]. Although the schists within this basement complex are not as extensive as those in the western part of the country [16–18], they occur as enclaves with reasonable extent within the Oban basement. Of interest to this work are the schist enclaves and the way they deform within this Precambrian Basement complex.

3. MATERIALS AND METHODS

This study involves a field work exercise spanning over a period of three weeks. Field exposures of schists in Akparavuni, Agoi Ibami, Calaro plantation, Ikot Ana (all in the western part of Oban massif) and Kwa falls in the southeastern part of the study area were studied with particular attention paid to the conjugate shear fractures thereof in the different locations. The attitudes of one hundred and ninety five (195) conjugate shear fracture sets were measured from the areas of interest. Thirty eight (38) pairs of conjugate fracture data were from Akparavuni schist, fifty (50) from Agoi Ibami, thirty (30) from Calaro plantation, fifty (50) from Ikot Ana and twenty seven (27) pairs from Kwa falls schist. The collected data were subjected to standard structural analytical (stereographic projection) technique to obtain the dihedral angles. Some natural mechanical properties (ϕ, μ and K) of this material were also obtained using the following mathematical relationships which were all derived from the Coulomb fracture criterion;

$$\phi = 90^{o} - 2\Theta \tag{1}$$

$$\Theta = \frac{90^{o} - \phi}{2} \tag{2}$$

$$\mu = \tan \phi \tag{3}$$

$$K = \frac{(1+\sin\phi) \text{ or } [(\mu^2+1)^{1/2}+\mu)]^2}{(1-\sin\phi)} \tag{4}$$

Where, ϕ is angle of internal friction, Θ is the angle between the fracture surface and the direction of the maximum principal stress, μ is coefficient of internal friction and K is earth pressure coefficient.

4. RESULTS

4.1 Conjugate Shear Fractures

Conjugate shear fractures are generally of tectonic origin and were encountered in the schist enclaves of Oban massif (Fig. 2a-e). The conjugate shear fractures in the study area trend mainly in NE-SW and NW-SE directions, however, a few pairs are oriented in the NNW-SSE and E-W directions. The dip angles of these shear fracture planes are predominantly between 60° and 70° (Fig. 3a-f) however, some shear fractures occur with lower and higher dip angles between 44° -50° and 70°-80° respectively, but these are in the minority. The most frequently occurring dip angle of the conjugate shear fractures is 65°. No conjugate fractures with dips of 90° were measured or observed in any of the schists.

4.2 Dihedral Angle (2θ) of Conjugate Shear Fractures

The acute angle existing between the two shear fractures of a conjugate pair- dihedral angle (2Θ) has been shown to be sensitive to the confining pressure [4,8]. The dihedral angles (2Θ) existing between the conjugate shear fractures obtained within this study area were statistically analysed and histograms were plotted to obtain the most frequently occurring values of 2Θ. They were then compared for all the locations under study. The dihedral angles (2Θ) of conjugate fractures in Akparavuni schist ranged from 41° to 80°, with the most frequently occurring values between 55°- 60° (Fig.4a). Dihedral angles from the other four locations (Agoi Ibami, Calaro plantation, Ikot Ana and Kwa Falls) also show a similar behavior, having 55°- 60° as their most frequently occurring values (Fig. 4b - e). Although 2Θ value as low as 37° and as high as 87° were recorded in Ikot Ana (Fig. 4e).

Fig. 2. Conjugate shear fractures in schists of the study area; (a) Akparavuni (b) Agoi Ibami (c) Calaro plantation (d) Ikot Ana (e) Kwa falls

From the analysis, dihedral angles between 55°-60° are most frequently occurring and constitute 26.66% of the general data population. Dihedral angles between 51°-55° and 61°- 65° constitute 18.46% each of the total data population, while values between 46°-50° and 71°-75° make up 7.69% each. 2Ө values between 66°-70° make up 10.76%, while dihedral angles between 31°-35°, 36°- 40°, 41°- 45°, 76°- 80°, 81°- 85° and 86°- 90° make up 0.51%, 1.02%, 3.58%, 4.10 %, 0.51% and 0.51% respectively (Table 1). From these values, it appears that the most frequently occurring dihedral angle in the schist enclaves range from 55°-60°, (Fig. 4f) and this was consistent in all the locations.

4.3 Angle of Internal Friction (ϕ)

The angle of internal friction (ϕ) in the study area is consistent in all the locations visited (Fig. 5a - e). ϕ values from the entire area are mainly between 21° and 40° (Fig. 5f) and these account for 78.87% of the total data population. ϕ values above 60° were not obtained in the study area and those between 1° and 20° constitute 14.35% of the total data population, while ϕ angles between 41° and 60° represent 9.74% of the total data points (Table 2). The most frequently occurring value of ϕ in all the sub-areas studied is in the range of 31°-35° (average is 33°).

4.4 Coefficient of Internal Friction (µ)

The natural coefficient of internal friction (µ) is also consistent in all the locations studied and the values were mostly between 0.3 and 0.8 (Fig. 6a - e), making up 85.64% of the total data population with the most frequently occurring value of 0.7 (Fig. 6f) constituting 23.59% of the data. Values of μ between 0.1-0.2, 0.9-1.3 and 1.7- 1.8 constitute 3.59%, 9.93% and 1.02% of the total data population respectively, but values between 1.4-1.6 were not found in the study area and those between 1.7 and 1.8 were only recorded in Ikot Ana (Table 3).

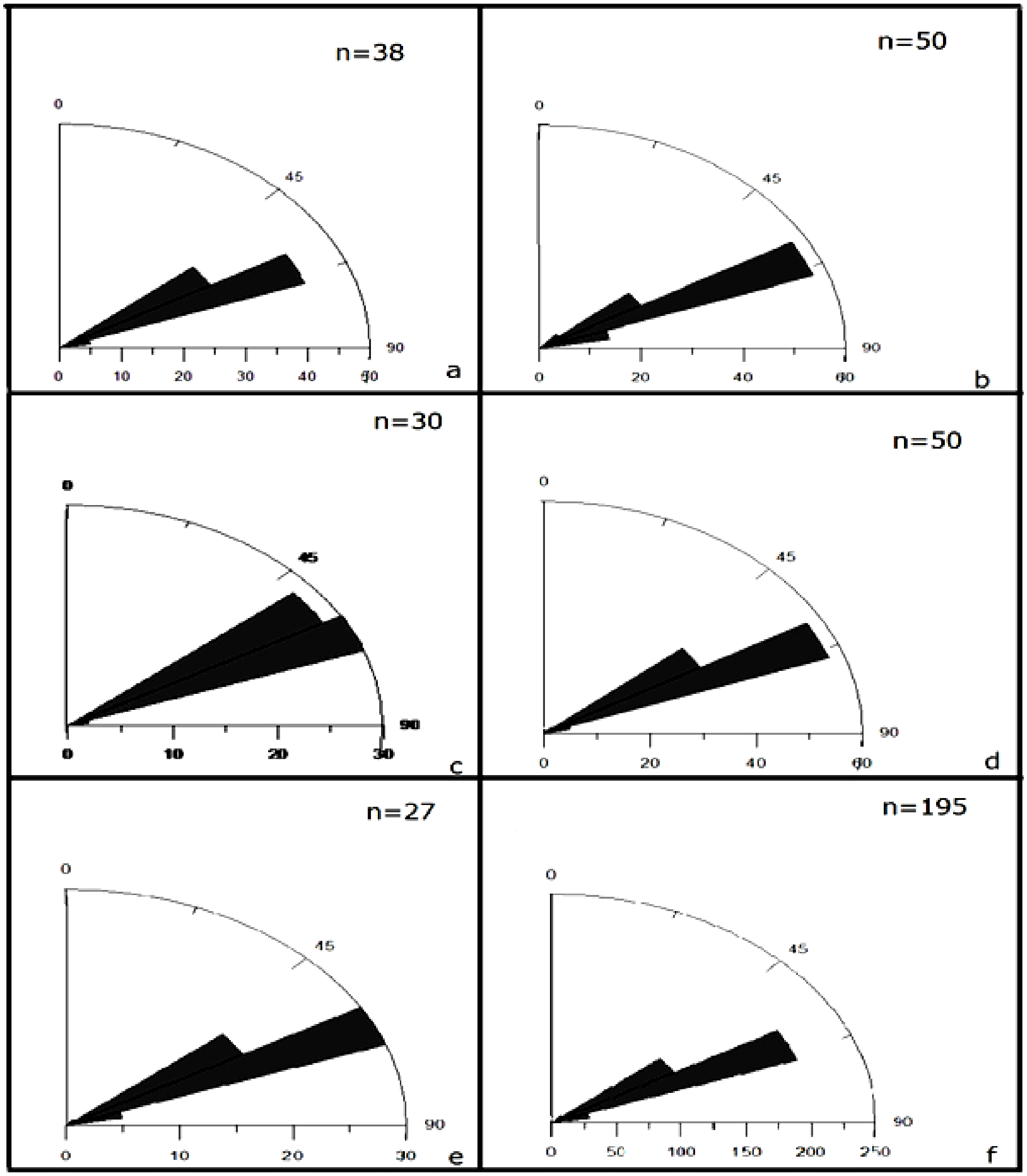

Fig. 3. Dips of conjugate shear fractures in schists of the study area; (a) Dip of conjugate fractures in Akparavuni schist, (b) Dip of conjugate fractures in Agoi Ibami schist. (c) Dips of conjugate fractures in Calaro plantation schist, (d) Dip of conjugate fractures in Ikot Ana schist, (e) Dip of conjugate fractures in Kwa falls schist, (f) Combined dip of conjugate fractures in the study area

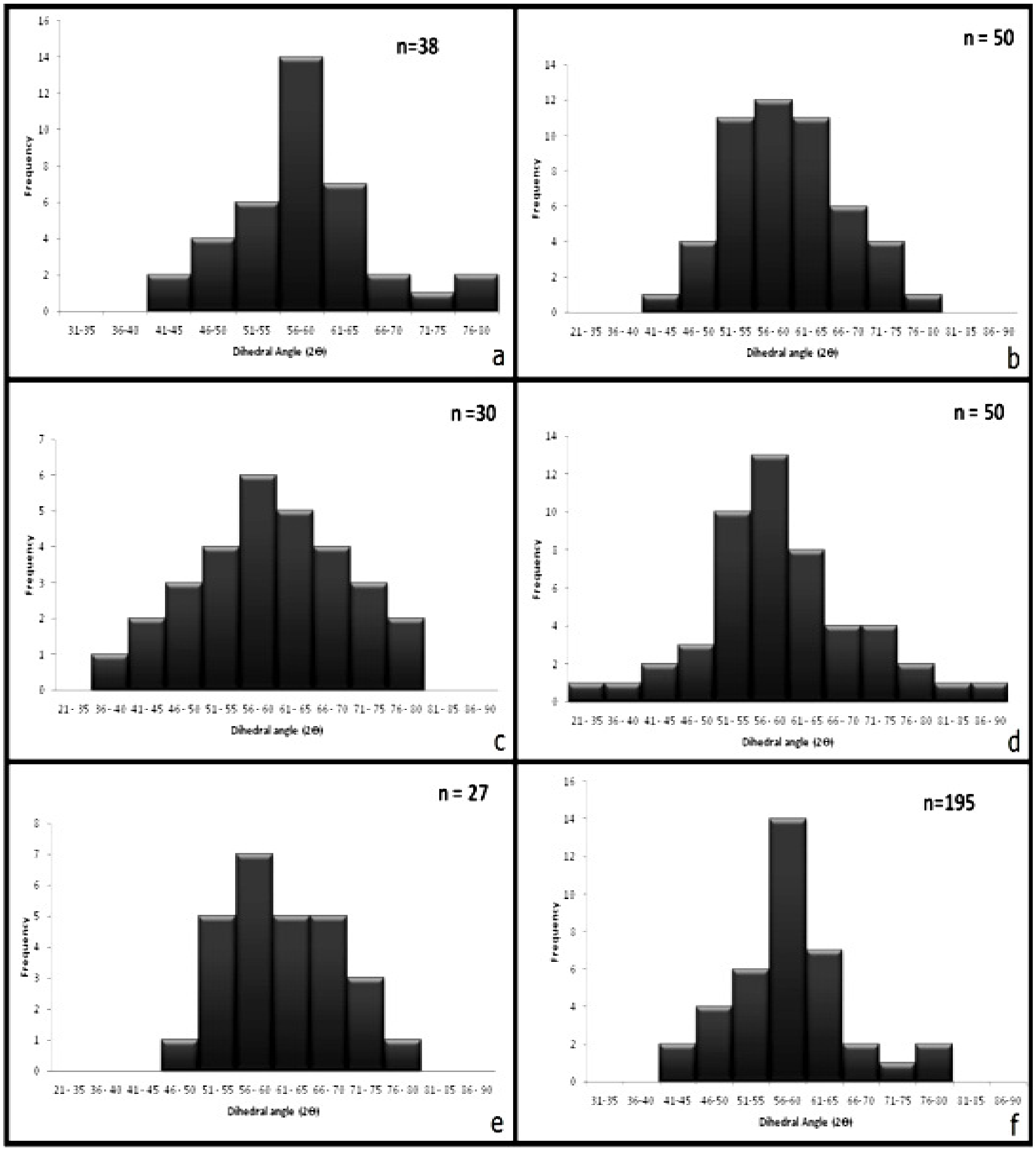

Fig. 4. Histograms of Dihedral angles (2Θ) in schists of the study area; (a) Dihedral angles (2Θ) in Akparavuni, (b) Dihedral angles (2Θ) in Agoilbami, (c) Dihedral angles (2Θ) in Calaro plantation, (d) Dihedral angles (2Θ) in Ikot Ana, (e) Dihedral angles (2Θ) in Kwa falls, (f) Combined dihedral angles (2Θ) in the study area

4.5 Earth Pressure Coefficient (K)

The natural earth pressure coefficient (K) in the schist enclaves of Oban massif also displays consistent values and the most frequently occurring K value is between 3.00 and 3.99 (Fig. 7a - f). Values of K within this area are within 1.00-6.99, consisting about 98.47% of the total data population. The maximum K value recorded in this region was 13.00 and this was obtained from Ikot Ana area, while values ranging from 9.00 to 12.99 were not measured (Table 4). From the most frequently occurring values of K (3.00 -3.99), the schists can be classified as moderately competent during their natural deformation.

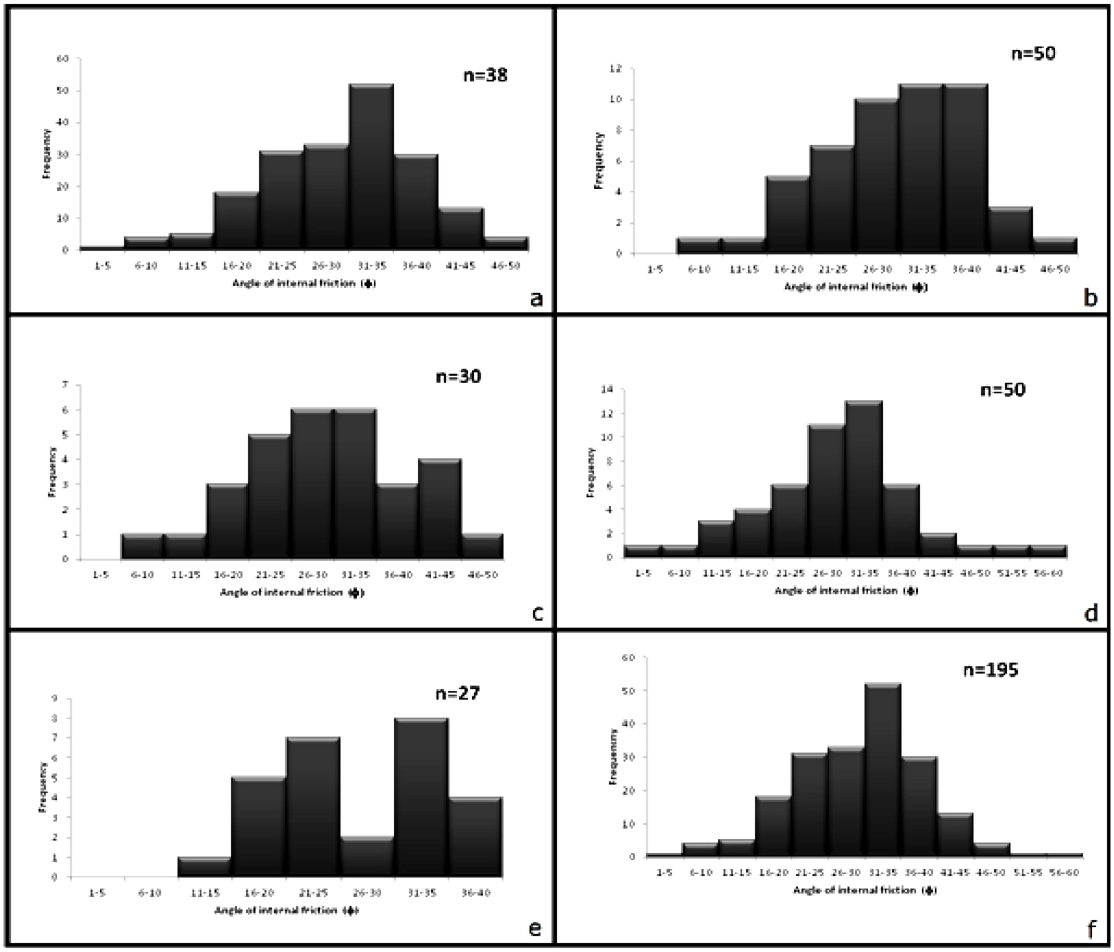

Fig. 5. Histograms of angle of internal friction (*ϕ*) for schist in the study area; (a) angle of internal friction (*ϕ*) in Akparavuni schist, (b) angle of internal friction (*ϕ*) in Agoi Ibami schist, (c) angle of internal friction (*ϕ*) in Calaro plantation schist, (d) angle of internal friction (*ϕ*) in Ikot Ana schist, (e) angle of internal friction (*ϕ*) in Kwa falls schist, (f) combined angle of internal friction (*ϕ*) in schists of the study area

Table 1. Frequency of dihedral angle (2Θ) distribution and percentage frequency in schists of Oban massif

S/N	Dihedral angle(2Θ) interval (°)	Dihedral angle (2Θ) frequency in various locations					Composite (2Θ) frequency	Percentage frequency (%)
		Akparavuni	Agoilbami	Calaro plantation	Ikot Ana	Kwa Falls		
1.	31 - 35	-	-	-	1	-	1	0.51
2.	36 - 40	-	-	1	1	-	2	1.02
3.	41 - 45	2	1	2	2	-	7	3.58
4.	46 - 50	4	4	3	3	1	15	7.69
5.	51 - 55	6	11	4	10	5	36	18.46
6.	56 - 60	14	12	6	13	7	52	26.66
7.	61 - 65	7	11	5	8	5	36	18.46
8.	66 - 70	2	6	4	4	5	21	10.76
9.	71 - 75	1	4	3	4	3	15	7.69
10.	76 - 80	2	1	2	2	1	8	4.10
11.	81 - 85	-	-	-	1	-	1	0.51
12.	86 - 90	-	-	-	1	-	1	0.51
		38	**50**	**30**	**50**	**27**	**195**	**100**

Table 2. Frequency of angle of internal friction (ϕ) intervals and percentage frequency

S/N	Angle of internal friction (°) interval	Angle of internal friction (ϕ) frequency in various locations					Composite (ϕ) frequency	Percentage frequency (%)
		Akparavi	Agoilbami	Calaro Plantation	Ikot Ana	Kwa Falls		
1.	1 – 5	-	-	-	1	-	1	0.51
2.	6 – 10	1	1	1	1	-	4	2.15
3.	11 – 15	1	1	1	3	1	5	2.56
4.	16 – 20	1	5	3	4	5	18	9.63
5.	21 – 25	6	7	5	6	7	31	15.89
6.	26 – 30	4	10	6	11	2	33	16.92
7.	31 – 35	14	11	6	13	8	52	26.66
8.	36 – 40	6	11	3	6	4	30	15.38
9.	41 – 45	4	3	4	2	-	13	6.66
10.	46 – 50	1	1	1	1	-	4	2.15
11.	51 – 55	-	-	-	1	-	1	0.51
12.	56 - 60	-	-	-	1	-	1	0.51
		38	**50**	**30**	**50**	**27**	**195**	**100**

Table 3. Frequency of coefficient of internal friction (µ) interval and percentage frequency

S/N	coefficient of internal friction (µ)	Coefficient of internal friction (µ) frequency in various locations					Composite (µ) frequency	Percentage frequency (%)
		Akparavuni	Agoi Ibami	Calaro Plantation	Ikot Ana	Kwa Falls		
1.	0.1	-	-	-	2	-	2	1.03
2.	0.2	1	1	1	1	3	5	2.56
3.	0.3	1	4	3	7	4	18	9.23
4.	0.4	1	5	3	4	6	17	8.72
5.	0.5	7	11	5	8	4	37	18.97
6.	0.6	6	8	4	8	7	30	15.38
7.	0.7	12	10	7	10	2	46	23.59
8.	0.8	4	7	2	4	-	19	9.74
9.	0.9	2	2	1	-	-	5	2.56
10.	1.0	2	1	3	3	-	9	4.62
11.	1.1	1	-	1	-	-	2	1.03
12.	1.2	1	1	-	-	-	2	1.03
13.	1.3	-	-	-	1	-	1	0.51
14.	1.4	-	-	-	-	-	-	-
15.	1.5	-	-	-	-	-	-	-
16.	1.6	-	-	-	-	-	-	-
17.	1.7	-	-	-	1	-	1	0.51
18.	1.8	-	-	-	1	-	1	0.51
		38	**50**	**30**	**50**	**27**	**195**	**100**

5. DISCUSSION

This study investigated the natural mechanical properties of the schist enclaves of Oban massif. The use of stereographic projection technique to analyse conjugate shear fractures in the schist enclaves of Oban massif shows that 2Θ is mainly between 55° and 60° which indicates that the deformation is mainly brittle and its consistency in all the locations. This is an indication that these materials were deformed at the same confining pressure, depth of burial or metamorphic grade.

The way confining pressure relates with dihedral angle in experimentally deformed rocks is shown graphically by [4,8]. At constant confining pressure, the deformation of a rock type will produce a constant dihedral angle (2Θ). This angle increases as the confining pressure increases. From this analysis, it could be concluded that natural rock deformation in a quartzo-feldspathic rock mass at the level that schistose grade is produced, will result in dihedral angles mainly in the range of 55°-60°.

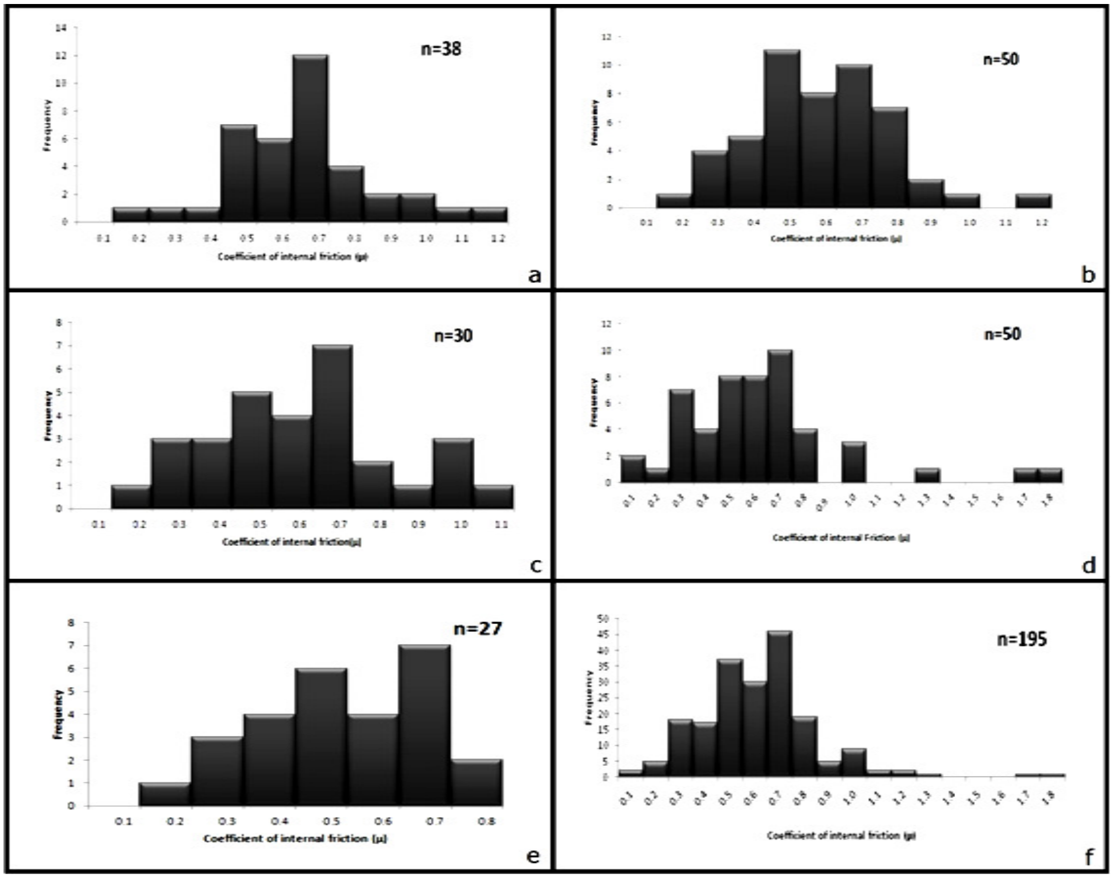

Fig. 6. Histograms of coefficient of internal friction (μ) for schist in the study area; (a) coefficient of internal friction (μ) in Akparavuni schist, (b) coefficient of internal friction (μ) in Agoilbami schist, (c) coefficient of internal friction (μ) in Calaro plantation schist, (d) coefficient of internal friction (μ) in Ikot Ana (e) coefficient of internal friction (μ) in Kwa falls schist, (f) combined data of coefficient of internal friction (μ) in the study area

Table 4. Frequency of earth pressure coefficient (K) intervals and percentage frequency

S/N	Earth pressure coefficient (K) interval	Earth pressure coefficient (K) frequency in various locations					Composite (K) frequency	Percentage frequency (%)
		Akparavuni	Agoi Ibami	Calaro plantation	Ikot Ana	Kwa Falls		
1.	1.00 - 1.99	3	5	4	9		25	12.82
2.	2.00 - 2.99	8	17	9	12		56	28.72
3.	3.00 - 3.99	18	17	10	19		75	38.46
4.	4.00 - 4.99	4	6	2	5		18	9.23
5.	5.00 - 5.99	4	4	4	2		15	7.69
6.	6.00 - 6.99	1	-	1	1		3	1.54
7.	7.00 - 7.99	-	1	-	-		1	0.51
8.	8.00 - 8.99	-	-	-	1		1	0.51
9.	9.00 - 9.99	-	-	-	-		-	-
10.	10.00 -10.99	-	-	-	-		-	-
11.	11.00 -11.99	-	-	-	-		-	-
12.	12.00 - 12.99	-	-	-	-		-	-
13.	13.00 - 13.99	-	-	-	1		1	0.51
		38	**50**	**30**	**50**	**27**	**195**	**100**

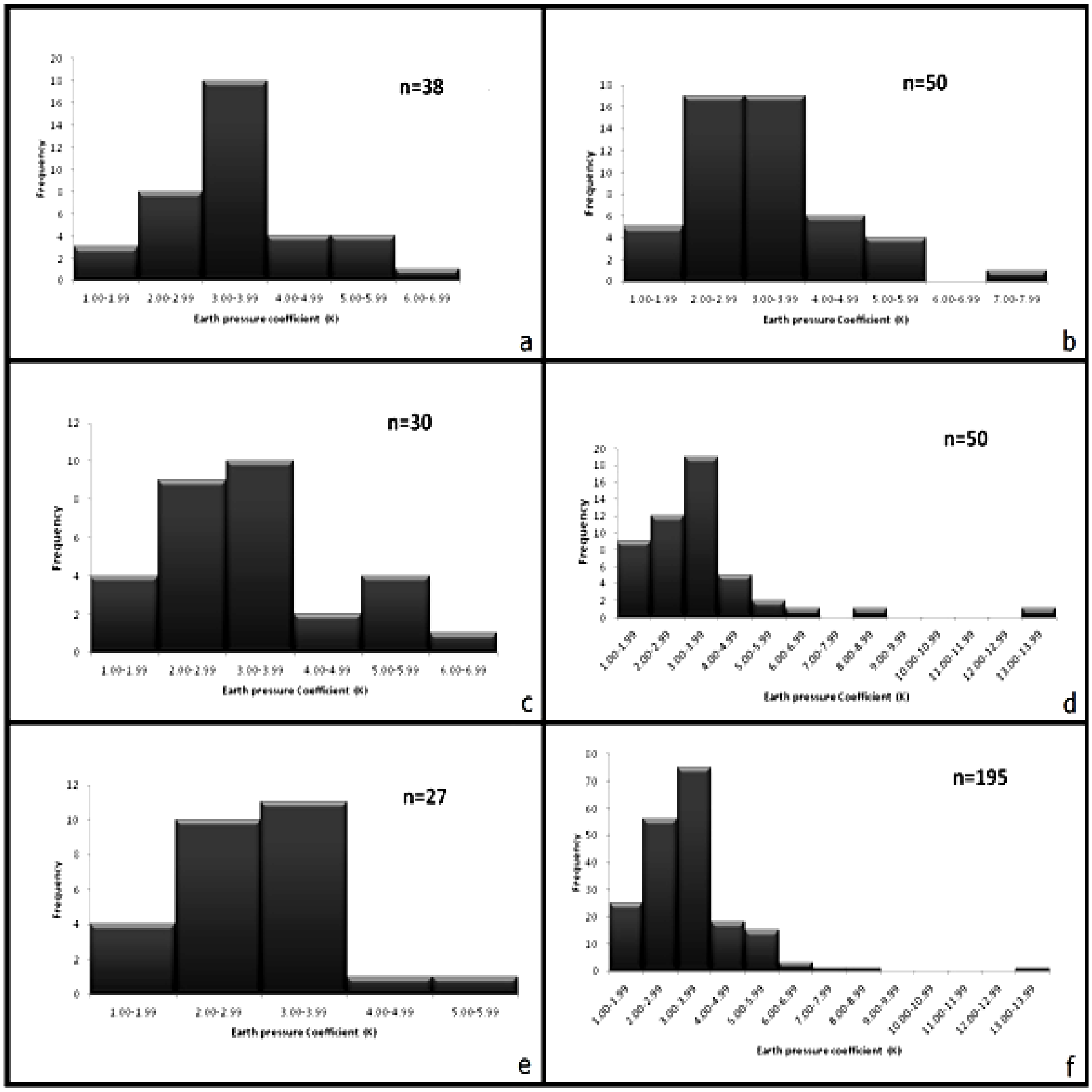

Fig. 7. Histograms of earth pressure coefficient (K) for schists in the study area; (a) earth pressure coefficient (K) in Akparavuni schist, (b) earth pressure coefficient (K) in Agoi Ibami schist, (c) earth pressure coefficient (K) in Calaro plantation schist, (d earth pressure coefficient (K) in Ikot Ana schist, (e) earth pressure coefficient (K) in Kwa falls schist, (f) combined earth pressure coefficient (K) in the study area

The Navier-Coulomb criterion of brittle failure is the simplest and most used criterion. This criterion is very vital in understanding rock deformation and is based upon the concept that shear failure will only occur along a potential surface when the shear stress (τ) acting on the plane is large enough to exceed the original cohesive shear strength (τ_o) of the material combined with the product of the normal stress (σ_n) and coefficient of internal friction (μ). This relationship which must be satisfied for shear fracture to develop is shown in Fig. 8. The straight line is the Mohr envelope and equation 3 and 5 define the relationship and slope respectively.

$$\tau = \tau_o + \sigma_n \tan \phi \qquad (5)$$

The angle of internal friction (ϕ) determines Θ (the angle between the maximum compressive principal stress and each of the fracture planes of a conjugate pair) and the departure of Θ from 45° (equation 1) varies with the value of ϕ [19].

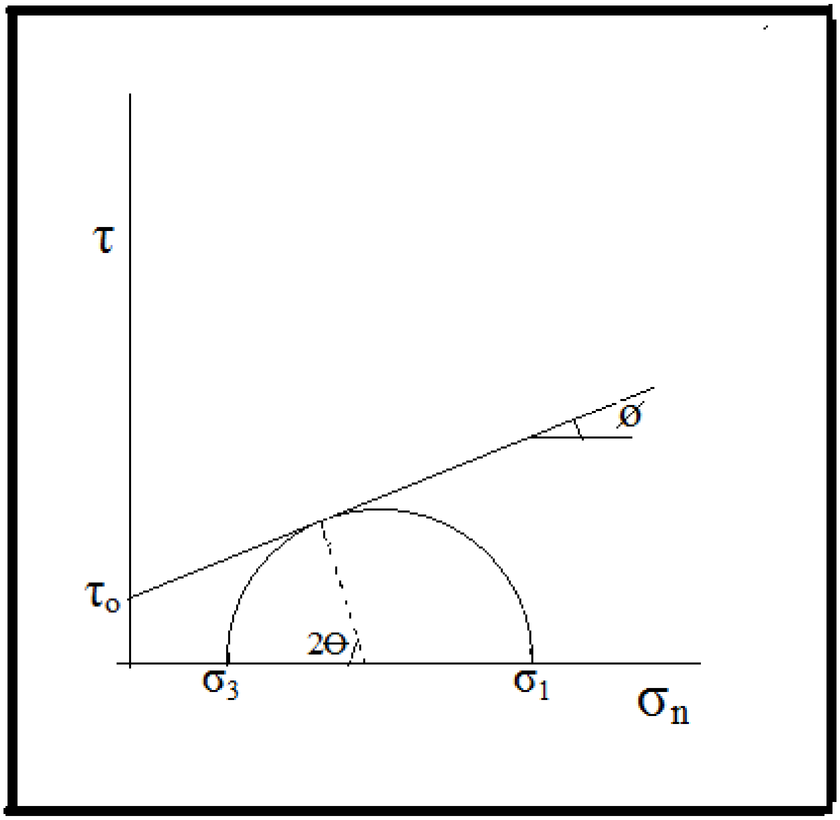

Fig. 8. Graphical representation of Navier-Coulomb criterion of brittle failure

Unlike extension fractures, conjugate shear fracturing is consistent with the Coulomb fracture criterion [7] and Coulomb's theory is also used to define the earth pressure coefficient (K) which is a property of the rock that is related to the competence of the rock material. The Coulomb fracture criterion (eq. 5) can be written in terms of the principal stresses in the form

$$\sigma_1 = C_o + K\,\sigma_3 \quad (6)$$

$$C_o = \sigma_1 - K\,\sigma_3 \quad (7)$$

where, C_o is the uniaxial compressive strength of the material, σ_1 and σ_3 are the maximum and minimum principal stresses, respectively.

The relationship between K and ϕ is shown in equation 4.

The natural mechanical properties are obtained simply by using the appropriate equations and substituting the measured parameters.

The angle of internal friction (ϕ) is a shear strength parameter. ϕ is the angular ratio between the normal shear stress and the normal stress that are attained when failure just occurs in response to a shearing stress. Its definition is derived from the Mohr- Coulomb failure criterion (Fig. 8) and the tangent of this angle is the coefficient of internal friction μ and this is often determined experimentally although the natural angle of internal friction can be obtained using the dihedral angle from conjugate shear fractures. The higher the dihedral angle between the two fractures constituting a set of conjugate shear fractures, the smaller is the angle of internal friction (eq.1). Since the dihedral angle (2Θ) of conjugate shear increases with depth and increasing confining pressure [6,20], it is safe to say that the angle of internal friction ϕ decreases with depth and increasing confining pressure. In this study, the angles of internal friction (ϕ) recorded in the schist enclaves of this basement area is consistent in all the locations and its value mostly ranges from 20°-40° (Fig. 5). The resistance to sliding at a fracture interface is usually expressed in terms of the coefficient of internal friction (μ), and it is defined as the ratio of shear force to normal force which is necessary either to initiate sliding or to maintain continuous sliding [8]. From the relation $\mu = \tan\phi$, μ is dependent on the angle of internal friction (ϕ)and they are similar parameters that characterize the failure properties of materials. They vary from one material or rock type to another (Twiss and Moores, 1992). [21] collated typical experimental values of μ for different rock types and the range was between 0.2 to 0.8. [8] also reported a range of experimental values of μ from 0.2 – 0.8 for a variety of rock types.

The values of natural coefficient of internal friction (μ) in the study area are consistent in the five locations studied and in these schist enclaves, they mostly range between 0.3-0.8 (Fig. 6). The earth pressure coefficient K is a property that is related to the competency of rock materials. Thus high values of K indicate high competence while a low K value is indicative of low competency. The value of earth pressure coefficient (K) helps us to predict how rock materials will behave in a differential stress field. A rock with good competency is capable of withstanding a higher differential stress than an incompetent material and this helps in predicting the kind of structures that would be associated with such a rock during deformation [22], although, other factors like depth of burial of the rock, the temperature condition at the time of formation, pore fluid and the nature of the surrounding rocks also influence the rock competency. Therefore, depending on these factors, a particular rock type may display different competency under different conditions. K under laboratory conditions usually shows values between 2.0-15.0 and moderately competent arenaceous rocks generally have experimental K values between 2.0 and 5.0, the more competent arenaceous rocks and competent limestones generally have values ranging from 5.0- 10.0 while igneous rocks usually have experimental K values above 10.0 [3]. The natural K values for the schist of Oban massif range between 2.0 -4.0 (Fig. 7). Following the grading of [3] for competency of rocks based on K values, these schists are said to be moderately competent. Considering the average values of the different mechanical properties for the schist enclaves of Oban massif, the most likely stress relations in the schists during the deformation that affected the schist enclaves are

$$\tau = \tau_o + 0.65\sigma_n \qquad (8),$$

and

$$\sigma_1 = C_o + 3.0\sigma_3 \qquad (9),$$

where 0.65 is the average $\tan\phi$ (= μ) and 3.0 is the average K value.

6. CONCLUSION

The study of the schist enclaves of Oban massif, southeastern Nigeriafrom the analysis of conjugate shear fractures using stereographic projection technique and statistical analysis reveals that the dihedral angles (2θ) and other mechanical properties of the different schist enclaves studied are consistent, irrespective of location. This consistency suggests that these rocks were most probably metamorphosed and deformed under similar conditions. The schistose grade of metamorphism in a quartzo-feldspathic rock mass undergoing natural deformation is probably most consistent with a dihedral angle of 55°-60° range. This range indicates a brittle deformation condition, while thenatural earth pressure coefficient (K) ranges from 2.0 to 4.0 suggesting that the schists of Oban massif, even though somewhat variable in mineralogy have a consistently moderate natural competence. Laboratory data on the physical and mechanical properties of schists are quite difficult to see due mainly to the presence of discontinuities and anisotropy in such rocks. It appears that nature has found a way around those difficulties.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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