Strength anisotropies in mudrocks

R. Ajalloeian · G. R. Lashkaripour

Abstract Mudrocks exhibit a variation in compressive strength when the direction of the plane of weakness is varied with respect to the direction of the principal stresses. Uniaxial compression tests were performed on two anisotropic mudrocks (siltshale and mudshale). The sample laminations were at orientation angles of 0, 15, 30, 45, 60, 75 and 90° relative to the direction of loading. The anisotropy strength ratio (the ratio of the maximum compressive strength to the minimum strength) over the full range of the lamination orientations was determined. The results of the uniaxial compressive strength tests were compared with the strength anisotropy index ratio [$I_{S(50)}$] determined from the point load strength tests. The difference between the anisotropy ratios from the individual point load test results and from the uniaxial compressive test results indicates the difficulty of determining the anisotropy from point load tests.

Résumé Les argilites présentent une résistance à la compression variable suivant l'orientation des contraintes principales par rapport à l'orientation des plans de faiblesse du matériau. Des essais de compression simple ont été réalisés sur deux argilites anisotropes (une siltite et une argilite). Les lamines étaient orientées à 0, 15, 30, 45, 60, 75 et 90° par rapport à la direction du chargement. Le rapport d'anisotropie de résistance (rapport de la résistance maximale à la compression sur la résistance minimale) a été calculé à partir de l'ensemble des essais. Les résultats des tests de compression simple ont été comparés avec l'indice d'anisotropie de résistance [$I_{S(50)}$] déterminé à partir de tests de compression entre pointes. La différence entre les indices d'anisotropie déterminés à partir d'essais de compression entre pointes et les rapports d'anisotropie déterminés à partir d'essais de compression simple montre qu'il est difficile de quantifier l'anisotropie des argilites à partir des essais de compression entre pointes.

Keywords Mudrocks · Mudshale · Clayshale · Anisotropy · Point load · Uniaxial Compression

Mots clés Argilites · Anisotropie · Résistance · Essai de compression entre pointes · Essai de compression simple

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Introduction

The term "mudrock" in this study has been used for a general class of fine-grained sedimentary rock that includes claystone and clayshale, mudstone and mudshale, and siltstone and siltshale. This type of rock is formed in both marine and non-marine environments and is one of the most abundant sedimentary rocks. Tucker (1991) reported that mudrock is the most abundant of all lithologies, constituting some 45–55% of sedimentary rock sequences. Because of its abundance, mudrock is the most frequently encountered rock type in engineering construction. King et al. (1994) reported that mudrocks are found in many large civil engineering structures in the UK and elsewhere.

Rocks are anisotropic with regard to their mechanical behaviour. Well-defined anisotropy is found notably in sedimentary and metamorphic rocks. The anisotropy of mudrocks results from a partial alignment of anisotropic plate-like clay minerals with small thickness compared to the lateral dimension. All the sedimentary rocks exhibit maximum compressive strength in the direction perpendicular to the planes of anisotropy.

The anisotropic behaviour of mudrocks is considered to be of major importance in a number of key geotechnical structures, e.g. the design of tunnels, underground space, dams and the stability of rock slopes; hence it is of interest to many researchers.

Evaluation of anisotropic behaviour using strength tests

Theoretical and laboratory studies to estimate the strength and deformation properties of anisotropic rocks in relation to the anisotropy angle have been undertaken by many researchers (Lo and Hory 1979; Lekhnitskii 1981; Broch 1983; Singh 1988; Singh et al. 1989; Farough Hossaini 1993; Ghafoori et al. 1993). The degree of mechanical anisotropy in fine-grained sedimentary rocks can best be measured quantitatively using strength tests with loading at various orientations to the laminations, i.e. uniaxial or point load strength tests.

The uniaxial compression test

Uniaxial compression tests were carried out on two types of fissile mudrock from different sites. The International Society of Rock Mechanics (1981) suggested method for determination of uniaxial compressive strength was closely followed. In the literature, maximum compressive strengths are reported at angles of $\beta = 0$–$90°$ and minimum strengths at orientations of $\beta = 30$–$40°$, where β is the angle between the direction of the axial stress and the plane of weakness.

The sample laminations for this research were at orientation angles of 0, 15, 30, 45, 60, 75 and 90° to the direction of loading. Three uniaxial compressive strength tests were carried out for each orientation. The results indicated a variation in the compressive strength, deformation and wave velocity. In order to study the strength anisotropy, the results were plotted in the form of maximum axial stress against orientation (Fig. 1). As shown in this figure, the uniaxial compressive strength was at a maximum when the load was applied perpendicularly and at a minimum when $\beta = 30°$.

The shape of the curve relating the uniaxial compressive strength to the lamination angle can be predicted by an equation proposed by Singh et al. (1989) in the form:

$$\sigma_c = A - B[\cos 2(\zeta - \beta)] \quad (1)$$

where σ_c is uniaxial compressive strength at orientation angle β, ζ is value of the orientation angle, β, at which the strength is at a minimum (usually found to be approximately 30°), and A and B are material constants.

The values A and B may be determined over two sets by using the uniaxial compressive strength at $\beta = 0$ and 30° and at $\beta = 30$ and 90°. Strength prediction may be made using various values of β. The equations providing the best fit for the siltshale and mudshale respectively are as follows:

$$\sigma_c = 60.308 - 50.374[\cos 2(30 - \beta)] \quad (2)$$

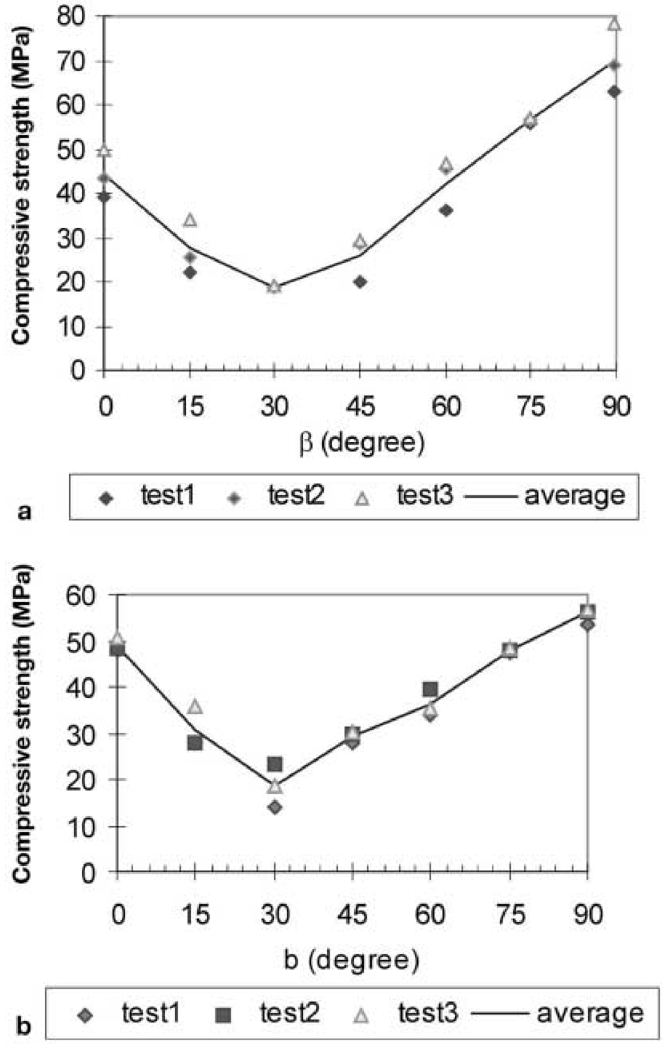

Fig. 1
Anisotropic behaviour of uniaxial compressive strength at different orientations to lamination planes; **a** siltshale and **b** mudshale

$$\sigma_c = 79.488 - 60.734[\cos 2(30 - \beta)] \quad (3)$$

for $0° \leq \beta \leq 30°$

$$\sigma_c = 50.032 - 34.089[\cos 2(30 - \beta)] \quad (4)$$

$$\sigma_c = 43.875 - 25.120[\cos 2(30 - \beta)] \quad (5)$$

for $30° \leq \beta \leq 90°$, where σ_c is the predicted value of uniaxial compressive strength in MPa.

The predicted values of uniaxial compressive strength and the experimental results for the tested mudrocks are compared in Fig. 2. As can be seen, there is reasonably good agreement between the experimental data and the predictions across the full range of β values for both mudrocks. Static modulus of elasticity was also measured in different directions to study anisotropic deformation behaviour in various orientations in the range from 0 to 90°. The results for all the samples with different lamination orientations were plotted as applied axial stress versus

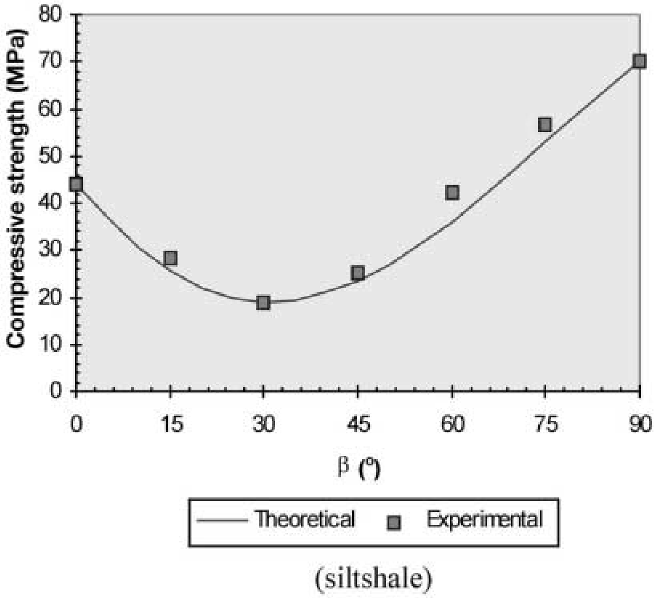

Fig. 2
Comparison between predicted values of uniaxial compressive strength by the theoretical method and experimental method for siltshale and mudshale

axial strain. The stress-strain curves of the compression tests show that there is a variation in the slope of the curves with orientation of the laminations. The static modulus of elasticity was at a maximum when the load was applied parallel to the laminations and at a minimum when it was perpendicular to the lamination planes.

The point load strength anisotropy index

The point load strength anisotropy test is reported to be a good index of anisotropy for shaley and bedded rocks. The strength anisotropy index $I_{a(50)}$ is defined as the ratio of mean $I_{s(50)}$ values measured in the strongest and weakest directions (perpendicular and parallel to planes of weakness). The ratio of greatest to least point load strength index $I_{a(50)}$ assumes values close to 1.0 for quasi-isotropic rocks and higher values when the rock is anisotropic (ISRM 1985).
As suggested by the ISRM (1985), the mean values of $I_{s(50)}$ were calculated for two types of fissile shale. A total of 48 point load tests were undertaken, using the same blocks of shale as for the uniaxial tests in different directions. A total of 24 axial point load strength tests were carried out – 12 in an orientation perpendicular to the laminations and 12 parallel to laminations. The highest and lowest values for each series of tests were discarded and the mean calculated from the ten remaining tests used for the comparison. Ratios of $I_{s(50)}$ values for the strongest and weakest direction for siltshale and mudshale were measured as 2.865 and 2.650 respectively.

Wave velocity anisotropy test

The anisotropic behaviour of P and S velocities in the field and in the laboratory is well documented for shales. Prior to the uniaxial compressive strength tests, the P-wave was measured for all the samples in different orientations from 0 to 90°. As seen in Fig. 3, the results indicate a trend towards the P-wave decreasing with increasing β from 0 to 90°.

Results and discussion

Various mudrocks from two different sites have been tested. The results are summarised in Table 1. As can be seen from the table, the maximum uniaxial compressive strength was obtained for the samples with $\beta=90°$, while samples with $\beta=30$ and 45° showed failure along the laminations. The lowest strength was measured for the sample with $\beta=30°$.
The anisotropy strength ratio can be defined as the ratio of the maximum compressive strength to the minimum compressive strength over the full range of β values. As mentioned above, the maximum uniaxial compressive strength for both shales tested was found to be at an orientation of $\beta=90°$ while the minimum compressive strength was measured at $\beta=30°$. The anisotropy ratios ($\sigma_{c90°}/\sigma_{c30°}$) of the siltshale and mudshale were 3.701 and 3.009 respectively. This is significantly greater than the anisotropy ratios of 2.865 and 2.650 measured from the point load strength test results.
The results of the P-wave velocity measurements at different orientations to the lamination planes indicate that the maximum P-wave for both mudrocks was found at an orientation of $\beta=0$ (parallel to the laminations), with the minimum P-wave measured at $\beta=90°$. The anisotropy P-wave ratios ($V_{p0°}/V_{p90°}$) of the siltshale and mudshale were approximately 1.67 and 1.44 respectively. It can be

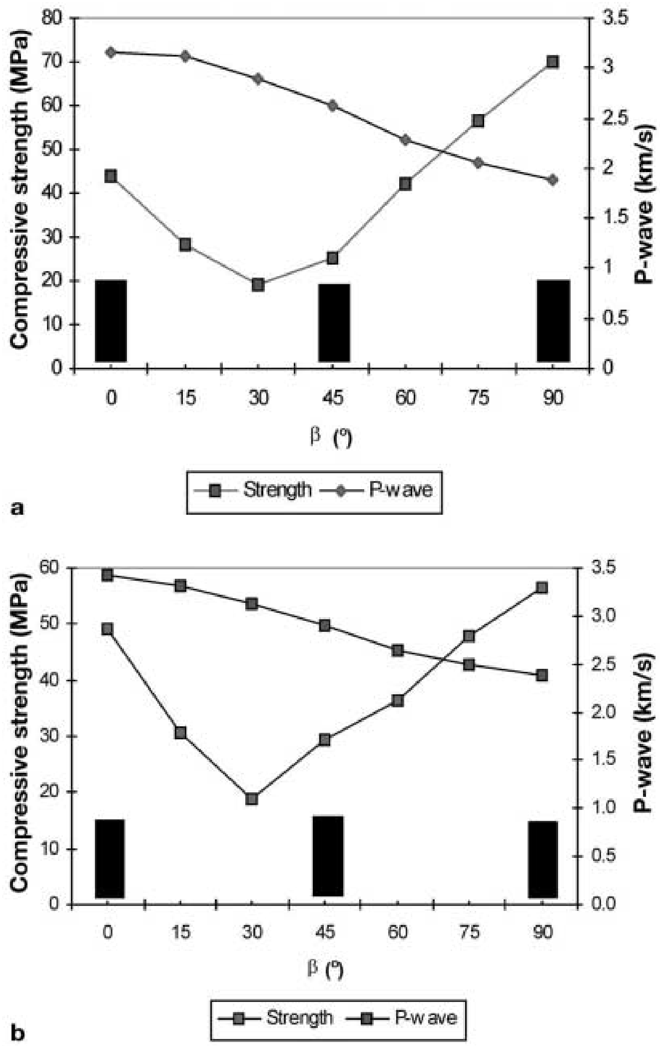

Fig. 3
Anisotropic behaviour of P-wave at different orientations with lamination planes; **a** siltshale and **b** mudshale

concluded that the variation in elastic wave velocity increases for highly anisotropic mudrocks and it would be anticipated that fissile mudrock will show a higher ratio of elastic wave velocity.

It is likely that the value of the anisotropy ratio is controlled by the degree of fissility, i.e. the higher the ratio, the more anisotropic and fissile the mudrock. King et al. (1994) found the ratio of $E_h/E_v = 1.52$ for a type of mudstone of Carboniferous age from northern England. This lower ratio in comparison to the test results obtained in the present study may be due to a more anisotropic behaviour of mudshale and siltshale compared to mudstone.

Conclusions

Uniaxial compression tests have been carried out on mudrock specimens cut at different directions. Anisotropy has been demonstrated to have a marked influence on the strength properties of the mudrocks. Both mudshale and siltshale exhibited maximum uniaxial compressive strength in the direction perpendicular to the planes of anisotropy. The minimum compressive strength value was measured for $\beta = 30°$. From the uniaxial compressive strength test results, the average strength anisotropy ratio appears to be 3.35. This is significantly greater than the average anisotropy index ratio [$I_{s(50)}$] of about 2.76 determined from the point load strength tests. The anisotropy ratios of $V_{p0°}/V_{p90°}$ of the siltshale and mudshale were approximately 1.67 and 1.44 respectively. Furthermore, it was found that the fissile mudrock shows a higher anisotropy ratio for elastic wave velocity.

Failure of the laminated samples occurred through extension fractures on the lamination planes for samples with β in the range of 0 to 15°. For specimens with lamination angles from $\beta = 30$ to 45°, failure occurred as a slip on the lamination planes. For $\beta = 60$ to 90°, shear fracture occurred across the laminations, with failure at 20 to 30° to the axial stress direction. The static modulus of elasticity was at a maximum when the load was applied parallel to the laminations and at a minimum when the load was applied perpendicular to the lamination planes.

The study of the influence of the lamination angle indicated that the average ratio of maximum to minimum static modulus of elasticity is less than the average ratio of maximum to minimum compressive strength and the

Table 1
Summary of test results

β (°)	**No. of samples**	**Compressive strength (MPa)**		**Young's modulus (GPa)**		**P-wave (km/s)**	
		Siltshale	**Mudshale**	**Siltshale**	**Mudshale**	**Siltshale**	**Mudshale**
0	3	44.121	49.064	8.611	7.136	3.155	3.427
15	3	22.389	30.585	6.032	6.037	3.113	3.308
30	3	18.934	18.754	5.058	4.964	2.900	3.136
45	3	31.228	27.615	5.026	4.728	2.637	2.908
60	3	42.072	39.120	4.952	4.681	2.286	2.638
75	3	56.532	46.786	4.861	4.638	2.062	2.499
90	3	70.081	56.435	4.174	4.146	1.887	2.382
Anisotropy ratio		3.701	3.009	2.063	1.721	1.672	1.439

angles at which they occur are different. The equation suggested by Singh et al. (1989) to predict the variation of uniaxial compressive strength over the range of β from 0 to 90° is in good agreement with the experimental results. The minimum requirement for any degree of confidence in this prediction is three uniaxial compressive strength tests at $\beta = 0$, 30 and 90°.

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