Mineralogical control on the intact strength of schist in Central Otago, New Zealand

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Abstract. Schist is highly variable in terms of intact strength, mineralogical composition and structure due to the provenance of parent rock and metamorphic conditions during formation. This paper explores the mineralogical and structural control on the intact strength properties of schist. The analysis is initially based on laboratory tests (compressional and petrographic analysis) carried out on quartz-mica schist specimens taken from Central Otago in New Zealand, and is subsequently compared to international experimental studies on schist. The results show that the foliated fabric produces directionally dependent strength anisotropy which shifts with compressional confinement exceeding 10 MPa. Furthermore, the significant variability of intact strength data of up to 48 MPa for the same loading orientation can be constrained if the mineralogical composition and degree of mineral segregation are considered. Review of the petrography of the schist shows that the relative melanocratic (mica, biotite) and leucocratic (quartz, feldspar, calcite, epidote) content of the schist strongly controls its strength due to failure mechanisms associated with the crystal lattice structure. The study results highlight the importance of detailed mineralogical estimates and descriptions of mineralogical segregation during mapping and borehole profiling.

1. Introduction

1.1. Compositional and textural variability
Schist is the product of metamorphism of sedimentary, igneous or metamorphic sequences resulting in a strongly foliated anisotropic rock. The wide range of protoliths compounded by the variability of metamorphic facies conditions (different pressures and temperatures) results in significant variations in the physical, compositional and mechanical properties of schist. Metamorphic differentiation through mineral recrystallization and segregation is influenced by the metamorphic grade, and results in compositional layering into foliations with a lepidoblastic texture of preferentially aligned elongate or lamellar minerals [1].

1.2. Anisotropic nature
The penetrative foliated fabric of schist produces an inherently anisotropic mechanical behaviour where the strength of the rock is directionally dependent on the orientation of the schistosity in relation to applied stress, as illustrated in figure 1 [2]. The mechanical strength and anisotropic nature of schist has been highlighted in multiple studies, such as: the laboratory characterization of the DanBa quartz
mica schist from Sichuan, China [3], anisotropic laboratory data obtained from Angers Schist in France [4], the study of schistose anisotropy of the Athens schist [5], evaluation of the strength anisotropy of four different lithological variations of schist from the Himalayas in India [6–10], strength variation of the Hamedian schist from Iran under variable confining stresses [11], laboratory characterization of the anisotropic nature of the Yeoncheon Schist from Korea [12], characterization of the strength of the Otago schists in New Zealand [13–17], and the compression testing of schists from the Neelum Valley in Pakistan [18].

Published geotechnical data on intact strength of schist is provided in figure 2 and shows that the unconfined anisotropic nature is typically U-shaped to shoulder-shaped, but with a wide scatter of intact strength values. The primary objective of this paper is to evaluate the scatter of intact schist strength in terms of mineralogical composition and degree of mineral segregation in order to explore whether the intact strength variability of schist can be constrained by considering qualitative descriptions.

This objective is achieved by the following:

- Assessing the results of compressional tests on intact specimens of Central Otago Schist from New Zealand.
- Studying the anisotropic nature of schist under unconfined and confined loading conditions.
- Evaluating the mineralogical composition and degree of segregation of schist with the compressional strength data.
Comparing the experimental data presented in this paper with existing strength data on schist from New Zealand and other international studies.

2. Study area
Central Otago in the South Island of New Zealand is dominated by Otago Schist (figure 3). Otago Schist is mainly composed of quartz-mica schist, which is referred to as greyschist in New Zealand, and ranges from psammitic (quartzofeldspathic) to pelitic (micaceous) end-members. Subordinate bands of chlorite-epidote-calcite schist, referred to as greenschist in New Zealand, are also present [19, 20]. Several studies on the mechanical properties of Otago Schist have been carried out [13–15] as shown in figure 2A and 3B. The greyschist data provided in figure 2A show over 60 MPa difference in uniaxial compressive strength (UCS) tests carried out on samples from the same location and similar orientation.

In this present study greyschist specimens were collected from the Cromwell Gorge for laboratory testing from the approximate location shown as point B in figure 3B. The Cromwell Gorge is of particular interest due to the extensive geotechnical database associated with the Clyde Power Project. The Clyde Project involved the construction of the Clyde Dam across the Clutha River, development of the Lake Dunstan reservoir, extensive investigation of ~17 large-scale landslides within the Cromwell Gorge, and stabilization works that were carried out between 1989 and 1992 [21]. Works included a network of ~16 km of exploration/drainage tunnels, ~52 km of boreholes (exploration and drainage), and a robust monitoring network of piezometers, inclinometers, extensometers, and survey points [21].

![Figure 3](image_url)

**Figure 3.** A) Geographical boundaries of schist in the South Island of New Zealand is broadly subdivided into Marlborough Schist, Alpine Schist and Otago Schist. B) Approximate locations of geotechnical investigations of the intact strength of Otago Schist; where A is the Kawarau Gorge, B is the Cromwell Gorge, C is the Clyde Dam foundations, and D is the Maniototo Irrigation Project.

3. Laboratory testing
For the present study schist specimens were obtained from HQ borehole core and boulder specimens taken from a network of drainage and exploration adits (tunnels) which extend into the slope through the deep-seated landslides into in situ undeformed bedrock. Specimens were selected from the unweathered bedrock below the landslide basal shear zone. Due to the limited extent of the chlorite-epidote greenschist, the focus is on the quartz-mica greyschist which is the dominant lithology within the central portion of the Cromwell Gorge.

Schist hand specimens were visually assessed [22] with a detailed description of the relative percentage of leucocratic (quartz, feldspar, calcite, epidote) and melanocratic (mica, chlorite, biotite) minerals. Thin sections were prepared for petrographic analysis. HQ or NQ core specimens were
prepared following ASTM:D4543 [23] for compressive strength testing from borehole and boulder specimens, respectively. The results were normalized to 50 mm core diameter. The core specimens were prepared at various orientations to foliation inclination, specifically parallel (β<30°), oblique (30°≤β≤60°) and perpendicular (β>60°).

The core specimens were subjected to uniaxial and triaxial compressive strength tests following ASTM:D7012 [24] at confining stresses of 0 MPa, 10 MPa, and 20 MPa. The selected confining stresses were based on simplistic Finite Element Method (FEM) models of the stress states associated with the progressive landscape evolution of the Cromwell Gorge from initially a relatively low relief surface to the present-day ~1400 m deep gorge [25].

4. Results

4.1. Uniaxial Compressive Strength (σ_{c50})

The σ_{c50} data provided in figure 4A shows the U-shaped anisotropy from the foliated fabric where the intact rock is strongest when loaded at an orthogonal direction (β = 90°) to the foliation planes, and weakest when loaded at an oblique orientation to the foliation planes (β = ~30°). The σ_{c50} data is scattered with a range in σ_{c50} results derived from similar foliation orientations (figure 4A and table 1).

![Figure 4](image)

**Figure 4.** Greyschist strength results for a range of foliation orientations (β) from A) Uniaxial Compressive Strength tests and B) Triaxial Compressive Strength tests.

| Table 1. Mean greyschist results from uniaxial and triaxial compression tests, with (range) and (number of specimens tested). |
| --- | --- | --- | --- |
| σ3 | Foliation orientation | Strength Anisotropy (R_{c}=Max. strength/Min. strength) |
| --- | --- | --- |
| 0 MPa | Parallel (β<30°) | Oblique (30°≤β≤60°) | Perpendicular (β>60°) |
| 41 (15-65) | 26 (10-45) | 69 (54-102) |
| {5} | {9} | {7} |
| 10 MPa | 125 (92-169) | 59 (41-72) | 127 (101-153) |
| {5} | {5} | {2} |
| 20 MPa | 215 (165-275) | 89 (70-102) | 177 (162 – 204) |
| {7} | {10} | {3} |
| 2.7 | 2.2 | 2.4 |
4.2. Triaxial Compressive Strength
The inherent anisotropic nature of the schist is maintained under confined conditions (figure 4B). The morphology of strength anisotropy, however, shifts with increasing confining stress. It is strongest when the major principal stress ($\sigma_1$) is oriented perpendicular to foliations ($\beta > 60^\circ$) for unconfined tests, and strongest when the major principal stress is parallel to foliations ($\beta < 30^\circ$) in confined conditions when $\sigma_3 > 10$ MPa. There is also a shift from the minimum strength oriented at $\beta = \sim 30^\circ$ towards $\beta = \sim 40^\circ$ with increasing confining stress, which has been observed in other studies such as [8,26].

4.3. Mineralogical composition
The results of the visual assessment of the hand specimens were similar to the petrographic analysis of thin sections in terms of the relative percentage of leucocratic and melanocratic minerals. Petrographic analysis under 4x, 10x and 40x magnification showed that the leucocratic foliations are dominated by quartz with subordinate volumes of feldspar (albite), epidote, sphene and calcite, with a scattering of some melanocratic minerals. The melanocratic foliations are dominated by phyllosilicates such as muscovite, chlorite and biotite, with subordinate volumes of magnetite, graphite, clay and a scattering of some leucocratic minerals.

Deformational metamorphic features observed at a microscopic scale are analogues for macroscopic deformational and strength characteristics. Strain partitioning is evident as a result of the rheological contrasts in crystallographic lattice structures between the more competent leucocratic (framework silicates) and the weaker melanocratic minerals (sheet silicates). Strain partitioning includes dislocation glide (shearing) along phyllosilicate foliation, cataclastic deformation, and intergranular brittle fracturing of the quartz and feldspar grains (figure 5B).

5. Discussion
5.1. Correlation of mineral composition and intact strength characteristics
There is a direct relationship between the intact strength and the leucocratic content (figure 6). The dashed line in figure 6A represents the $\sim 60\%$ leucocratic content based on visual qualitative assessment of a hand specimen of greyschist. By subdividing the strength data based on the relative leucocratic content the variability of strength data can be constrained as indicated by the range arrows in figure 6A. The degree of mineral segregation also has an effect on the intact strength, with weakly foliated specimens showing a $> 20\%$ higher strength than strongly segregated specimens (figure 6B).
Figure 6. Uniaxial Compressive Strength data normalized to 50 mm diameter core ($\sigma_{50}$) versus foliation angle ($\beta$) categorised in accordance with leucocratic content and degree of segregation.

The influence on strength is a function of the crystallographic structure of the minerals and the persistence of phyllosilicate foliations. The phyllosilicate minerals (muscovite, biotite, chlorite) are characterised by low tensile and shear strengths facilitated by their elongate to platy crystallographic habit and weak van der Waals chemical bonds. The leucocratic minerals are dominated by framework silicates (quartz, feldspar) which are structurally stronger due to strong polar covalent chemical bonds and granular, euhedral to anhedral crystal structures, often with sutured crystal boundaries.

Phyllosilicate-rich foliations in strongly segregated Otago greyschist specimens are often 1 to 3 mm in thickness and are laterally highly to very highly persistent (10 m to > 20 m). In contrast, the weakly segregated Otago Schist samples comprise laterally impersistent (< 1 m) phyllosilicate-rich and leucocratic-rich foliations, and are dominated by foliations composed of a mixture of phyllosilicate and leucocratic minerals. Strain along the foliation planes is facilitated on phyllosilicate grain boundaries, resulting in stress redistribution on to the more competent leucocratic minerals.

5.2. Comparison with other studies

The strength data from this study is comparable to existing data for Otago Schist [13–17], although the results generally plot in the lower range of the Otago Schist values (figure 2B). This is to be expected as the majority of the previously published results are associated with dam foundations or road cuttings, which are located along competent bluffs characterised by a high quartzofeldspathic content (psammitic schist) [13,15].

Comparison of the ~ 60% leucocratic boundary from this study with strength data from New Zealand and international experimental data (figure 2) suggests there is a correlation between strength and mineral composition. The relative mineralogical composition of the schist from international experimental studies is provided in table 2. It should be noted that the mineral composition of Yeoncheon schist [12] and Athens schist [5] was not reported. Visual inspection of photographs in [12] suggests that the Yeoncheon schist tested ranged between pelitic (<60% leucocratic) and psammitic (>60% leucocratic) content, and that the Athens schist in [27] comprises <60% leucocratic content.

The ~ 60% boundary line fits the international data if chlorite is included in the leucocratic content. This could be validated by the fact that the Otago greenschists (chlorite-rich schist) are inherently stronger than Otago greyschist (pelitic quartz-mica schist) [15]. The increase in strength imposed by chlorite may be due to differences between the sheet silicate structure of micas (denoted TOT + c) and chlorite (denoted TOT + O). The sheet silicate structure of mica and chlorite is similar, comprising layers of tetrahedral sheets (T) and an octahedral sheet (O) in a ratio of 2:1 (TOT) [30]. The difference between the structure of mica (TOT+c) and chlorite (TOT+O) are the interlayer charges between the TOT sheets. Micas have a net negative charge between TOT sheets therefore are bonded together with
an interlayer cation by weaker van der Waals forces and ionic bonds. Chlorite sheet structure is bonded together by a net positive charge with an additional octahedral sheet (O), and therefore comprises a 2:1+1 structure (TOTO) [30].

These results highlight the importance of detailed mineralogical estimates and descriptions of mineralogical segregation during mapping and borehole profiling. A first-indication field-based estimate of the intact strength of schist can be made based on relative leucocratic content of schist. The degree of mineral segregation, foliation shape and degree of weathering will influence the strength, and thus also should be considered for detailed rock mass characterisation.

Table 2. Mineralogical composition of international schist.

| Schist          | Baramula Quartzite schist [6,8] | Baramula Chlorite schist [6,8] | Kinaur quartz mica schist [6,8] | Kinaur biotite schist [8,28] | DanBa Schist [3] | Angers Schist [29] |
|-----------------|---------------------------------|---------------------------------|---------------------------------|-----------------------------|-----------------|-------------------|
| Quartz          | 48                              | 29.2                            | 31                              | 10                          | 40-60           | 23                |
| Mica            | 15                              | 11.3                            | 22.3                            | 56                          | 30-50           | 40                |
| Chlorite        | 2.5                             | 25.4                            | 26.5                            | 45                          |                 |                   |
| Feldspar        | 12.6                            | 3.8                             | 2.8                             | 3                           | 1-15            |                   |
| Kaolinite       | 11.5                            | 8.8                             | 7.9                             | 6                           |                 |                   |
| Illite          | 4.7                             | 1.1                             | 2.8                             | 5                           |                 |                   |
| Saponite        |                                 | 6.3                             |                                 | 20                          |                 |                   |
| Carbonate       |                                 |                                 |                                 | 6                           |                 |                   |
| Vermiculite     | 4.7                             | 14.8                            |                                 |                             |                 |                   |
| Chloritoid      |                                 |                                 |                                 |                             | 12              |                   |
| Leucocratic + chlorite | 63.1                           | 64.8                            | 60.3                            | 10                          | 40-60           | 68                |

6. Conclusion

Unconfined and triaxial compression data of greyschist obtained from the Cromwell Gorge in Central Otago, New Zealand were provided. The results showed that the U-shaped anisotropy of schist shifted from strongest when loaded perpendicular to foliations (β<60°) in unconfined conditions, to strongest when loaded parallel to foliations (β>30°) in confined conditions (σ3>10 MPa). Confinement during testing also shifted the weakest strength orientation from 30° to 40° in unconfined and confined conditions, respectively.

Comparison of the strength data with the mineralogical composition of schist indicates that the relative leucocratic content has a direct influence on intact strength of schist. A boundary division of ~60% leucocratic content was used to limit the range of intact strength. This boundary line appears to fit international schist data, if chlorite is included in the leucocratic content. The inherent strength of chlorite-rich schist may arise from the slight differences in crystallographic structure and interlayer charges between the sheet silicate groups between mica and chlorite. It is acknowledged that the variability in the mechanical properties of schist arise from differences in provenance and metamorphic history which has not been investigated in this paper, and is a possible topic for future research.

This paper demonstrates the significant variation of the intact strength of schist due to strength anisotropy from the foliated fabric, mineral composition, and degree of mineral segregation. Field characterisation of schist should include the aforementioned parameters and weathering grade for a better estimation of schist strength for geotechnical projects.

References

[1] Best M G 2002 Igneous and Metamorphic Petrology, 2nd Edition (John Wiley & Sons)
[2] Ramamurthy T 1993 Strength, modulus responses of anisotropic rocks Comprehensive Rock Engineering Volume 1: Principles, Practice & Projects ed J A Hudson (Oxford: Pergamon
3] Zhang X P, Wong L N Y, Wang S J and Han G Y 2011 Engineering properties of quartz mica schist Eng. Geol. 121 135–49
4] Duveau G, Shao J F and Henry J P 1998 Assessment of some failure criteria for strongly anisotropic geomaterials Mech. Cohesive-Frictional Mater. 3 1–26
5] Saroglou H, Marinos P and Tsiambaos G 2004 Applicability of the Hoek-Brown failure criterion and the effect of the anisotropy on intact rock samples from Athens Schist J. South African Inst. Min. Metall. 104 209–15
6] Behrestaghi M, Seshagiri Rao K and Ramamurthy T 1996 Engineering geological and geotechnical responses of schistose rocks from dam project areas in India Eng. Geol. 44 183–201
7] Chawre B 2018 Correlations between ultrasonic pulse wave velocities and rock properties of quartz-mica schist J. Rock Mech. Geotech. Eng. 10 594–602
8] Nasseri M H B, Rao K S and Ramamurthy T 2003 Anisotropic strength and deformation behavior of Himalayan schists Int. J. Rock Mech. Min. Sci. 40 3–23
9] Singh V K, Singh D and Singh T N 2001 Prediction of strength properties of some schistose rocks from petrographic properties using artificial neural networks Int. J. Rock Mech. Min. Sci. 38 269–84
10] Singh T N and Verma A K 2012 Comparative analysis of intelligent algorithms to correlate strength and petrographic properties of some schistose rocks Eng. Comput. 28 1–12
11] Fereidooni D, Khanlari G R, Heidari M, Sepahigero A A and Kolahi-Azar A P 2016 Assessment of inherent anisotropy and confining pressure influences on mechanical behavior of anisotropic foliated rocks under triaxial compression Rock Mech. Rock Eng. 49 2155–63
12] Cho J-W, Kim H, Jeon S and Min K-B 2012 Deformation and strength anisotropy of Asan gneiss, Boryeong shale, and Yeoncheon schist Int. J. Rock Mech. Min. Sci. 50 158–69
13] Smith A and Salt G 1991 Clyde Power Station Reservoir. General report on geotechnical materials involved in landsliding: mineralogical, shear strength and related properties. Volume 1: Text and Volume 2: Appendices (New Zealand Geological Survey: Department of Scientific and Industrial Research: Geology & Geophysics)
14] Perrin N D 1979 Geotechnical testing of schists from the Maniototo Irrigation/Power Project (NZGS Report)
15] Mills K W and Gray W J 1985 Kawarau River Power Investigations In Situ Stress Measurements and Laboratory Testing
16] Read S A L, Perrin N D and Wong D 1985 Uniaxial Compression Testing and Determination of Modulus of Elasticity and Poisson’s Ratio of Highly Anisotropic (Schistose) Rocks N.Z. Geomech. News No. 31 35–8
17] Read S A L, Perrin N D and Brown I R 1987 Measurement and analysis of laboratory strength and deformability characteristics of schistose rock Proceeding of the Sixth International Conference on Rock Mechanics, vol. 1 (Montreal) pp 233–8
18] Mustafa S, Khan M A, Khan M R, Hameed F, Mughal M S, Asghar A and Niaz A 2015 Geotechnical study of marble, schist, and granite as dimension stone: a case study from parts of Lesser Himalaya, Neelum Valley Area, Azad Kashmir, Pakistan Bull. Eng. Geol. Environ. 74 1475–87
19] Mortimer N and Roser B P 1992 Geochemical evidence for the position of the Caples-Torlesse boundary in the Otago Schist, New Zealand J. Geol. Soc. London. 149 967–77
20] Mortimer N 2003 A provisional structural thickness map of the Otago Schist, New Zealand Am. J. Sci. 303 603–21
21] Gillon M D and Hancox G T 1992 Cromwell Gorge landslides - A general overview Landslides ed D H Bell (Christchurch, New Zealand: A. A. Balkema) pp 83–102
22] NZGS 2005 Field description of Soil and rock (New Zealand Geotechnical Society Inc.)
23] ASTM D4543 2001 Standard Practices for Preparing Rock Core Specimens and Determining
Dimensional and Shape Tolerances (West Conshocken, PA)

[24] ASTM:D7012 2014 Standard Test Method for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures 1 ASTM International (West Conshocken, PA)

[25] Ridl R N 2021 Evaluation of Buckling Deformation in the Schist of the Cromwell Gorge, New Zealand (University of Canterbury)

[26] McLamore R and Gray K E 1967 The mechanical behaviour of anisotropic sedimentary rocks. Trans. Am. Soc. Mech. Eng. Scr. B. 89 62–7

[27] Hoek E, Marinos P and Benissi M 1998 Applicability of the geological strength index (GSI) classification for very weak and sheared rock masses. The case of the Athens Schist Formation Bull. Eng. Geol. Environ. 57 151–60

[28] Gattinoni P, Consonni M, Francani V, Leonelli G and Lorenzo C 2019 Tunnelling in landslide areas connected to deep seated gravitational deformations: An example in Central Alps (northern Italy) Tunn. Undergr. Sp. Technol. 93 103100

[29] Cuxac P 1991 Etude de la propagation d’ultrasons dans des roches fissurees et anisotropes (National Polytechnic Institute of Lorraine)

[30] Nesse W D 2000 Introduction to Mineralogy (New York: Oxford University Press)