Applicability of the Hoek-Brown failure criterion and the effect of the anisotropy on intact rock samples from Athens Schist

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Synopsis

The anisotropic behaviour of Athens Schist has been brought out through the testing of specimens with varying orientation of schistosity with respect to the major principal stress under uniaxial, triaxial and dynamic conditions. A large number of results from tests on intact rock specimens of the Athens Schist were statistically analysed and evaluated.

Introduction

The term 'Athens Schist' describes a geological formation comprising a variety of low-level metamorphic and sedimentary (non-metamorphic) weak rocks (Marinos *et al.*). Significant spatial variability in the degree of weathering exists ranging between slight weathering, where the material resembles a heavily crushed rock mass, and high weathering, where the material forms rock blocks 'floating' in a completely weathered soft matrix.

Consequently the Athens Schist is a heterogeneous formation that includes soil and rock-like members of different composition, grade of weathering, and anisotropy.

Experimental work

Two types of schist, namely graphitic and calcitic schist, were obtained in their intact rock state from surface excavations in the Pagrati and Ilisia area of Athens. Both types retain low metamorphism characteristics, well-developed schistosity planes, and have a significant amount of quartz in crypto-crystallized form or in veins. They are typical samples from categories D and E as classified by Marinos *et al.* (1994) and explained in a following paragraph.

The testing of numerous rock samples included: determination of physical properties (dry density, porosity), dynamic properties (longitudinal and transverse wave velocity on air dried samples), and mechanical properties including point load tests, unconfined compression tests, indirect tensile tests, and triaxial tests, according to ISRM (1981).

Large size blocks were trimmed with their sides perpendicular to each other to facilitate coring at different inclinations, using a special frame fitted to the base of the conventional laboratory-drilling machine. About 50 specimens, of length to diameter of 2 to 3 having a 5.4 cm diameter (NX-size) at different orientation angles β relevant to the core axis (0°, 15°, 30°, 45°, 60°, 75°, and 90°) were obtained from the rock blocks.

An attempt was made to drill cores with different values of β from the same block to minimize the lithological differences. The specimens meeting the tolerance limits were first oven dried at 105°C for 24 h.

Physical properties

The dry density of the samples of Athens Schist taken from Metro ranged between 20.8 and 28.8 kN/m^3 with an average of 25.1 kN/m^3.

The range of values obtained from 70 tests for each property for the two types of Athens Schist that were examined in detail is presented in Table I.

Wave velocity anisotropy

The ultrasonic pulse method was used to determine the anisotropy of P- and S-waves of intact schist. The correlation of these two follows the expression $V_p = 1.84 \cdot V_s$ with a correlation coefficient $r = 0.84$. Marinos *et al.* (1994) proposed a linear equation for samples of Athens Schist (belonging in categories D, E, F and G described later): $V_p = 1.51 \cdot V_s$ with a correlation coefficient $r = 0.72$.

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Table I
Physical properties

Rock type		Dry density (kN/m³)	Saturated density (kN/m³)	Void ratio	Porosity (%)
Graphitic schist	Min-Max	25.38–26.05	25.75–26.25	0.01–0.06	1.1–5.5
	Mean	25.78	26.05	0.03	2.8
Calcitic schist	Min-Max	25.02–26.47	25.36–26.78	0.02–0.05	2.4–5.1
	Mean	25.86	26.21	0.04	3.7

The correlation between the longitudinal and transverse wave velocity is poor, as seen in Figure 1, due to the lithological heterogeneity of the schist rock, as well as the presence of sealed joints and fissures. Additionally, samples with quartz veins can give significantly misleading values.

Although the heterogeneous nature of the schist impedes the determination of a relation between the wave velocity and the orientation β, the general trend of the wave velocity is obvious.

The variation of the wave velocity with the orientation of schistosity planes, β (the angle between the wave propagation direction and the foliation plane) is shown in Figure 2. The anisotropy degree is equal to 1.5 and 1.4 for the longitudinal and transverse wave velocity respectively.

Strength properties

The range of the Athens Schist strength is due to three main factors: (a) the variety of lithological-petrographical types of schist encountered within the Athens Schist formation, (b) the effect of the schistosity planes and their orientation on the failure of the intact rock, and (c) the variable degree of weathering which ranges between fresh rock and extremely weathered rock (resulting in a soil-like material).

The first and third factor is well understood and studied from many authors, including Sabatakakis (1991), Marinos *et. al.* (1994), Hoek *et al.* (1998), and others, while the second one has not been studied and requires careful experimental testing.

Marinos *et. al.* (1994) have classified the Athens schist in the following categories depending on the prevailing characteristics (lithology, grade of weathering, RQD):

- *Group A*: Completely decomposed shale, schist: stiff soil- like material. The uniaxial compressive strength of specimens in this category ranges between 1.3 MPa and 10.0 MPa
- *Group B*: Highly decomposed shale, schist: soft rock material with σ_c between 3.0–17.0 MPa
- *Group C*: Moderately decomposed shale, schist: soft to weak rock with σ_c between 6.0–25.0 MPa
- *Group D*: Slightly disintegrated—highly discoloured shale, schist: weak rock with σ_c between 10.0–30.0 MPa
- *Group E*: Moderately discoloured shale, schist: medium strong rock with σ_c between 15.0–50.0 MPa
- *Group F*: Slightly discoloured schist: medium strong to strong rock with σ_c between 20.0–70.0 MPa
- *Group G*: Fresh schist: strong rock with σ_c between 30.0–90.0 MPa.

Strength anisotropy

Uniaxial compression procedure

Uniaxial compressive strength of the schists was determined as per ISRM test procedure.

The tests were carried out using a servo-controlled 2.5 MN capacity-loading frame. The stress rate was kept constant at 13 kN/s such that failure occurred within 5–10 min of loading. For measuring axial (ε_α) and diametral (ε_d) strains under uniaxial compression, two LVDTs (one used to measure the axial and one for the diametral deformation) mounted properly on steel cylinder frames were used, measuring the deformation at the mid-height of the specimens.

The samples were cylindrical, with a height to diameter ratio of about 2.5. Prior to testing the samples were air-dried at room temperature.

Data presentation

Important aspects of the mechanical behaviour of the Athens Schist, related to the anisotropy due to the schistosity planes,

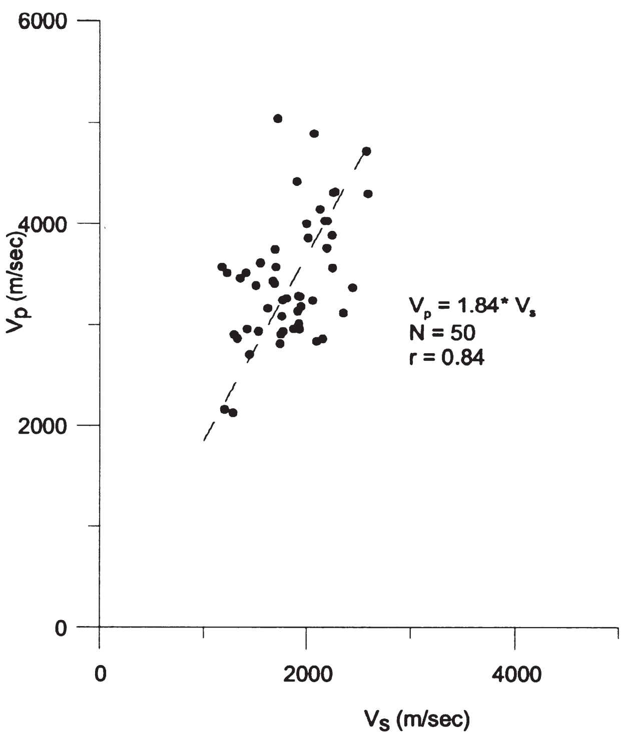

Figure 1—Correlation between longitudinal and transverse wave velocity

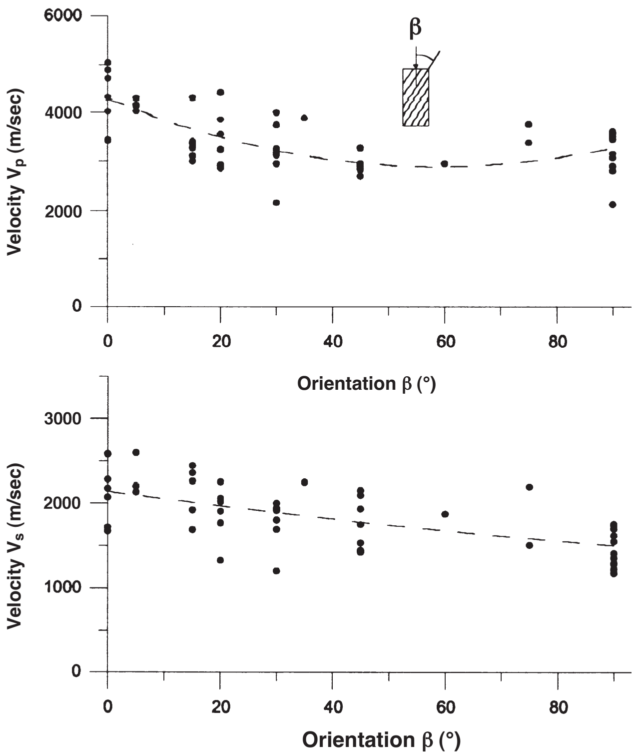

Figure 2—Variation of longitudinal and transverse wave velocity with inclination of schistosity

were found, based on the evaluation of a large number of uniaxial compression tests carried out on intact rock samples from the full range of low-level metamorphic rock types.

The lithological type is mainly schist intensely folded with yellowish, grey colour. Many samples have quartz veins and calcite joint infillings. The weathering degree ranges from fresh, slightly discoloured to medium weathering. Many samples have thin limestone intercalations aligned parallel to the schistosity planes. The samples belong mainly to categories C, D and E of Athens Schist and a limited number of them belong to categories A and B, as described earlier (after Marinos *et al.*, 1994).

The data were obtained by tests conducted on Athens Schist samples during the Geotechnical Study for the Athens Metro.

The variation of the uniaxial compressive strength with the inclination of schistosity planes is shown in Figure 3. Data are summarized in Table II.

From the data of the Athens Metro it was found that the mean uniaxial compressive strength σ_c ranges between 10.2 MPa and 28.6 MPa with an average value of σ_c = 20 MPa. The minimum strength coincides with an angle of the schistosity plane relevant to the load axis equal to 30°–45°. The anisotropy index is equal to $I_{\alpha\ (UCS)}$ = 2.4.

The minimum value shown at 60° is influenced by the small number of tests in that orientation and is not representative.

For the uniaxial compression tests carried out on samples of the graphitic schist, the range of the mean uniaxial compressive strength σ_c is between 24.7 MPa and 65.6 MPa with an average value of σ_c = 34.7 MPa. The minimum strength coincides with an angle of the schistosity plane relevant to the load axis equal to 30°–40°.

The anisotropy index for the graphitic schist was found equal to $I_{\alpha\ (UCS)}$ = 2.6.

Based on the above analysis, it can be concluded that the anisotropy index for the range of lithologies encountered in

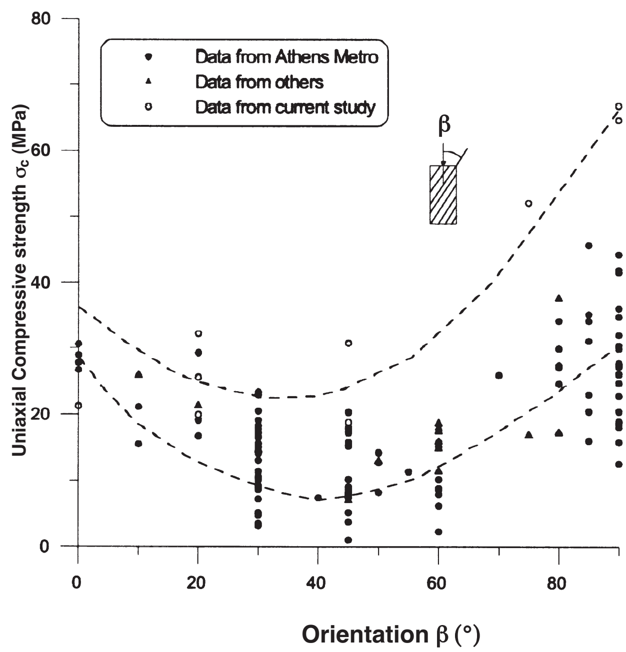

Figure 3—Variation of uniaxial compressive strength with inclination of schistosity

Table II

Strength and deformation properties

Orientation β (°)	**0**	**20**	**30**	**45**	**60**	**75**	**90**
	σ_{ci} (MPa)						
Graphitic schist Mean	21.2	25.9	–	24.7	–	52.1	65.6
Schist (data from Metro) Min–Max	26.7–30.6	16.7–29.3	3.2–23.4	1.0–20.3	2.3–17.7	24.6–34.2	12.6–44.3
Schist (data from Metro) Mean	28.6	23.6	11.7	11.2	10.2	28.6	27.7
	E_{t50} (GPa)						
Schist (data from Metro) Min–Max	10.5–45.0	15.0–23.0	0.9–27.0	0.8–20.4	2.5–18.8	5.0–16.7	3.5–20.4
Schist (data from Metro) Mean	22.3	20.7	11.7	7.0	10.3	11.4	11.4

the Athens Schist formation is approximately $I_{\alpha UCS} = 2.5$. That is true for the Schist in its fresh to medium weathered state (weathering category I to III) and can decrease significantly with increasing degree of weathering. The effect of weathering on the strength was studied by Kolaiti *et al.* (1993).

The work done by Papadopoulos and Marinos (1992) proves that an increasing degree of weathering leads to a dramatic decrease of point load strength and on the point load strength anisotropy index. This decrease was more pronounced at a direction of loading normal to schistosity planes. Values of anisotropy index ranged from just below 1 (very weathered specimens) to 3.1 (slightly weathered specimens).

According to Akai *et al.* (1970) the influence of the inclination of the schistosity on strength of schists (chlorite and graphitic) is maximum for $\beta = 30°$, while the decrease in strength is 75%–90% compared with that normal to the schistosity planes.

This agrees well with the results of the current study that show a decrease in strength as high as 60% in the direction of $\beta = 30°$ compared with that normal to the schistosity planes.

Modulus anisotropy

Young's modulus, E, refers to the tangent modulus measured at the 50% of the uniaxial compressive strength (E_{t50}).

The Young's modulus data assembled from the uniaxial tests are plotted against the orientation of the schistosity planes in Figure 4.

The mean Young's modulus ranges between 7.0 GPa and 22.3 GPa, while the lowest values were encountered at an inclination of 45° relevant to the loading axis (see Table II).

According to Marinos *et al.* (1994), the values of Young's modulus, E, for specimens classified in groups E, F and G vary from 3.0 GPa to 42 GPa.

The degree of modulus anisotropy as measured by the ratio E_1/E_2 has been extensively worked, where E_1 and E_2 are the Young's moduli in the plane of transverse isotropy and in direction normal to it, respectively.

Read *et al.* (1987), by evaluating the elastic constants for Hast schist, found that modulus of elasticity parallel to foliation $E_1 = 65$ GPa and normal to foliation $E_2 = 45$ GPa. It has been shown by Amadei (1996) that for most of the intact transversely isotropic rocks, the ratio of E_1/E_2 varies between 1 and 4. In a few cases E_1/E_2 were observed to be less than 1, but did not fall below 0.7.

In the current study the elastic constants for Athens Schist were found: modulus of elasticity parallel to foliation $E_1 = 22$ GPa and normal to foliation $E_2 = 11$ GPa, resulting in a ratio of E_1/E_2 equal to 2, a value close to that proposed by Anagnostopoulos (1981).

The mean Young's modulus normal to schistosity of the graphitic schist is found $E_2 = 16$ GPa.

Strength anisotropy in triaxial condition

Triaxial testing procedure

Triaxial compressive tests were carried out using a 70 MPa capacity triaxial cell placed in a 1.5 MN capacity-loading frame. The triaxial cell is a Hoek-Franklin cell for specimens of 1.5 mm or 54.74 mm diameter. Five different confining pressures applied during the triaxial tests were 3.6–5, 10, 16, 20, and 30–31MPa.

Since the scope of this work is to comment on the parameters σ_{ci} and m_i of the Hoek-Brown criterion for use in anisotropic materials such as the Athens Schist, the range of confining pressures of $0 < \sigma_3 < 0.5\ \sigma_{ci}$ proposed by Hoek and Brown (1980a) were used. The specimens were first subjected to the required confining pressure and then the axial load was applied until the specimen failed.

Triaxial data analysis

The plots of compressive strength between σ_1 and β at different confining pressures σ_3 for the two schists are presented in Figure 5. The plots have been drawn taking all the experimental results out of the triaxial sets into consideration. The overall strength behaviour of the intact schists is similar as far as the shape of the anisotropy curve in the unconfined state is concerned. The shape of the anisotropy curves for these three rocks is towards 'U-shaped' over the entire range of σ_3 adopted.

The anisotropic trend in the lower range of confining pressures retains the same trend in the higher confining pressures, up to half the uniaxial compressive strength of the schist (lower and upper bound lines in Figure 5). This agrees well with the triaxial data at similar pressures on schists published by Behrestaghi *et al.* (1996). At confining pressures approaching the compressive strength, the anisotropy curve does not retain this shape but shows flattening. The testing programme is still underway and research on the behaviour of Athens Schist at this range of σ_3 is done.

According to Akai *et al.* (1970) it is concluded that the decrease in strength of schists (chlorite and graphitic) at $\beta = 30°$ under confining pressure as high as 20 MPa is in the order of 50%.

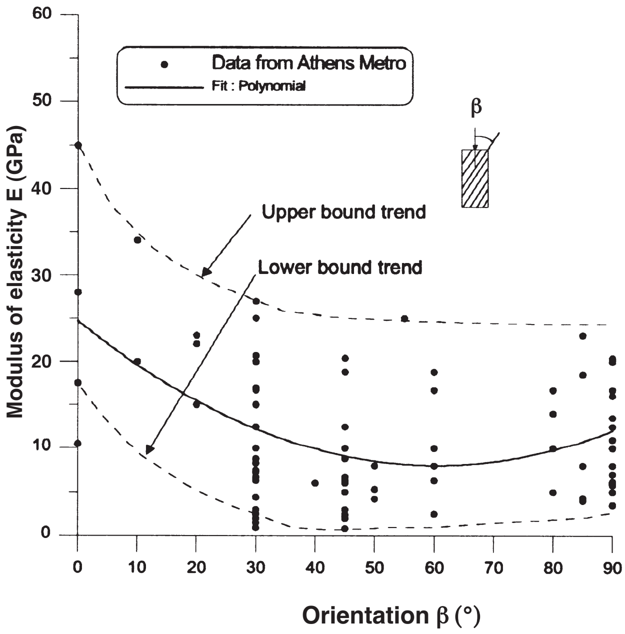

Figure 4–Variation of modulus of elasticity with inclination of schistosity

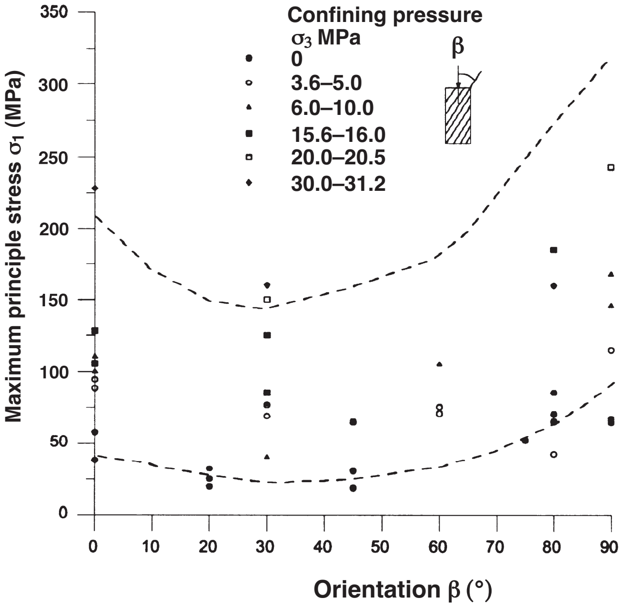

Figure 5—Compressive strength anisotropy

This agrees well with the results of the current study.

Applicability of the Hoek and Brown criterion

Based on the results of 40 triaxial tests on intact rock samples of Athens Schist (both graphitic and calcitic schist rock type) the applicability of the Hoek and Brown criterion on an anisotropic rock is made. Hoek (1980a) states that the failure criterion assumes isotropic rock and rockmass behaviour. Furthermore, he explains that the value of m_i refers to intact rock specimens tested normal to bedding or foliation and will be significantly different if failure occurs along a weakness plane, such as foliation, cleavage or schistosity.

The Hoek and Brown criterion is used extensively in anisotropic rocks, such as metamorphic and sedimentary formations that possess an inherent anisotropy due to foliation or bedding.

The Athens Schist formation possesses an inherent anisotropic nature defined by the closely spaced schistosity planes.

The triaxial data sets presented in Figure 6 were selected, in order to proceed with the determination of the Hoek and Brown criterion parameters, according to the following criteria:

- the range of confining pressures should lie within $0 < \sigma_3 < 0.5\ \sigma_{ci}$
- The data that didn't seem reliable, for instance samples that failed in decreased strength although the confining pressure was higher in comparision with previous sets, were excluded
- The mean uniaxial compressive strength was used for each orientation of foliation, as the range of the strength can have a significant effect upon the criterion parameters.

The data were then plotted irrespective of the orientation of foliation and are presented in Figure 7, while in the following paragraphs the effect of the orientation of the schistosity planes on the failure criterion is discussed in detail.

The Hoek and Brown criterion parameters in respect to the orientation of the schistosity planes are summarized in Table III.

The value of m_i normal to the foliation planes is equal to 13 and agrees well with the value proposed by Marinos and Hoek (2000) for schists (m_i = 12). The failure envelope is shown in Figure 8.

The lowest value of the parameter m_i is encountered when the inclination of the schistosity planes is 30° to the major loading axis. The decrease of the value is in the order of 30%. The failure envelope at this orientation is shown in Figure 9. The maximum value is found for specimens loaded parallel to the foliation planes (see Figure 10).

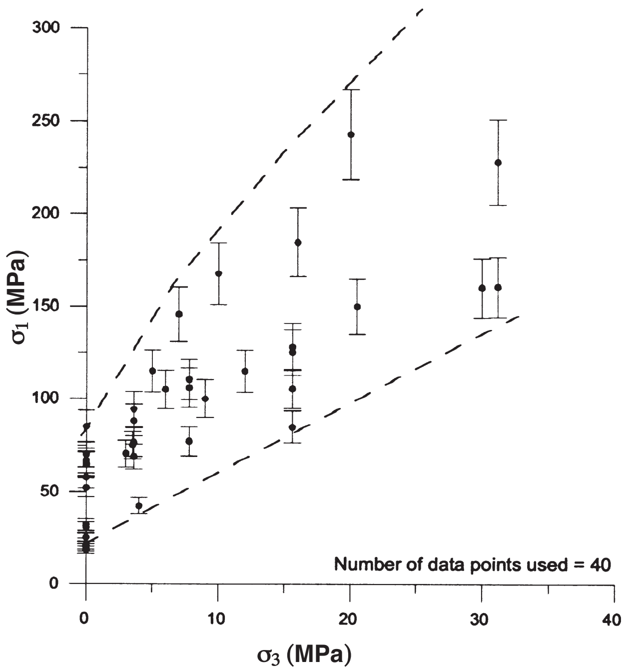

Figure 6—Triaxial data for Athens Schist

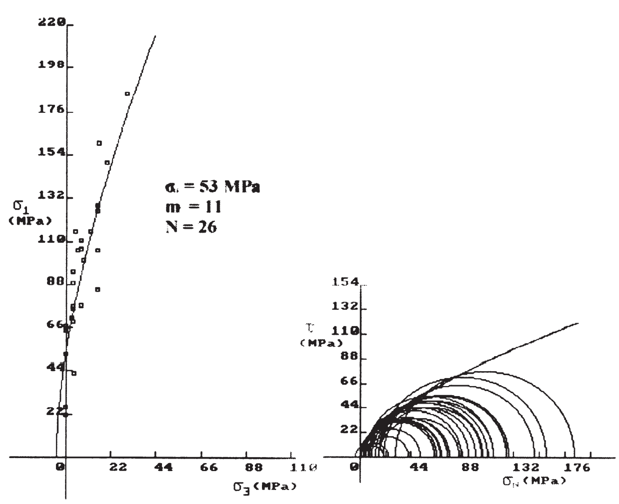

Figure 7—Failure envelopes of the selected data

Table III

Hoek and Brown criterion parameters

Orientation β (°)	0	30	90	All data
σ_{ci} (MPa)	46.7	44.3	56.1	53
m_i	15	9	13	11
No. of tests	7	6	13	26

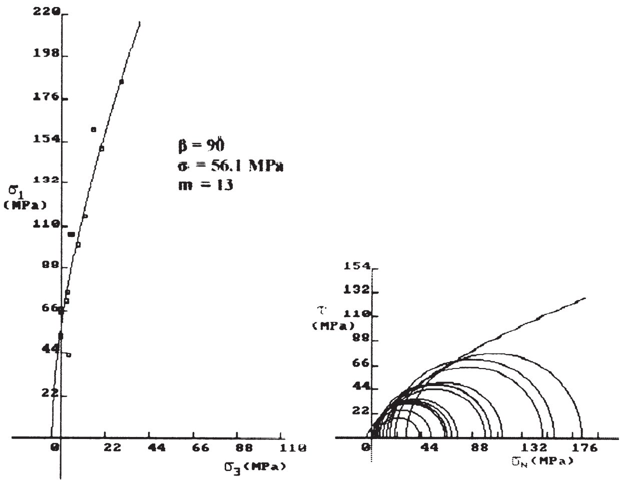

Figure 8—Hoek and Brown and Mohr–Coulomb failure envelopes for orientation of foliation 90°

Conclusions

The effect of the anisotropy on the mechanical properties of Athens Schist is very significant.

The longitudinal and transverse wave velocity perpendicular to the planes is approximately 30% lower than that parallel to them. The impact of the foliation on the dynamic Modulus of Elasticity (E_0) and the dynamic Poisson ratio (v_0) is proportional to that on the longitudinal and transverse wave velocity.

The variation of strength and deformability of the Athens Schist due to the presence of closely spaced planes of schistosity (or cleavage) was shown to be significant in uniaxial as well as triaxial conditions. This can have a major effect in the working strength values, not only in shallow foundations and surface excavations (uniaxial conditions), but also in tunnels and underground openings (triaxial conditions).

Based on the experimental testing and analysis of a large number of data, it can be concluded that the anisotropy index for the range of lithologies encountered in the Athens Schist formation is approximately $Ia_{UCS} = 2.5$.

Anisotropy has a major effect on the strength characteristics of the Athens Schist in its fresh or moderately weathered state where it prevails as the major structural feature. It is expected that, in highly weathered or closely jointed to heavily crushed Athens Schist rock masses, the variation of strength is overwhelmed by weathering, alteration and degree of fragmentation.

The selection of the strength parameters used in design, either directly the uniaxial compressive strength or the equivalent Mohr–Coulomb parameters, by using the Hoek-Brown criterion is critical.

The applicability of the Hoek-Brown criterion in anisotropic materials, such as schists, is questionable. The value of the parameter m_i in the direction of minimum strength ($\beta \approx 30°$) is 30% lower than that defined normal to the schistosity planes.

The use of the lower bound or upper bound parameters σ_{ci} or σ_{ci} and m_i in the design of surface or underground works is suggested by the field behaviour of the material, which is dependent upon the strength either parallel, normal or in the $\beta \approx 30°$ orientation to the schistosity.

It is proposed that the Hoek and Brown criterion is used for the schist–like members of the Athens Schist formation by taking into account lower values of uniaxial compressive strength and m_i when anisotropy, due to the presence of closely spaced schistosity planes, is predominant.

The amount of decrease can be found with the following procedure:

➤ Testing of intact rock samples oriented normal and at 30°–45° to the foliation planes in uniaxial compression.

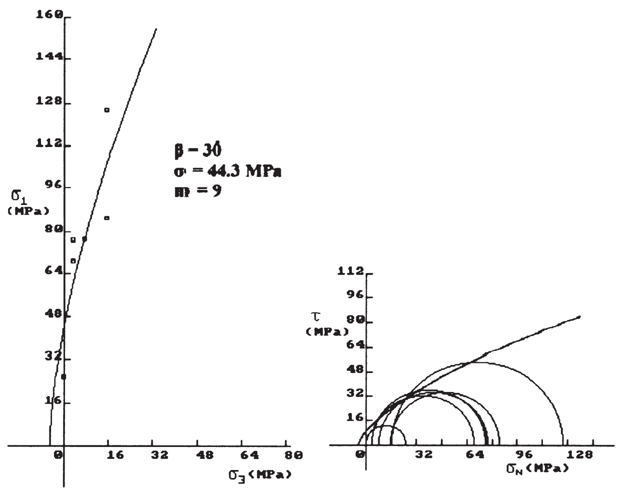

Figure 9—Hoek and Brown and Mohr-Coulomb failure envelopes for orientation of foliation 30°

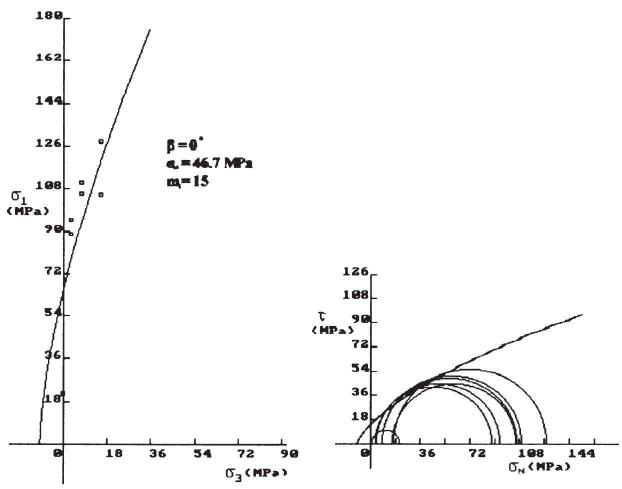

Figure 10—Hoek and Brown and Mohr-Coulomb failure envelopes for orientation of foliation 0°

- ➤ Determination of the decrease in uniaxial compressive strength between these two directions
- ➤ Application of a proportional decrease to the parameter of m_i.

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Similar but different: South African students slot into Aussie scholarship*

Like a well-oiled machine, the JKMRC international travelling scholarship offered by the University of Queensland to chemical engineering students at the University of Cape Town has found a 'smooth groove'.

Now having just completed its fourth year, the scholarship scheme is attracting some of the brightest engineering students, possibly in the world, to the JKMRC in Brisbane to undertake two-month's vacation work over the December–January summer break each year.

The scholarship is usually given to the best nomination from third year students at UCT's Department of Chemical Engineering. For the second successive year, the adjudicators couldn't split two UCT students Nomsa Yumba and Nick Smart, who both received the award and travelled together to Brisbane to undertake their assignments.

Nomsa's interests lay primarily in comminution, a JKMRC specialist area, which is essentially the breaking down of rocks to smaller, mineral production-scale particle sizes. Her assignment at the JKMRC, set by Dr Toni Kojovic, was to study precisely cut core samples for breakage analysis using the new SAG mill comminution (SMC) test.

Nomsa's task was to verify that diamond-cut quarter cores gave the same results as broken rock fragments through the SMC test, and whether the orientation of the samples affects breakage. During her assignment she learnt about the JKMRC's ore testing procedures.

A shortage of diamond-cut samples meant that it was difficult to derive a full set of statistics to uncover any differences, but she made the best of what was available within the two-month time frame.

Toni Kojovic praised Nomsa for her practical approach to the task and how she had picked up the rock breakage concepts very quickly.

Nomsa said the two-month scholarship to Australia was a great opportunity to get exposure to how research is done, with the view to perhaps working in this area with the sponsors of her UCT bursary, Anglogold.

It was the first time Nomsa had traveled outside South Africa, remarking that she was a bit surprised about the similarities between her home country and Australia.

She also had to endure one of the hottest Brisbane summers on record, working in the heat of the JKMRC metallurgical laboratory, sorting, sizing and then breaking rock samples with the JK drop weight tester: 'It was very hot in the pilot plant, but you had to grin and do it.'

One of the lessons Nomsa gained from her JKMRC experience was the benefit of planning and completing a project within a short time.

Nomsa's travelling companion and fellow UCT chemical engineering student, Nick Smart, teamed up with JKMRC Principal Research Fellow Dr Peter Holtham to look at cyclones, and in particular a cyclone insert developed by Professor Dan Walsh from the University of Alaska Fairbanks.

Nick's task was to check the performance of the cyclone operated at the JKMRC without the insert, and then put the insert into the rig, run the same experiment using quartz sand, and look for differences in how the cyclone classified—or re-streamed—the material. Small quantities of magnetite were added into the cyclone to see if this material was concentrated in the insert.

The idea behind the insert is to heighten the effect of gravity to separate material by the centrifugal action of the cyclone. Cyclones, devices used extensively in mineral processing, are used to separate different size particles.

'What we wanted to do was to introduce a section with the insert to separate more and less dense particles simultaneously, thereby making a simple hybrid hydrocyclone and centrifuge,' Nick said.

'My job was to test whether adding the modification would change the separation efficiency of the hydrocyclone.'

Nick essentially helped Dr Holtham look into the feasibility of developing the insert for industry-wide application.

This was Nick's first experience with a cyclone rig, although previous vacation work with his bursary sponsor AngloAmerican Base Metals, has given him working knowledge of flotation, spirals and also magnetic separation, the latter being at Nmakwa Sands near his home country of Namibia.

Although not sure what to expect on arriving in Brisbane, Nick said coming to the JKMRC had been a great experience: 'I was given my own project which gave me the chance to take it as far I could within the time period, which you don't always get on vacation work.'

Unlike Nomsa Yumba and many of the previous recipients of the JKMRC travelling scholarship, Nick Smart has had previous international travelling experience by virtue of growing up with a family background in mining engineering.

'My dad was a miner, so we moved around a lot, including a stint in Moscow,' Nick said. This was, however the first time Nick had been to Australia.

But like Nomsa's view of Australia, the well-travelled Nick had to agree that Australia in many respects is similar to South Africa. The landscape, the climate, the people and their lifestyles are very similar, he said.'Every work experience is useful, and coming to the JKMRC is good in that you get to work with high calibre people working on very interesting projects—and the JKMRC has quite a well-equipped lab that we wouldn't normally have access to as third or fourth year students at UCT,' Nick said.

Nomsa commented that she enjoyed her time in Brisbane, despite the heat and humidity. And while it had been a good experience, perhaps the pace of life in Brisbane was a lot slower than she was used to when compared to the hustle and bustle of South Africa, and in particular Nomsa's home town of Johannesburg.

She said there was greater emphasis on family in Australia than in South Africa, which she found refreshing, at least from her own experience.

Nomsa thoroughly recommended the scholarship programme to others, saying that it shouldn't be passed up if offered to other UCT students. ◆

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