Bull Eng Geol Environ (2008) 67:181–186
DOI 10.1007/s10064-008-0122-9

ORIGINAL PAPER

Relationship between cleavage orientation, uniaxial compressive strength and Young's modulus for slates in NW Spain

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Received: 11 August 2007 / Accepted: 21 December 2007 / Published online: 14 February 2008

Abstract Slates from North Western Spain have been studied to establish the influence of the cleavage orientation on the uniaxial compressive strength (UCS) and Young's modulus (E). Slate, sandstone and intercalated slate/sandstone lithologies were tested and the higher strengths were always obtained when the load was applied parallel, or close to parallel, to the slaty cleavage. This study suggests the following empirical relationships for unweathered slates in saturated conditions UCS $= 0.037\beta^2 - 7.622(\beta + 200.6$, $E \times 10^4 = 0.002\beta^2 - 0.134\beta + 3.453$. E can be estimated from UCS values using $E \times 10^4 = 429{,}56\ (\text{UCS})^{0.9122}$. These empirical equations will assist in geotechnical studies in this area of NW Spain where slate quarrying is an important industry.

Keywords Cleavage · Slates · Uniaxial compressive strength · Young's modulus · Casaio formation

Résumé Des ardoises du nord-ouest de l'Espagne ont été étudiées afin de mettre en évidence l'influence de la direction du clivage ardoisier sur la résistance à la compression simple (UCS) et sur le module de Young E. Des ardoises, des grès et des matériaux mixtes avec intercalations de lits gréseux et de lits d'ardoise ont été testés et les plus fortes résistances ont toujours été obtenues lorsque l'axe de chargement mécanique était parallèle ou sub-parallèle à la direction du clivage ardoisier. Cette étude conduit à proposer les relations empiriques suivantes, pour des ardoises saines et saturées: UCS $= 0{,}037\ \beta^2 - 7{,}622\beta + 200{,}6$ et $\text{E} \times 10^4 = 0.002\beta^2 - 0.134\beta + 3.453$. E peut être estime à partir de UCS par la relation: $\text{E} \times 10^4 = 429{,}56\ (\text{UCS})^{0{,}9122}$. Ces relations empiriques peuvent apporter une première aide dans la résolution de problèmes géotechniques dans cette région du NW de l'Espagne où l'industrie ardoisière joue un rôle important.

Mots clés Clivage ardoisier · Ardoises · Résistance à la compression simple · Module de Young · Formation de Casaio

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Introduction

This study shows the relationship between cleavage anisotropy, uniaxial compressive strength and Young's modulus for some slates from the northern border of Spain. These are important properties of metamorphic rocks with a high linear anisotropy in an area where there are a large number of quarries. Rock samples taken from the Truchas Syncline (NW Spain) were examined in the laboratory and their uniaxial compressive strength (UCS) and Young's modulus (E) values determined.

A number of research papers have described foliated rocks and related orientation with rock strength (e.g. Ramamurphy et al. 1993, Hawkins 1998; Bell 2000; Singh et al. 2002). Sachpazis (1990) has suggested formulae relating UCS and E for 33 lithological units including marble, limestone and dolomite, which has been applied in this study to slates.

Location and geology of the study area

Slates from the Casaio area in the south western zone of the Truchas Syncline in NW Spain (Fig. 1) have been examined.

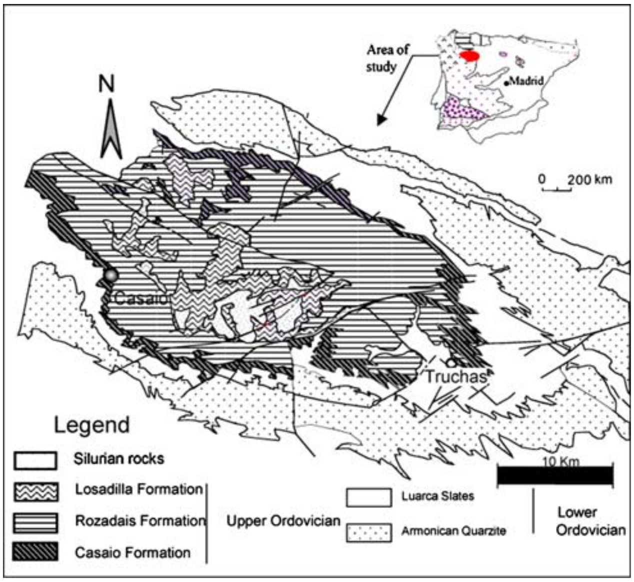

Fig. 1 Location and geology of the study area (Arias et al. 2002)

The Truchas Syncline is located in the Centroiberian Zone of the Iberian Variscan Belt (Lozte 1945; Jullivert et al. 1972; Farias et al. 1987; Arias et al. 2002).

During the Ordovician and Silurian, a marine basin existed in the Truchas area in which mudstones and sandstones accumulated. Subsequently, the mudstones were metamorphosed to slates and the sandstones to quartzites. A typical profile is given in Fig. 2. Unconformably overlying the Silurian rocks are Tertiary and Quaternary deposits.

Thin section examination of the slates indicated a good slaty cleavage in the fine-grained rocks, rough or spaced cleavage in the more silt-rich rocks and crenulations in some of the slaty material. The presence of chlorite as the main metamorphic mineral indicated that the rocks have experienced a low grade of metamorphism with temperatures of around 400°C and pressures of 300 MPa (Mesa López-Colmenar 2003).

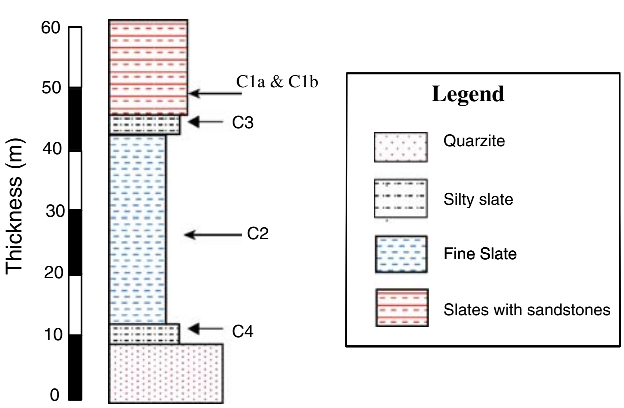

Fig. 2 Profile showing sampled lithologies

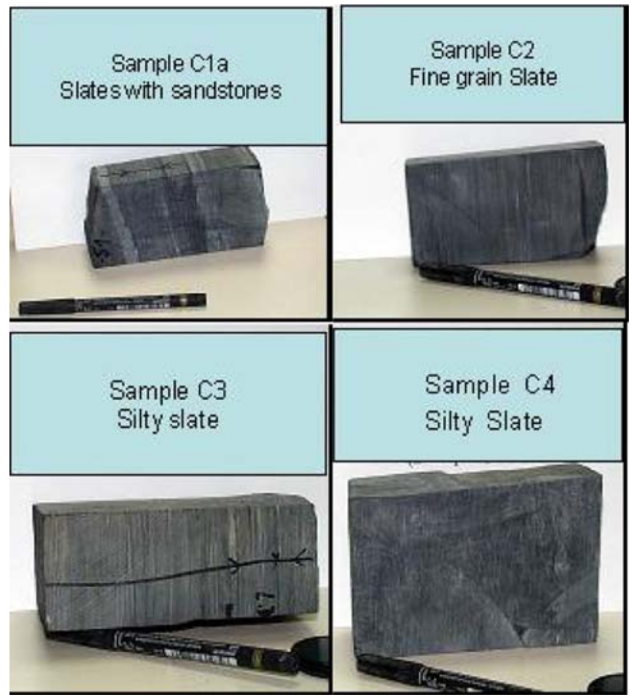

Fig. 3 Different lithological samples from the slates of the Casaio formation

The fine slate (C2 in Fig. 3) has been studied under the optical polarizing transmission and reflection microscopes. The mineralogical composition was recorded as muscovite (40%), quartz (35%) and chlorite (15%) with opaque minerals including magnetite, ilmenite, chalcopyrite, pyrite and sphalerite (7%) as well as plagioclase (2%) and

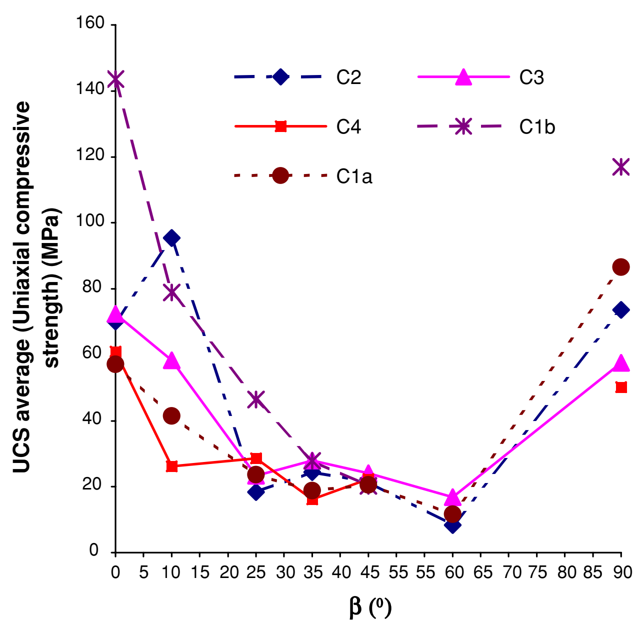

Fig. 4 Relationship between UCS value and orientation of the cleavage of the five different lithological types (Table 1)

Table 1 UCS test results for the five lithological types

Slate type	β (°)		H/D	Uniaxial compressive strength (MPa)			
				Maximum	Minimum	Average	Standard deviation
C1a	0 (5)		2.59	92.1	4.4	57.08	32.85
	10 (5)		2.02	48.9	37.3	41.48	4.97
	25 (5)		1.33	32.98	13.69	23.66	8.94
	35 (5)		1.48	23.27	13.22	18.83	3.71
	45 (3)		2.17	27.8	6.7	20.63	12.07
	60 (3)		1.82	14.1	9.78	11.62	2.23
	90 (6)		2.62	105.6	71.2	86.35	14.37
C1b	0 (5)		2.30	151.6	132.8	143.60	6.84
	10 (5)		2.25	102.3	33.9	78.9	31.93
	25 (5)		2.0	55.6	31.37	41.51	9.17
	35 (4)		1.47	33.1	15.4	24.10	8.13
	45 (2)		2.33	24.1	16.5	20.30	5.37
	90 (5)		2.26	151.5	92.3	116.94	23.06
C2	0 (5)		2.34	132.7	25.5	70.1	39.88
	10 (5)		2.24	126.1	53.1	95.36	35.67
	25 (5)		1.87	28.95	10.79	18.42	7.66
	35	1 (5)	1.22	48.5	23.57	24.41	10.80
		2 (5)	2.48	25.0	17.7	22.02	3.35
	45	1 (4)	1.49	25.29	18.81	21.45	2.77
		2 (5)	2.26	13.2	6.9	10.75	2.75
	60	1 (5)	1.93	10.83	3.87	8.36	2.89
		2 (4)	2.19	13.4	6.38	13.39	6.03
	90 (5)		2.60	131.2	39.6	73.64	39.58
C3	0 (5)		2.67	109.8	48.8	72.36	23.50
	10 (5)		2.36	75.6	36.8	58.32	15.88
	25 (5)		1.83	37.52	14.97	23.35	10.30
	35 (5)		1.47	40.78	23.56	27.92	7.32
	45	1 (5)	1.31	31.16	20.33	24.12	4.26
		2 (3)	2.27	14.2	10.1	11.8	2.14
	60	1 (4)	1.30	20.23	15.25	16.81	2.33
		2 (3)	2.30	26.7	22.5	24.43	2.12
	90 (5)		2.59	97.2	34.5	57.56	24.35
C4	0 (5)		2.65	100.4	9.3	60.94	33.19
	10 (5)		1.9	44.54	2.33	26.15	20.77
	25 (5)		2.75	41.0	13.19	28.63	10.19
	35 (5)		1.31	20.63	10.2	16.21	3.26
	45 (6)		1.05	29.08	18.20	23.15	4.48
	90 (5)		2.61	107.9	10.3	50.18	35.88

The number of samples tested at each orientation shown in brackets

tourmaline, zircon and organic matter together <1%. The largest grain size was <0.3 mm for some rounded chlorite minerals while quartz and muscovite were generally <0.1 mm. Some silty/sandy material in 1.7–2.3 mm thick bands occurs occasionally, related to the original bedding stratification. The microstructure was established using the Bastida et al. (1984) and Passchier and Trouw (1996) criteria for slaty cleavage in slate material and rough cleavage in the silty sand deposits.

Material and methodology

Samples (200 × 200 × 200 mm) were taken from different lithological levels in a quarry situated in the Casaio Formation on the southern limb of the Truchas Syncline (Fig. 2).

The Casaio Formation in the quarry outcrops as layers of quartzite, fine grained black-grey slate (C2), silty grey slate with millimetre sized nodules of quartz and sulphur mineral concretions (C3) and grey slate with millimetre intercalations of sandstone 3–5 mm thick (C4). The C1 unit is divided into two: C1a when the stratification/bedding is at an angle of <20° to the cleavage plane and C1b when the stratification is vertical and the cleavage planes oblique with angles of 50° or higher (Rodríguez Sastre 2003).

As indicated by Brown et al. (1977), the rock strength obtained varies significantly with the relationship between the orientation and the cleavage. In this study, rock samples were tested at different orientations–0, 10, 25, 35, 45, 60 and 90° (Fig. 4).

All tests were undertaken on water saturated rocks. Although it was intended to undertake the tests on the NX-sized rock cores with a length: diameter ratio of 2.5:1 following ISRM (1981), as seen in Table 1 in fact there was a considerable variation in the height:diameter ratio which ranged from 0.15 to 2.75:1; this may well have affected the uniaxial compressive strength (UCS) and Youngś modulus (*E*).

Test results

Of the 43 block samples taken from the study area, 16 were fine slates, 14 were silty slates and 13 were slates with sandstone intercalations. On these, 175 uniaxial compressive strength (UCS) tests were carried out at the different orientations mentioned above. The variation of UCS with orientation angle (β) for all the slates is depicted in Fig. 4.

As seen in Table 1, the UCS values for the slates varied between 4.4 and 151.6 MPa. The average values are when the orientation was at 0 and 90° to the cleavage and the minimum at 60°. The highest values were for the slates with sandstone laminations perpendicular to the main foliation plane (C1b) and lowest for the fine slate (C2). When correlation between UCS and the orientation plane of the anisotropy was made, it was found that the best fit line was for the polynomial equation (Table 2). These results are consistent with those obtained by Brown et al. (1977) on slate samples from Delabole Quarry in south west England.

Table 2 Statistical results relating average UCS and angle of orientation of the cleavage

Sample	Equation correlation (average UCS/β (°))	R^2
C1a	$UCS = 0.028\beta^2 - 2.28\beta + 60.54$	0.94
C1b	$UCS = 0.053\beta^2 - 5.00\beta + 135.99$	0.98
C2	$UCS = 0.032\beta^2 - 3.07\beta + 89.91$	0.73
C3	$UCS = 0.023\beta^2 - 2.24\beta + 73.87$	0.94
C4	$UCS = 0.017\beta^2 - 1.55\beta + 52.87$	0.82

A further series of tests were undertaken on another 16 samples of fine slates (C2) to determine the uniaxial compressive strength (UCS) and Young's modulus (*E*) relative to the orientation of the cleavage (Figs. 5,6). In this case the two samples were tested for each orientation of cleavage. It was found that the UCS values ranged between

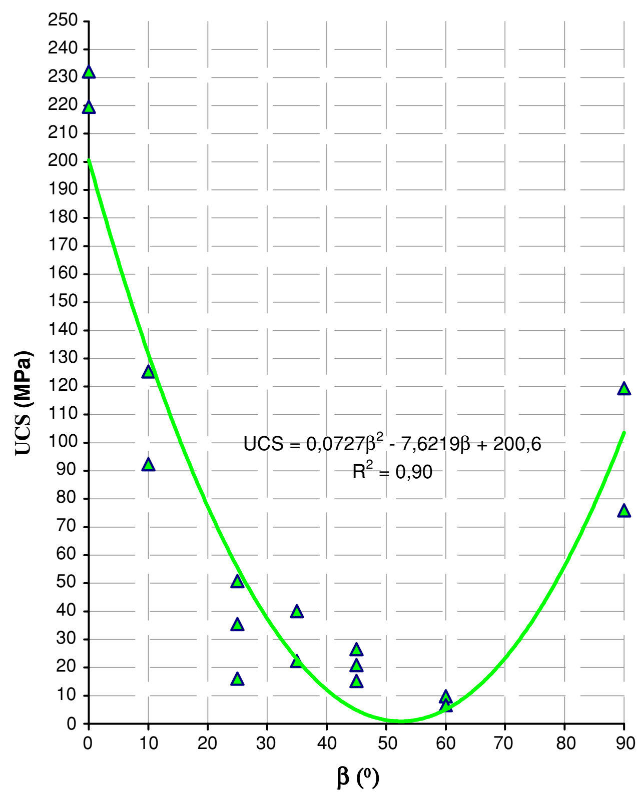

Fig. 5 Relationship between UCS value and orientation of the cleavage for C2 (fine slates)

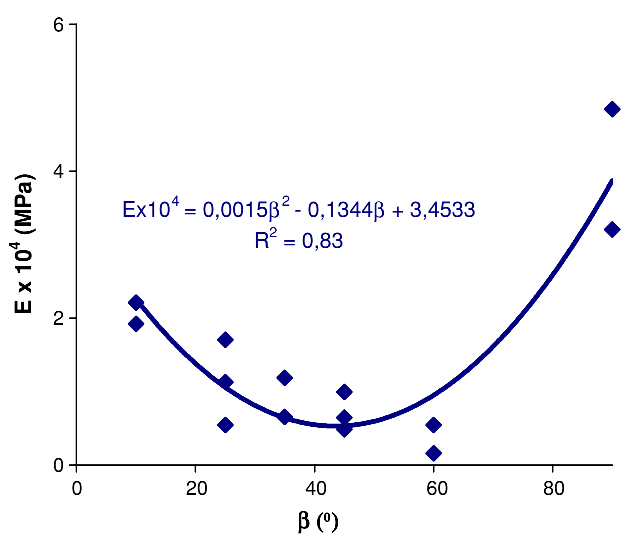

Fig. 6 Relationship between Young's modulus and the orientation of the cleavage for C2 (fine slates)

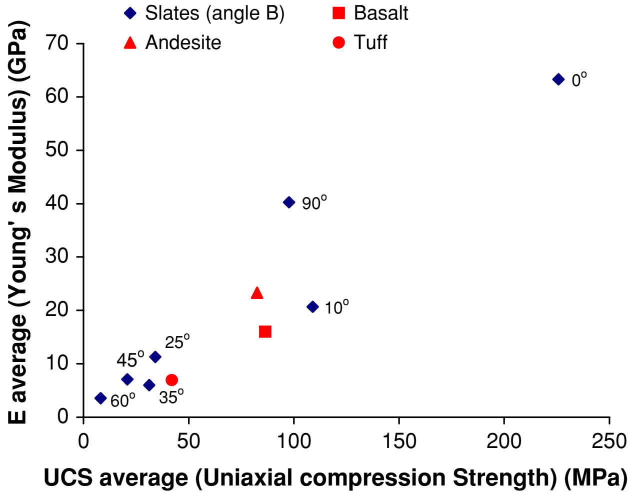

Fig. 7 Relationship between UCS and *E* values for C2 samples compared with the values for volcanic rock reported by Dinçer et al. (2004)

8.2 and 230 MPa whereas the Young's modulus varied between 3.5 GPa at 60° to 63.3 GPa when the stress was parallel to the cleavage (indicated as 0° in Fig. 7), and higher than those values reported by Dinçer et al. (2004).

Figure 8 presents the relationship between UCS and *E* in this study and the points from the empirical relationships proposed by Sachpazis (1990). Table 3 shows the equations proposed to relate *E* and UCS with the regression coefficient ($R^2 = 0.68$–0.90).

Discussion

Considerable differences are seen between the uniaxial compressive strength test results for the same lithologies

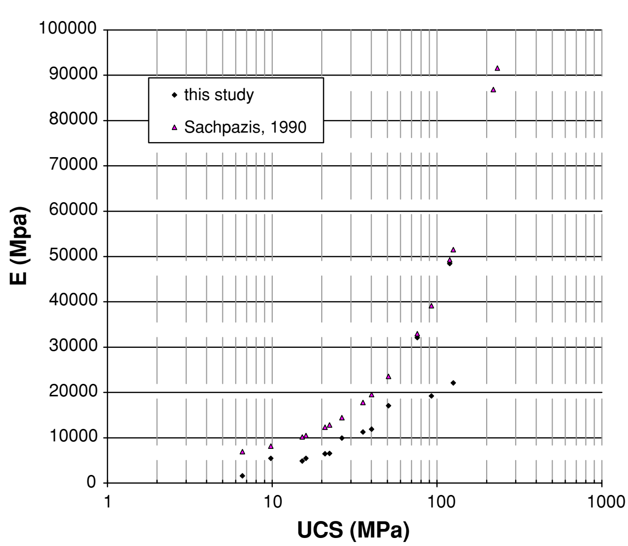

Fig. 8 Comparison of UCS and E values for C2 samples obtained in this study and those reported by Sachpazis (1990)

Table 3 Correlation of UCS and Young's modulus for the C2 samples

Type of model	Equation correlation (*E*/UCS)	R^2
Lineal	$E = 273.01\ (\mathrm{UCS}) + 1651.4$	0.739
Logarithmic	$E = 11541\ \mathrm{Ln(UCS)}\ -25724$	0.687
Polynomial	$E = -1.1789(\mathrm{UCS})^2 + 426.03\ \mathrm{(U)CS} - 1149.5$	0.751
Power	$E = 429.56\ (\mathrm{UCS})^{0.9122}$	0.900
Exponential	$E = 4249.7e^{\ 0.0188(\mathrm{UCS})}$	0.738

(C2) due to the high planar anisotropy present in these rocks. As can seen from Fig. 8, the values obtained by correlations proposed by other authors were similar to those observed in this study. This different levelling out of the results from Sachpazis can be explained by the wide variation in UCS values of the slate samples with orientations of 0 or 90° and the lower and closer UCS and *E* values obtained with inclinations of between 25 and 60°.

For the slates of the Casaio Formation the following empirical relationships have been derived between the UCS, *E* and orientation angle (β) of the cleavage of unweathered slates in saturated conditions:

$$\mathrm{UCS} = 0.0727\beta^2 - 7.6219\ \beta + 200.6$$

$$\mathrm{E} \times 10^4 = 0.0015\beta^2 - 0.1344\beta + 3.4533.$$

E can be estimated directly from the UCS value using the relationship:

$$\mathrm{E} \times 10^4 = 429,56\ (\mathrm{UCS})^{0.9122}.$$

Conclusions

By definition, slates are anisotropic. This work has separated four different types of slates depending on whether they contain sandstone or silt layers and whether they have inclusions. A study of the unconfined compressive strengths relative to various orientations of the cleavage has been undertaken. The highest UCS values were obtained when the cleavage was at right angles to or parallel with the applied stress, as expected. Whilst this is true for all the slates tested, it is particularly noticeable for the fine-grained slate (C2) which has strengths as low as 3.8 MPa at 50–60° but as high as 230 MPa parallel to the cleavage.

Comparing the UCS and *E* values obtained with those of Sachpazis (1990), it is noted that above 50 MPa the slates of the Casaio Formation do not increase in modulus as would be anticipated.

Acknowledgements Some part of the work presented in this paper has been taken from the PhD thesis of the first author. The authors gratefully acknowledge IGME for support with the geotechnical tests and the Secretary of Estate for Universities and Research for a postdoctoral award held at the British Geological Survey, through the Spanish Ministry of Education and Science, which is partly funded through the European Social Fund.

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