increases, but the confinement levels applied were insufficient (confinement system limit was reached) to provide peak strength values for the Φ_1-Φ_2 envelope. Envelopes from previous authors' test results (Figure 2) converge to this line with increasing stress. However, little information about the rock types tested, sample size or loading rates is provided by the authors. This makes impacts from ductility/brittleness, material fabric, loading and sample size effects, etc., difficult to define with respect to the results and the shape and trend of the failure envelopes.

3. FAILURE MECHANISMS

All samples ultimately failed suddenly and violently in brittle shear. The dominant shear failure mechanism for biaxially tested samples occurred through the Φ_1-Φ_3 plane (Φ_3=0) without exception. Varying degrees of rock spalling from the free faces were observed and

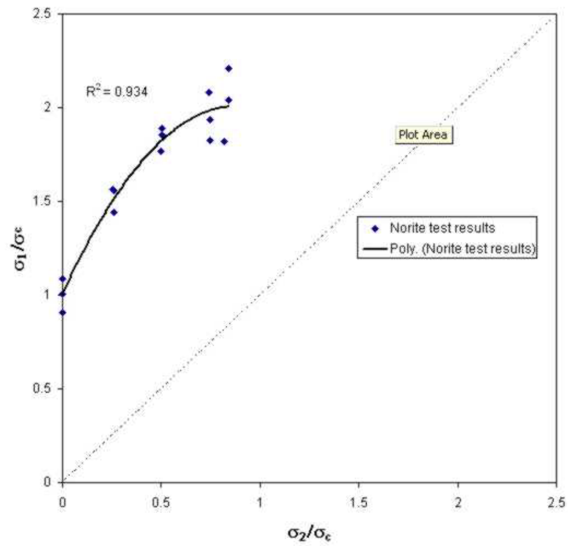

Figure 5. Norite samples biaxial test results.

heard during the test – however this occurred earlier than the dominant shear failure. Figures 6-10 show representative failure modes of blocks with test results shown in Table 1. Figures 11-14 provide failure mechanism evidence for samples tested at a loading rate of 2.25 MPa/sec, three times the rate of samples shown in Figures 6-10.

The effect of the 0.75 MPa/sec and 2.25 MPa/sec loading rate imposed several sample failure trends:

- The sample fails by shear along one diagonal plane under uniaxial conditions, along two intersecting diagonal plane under biaxial conditions
- Very little spalling occurs under uniaxial conditions. Spalling progressively increases with confinement reaching a large portion of the sample volume with highest confinement
- The spalled plates decrease in thickness with confinement, down to a granular size at higher confinements

Figure 6. Failure mode, uniaxial test, 0.75 MPa/sec loading rate.

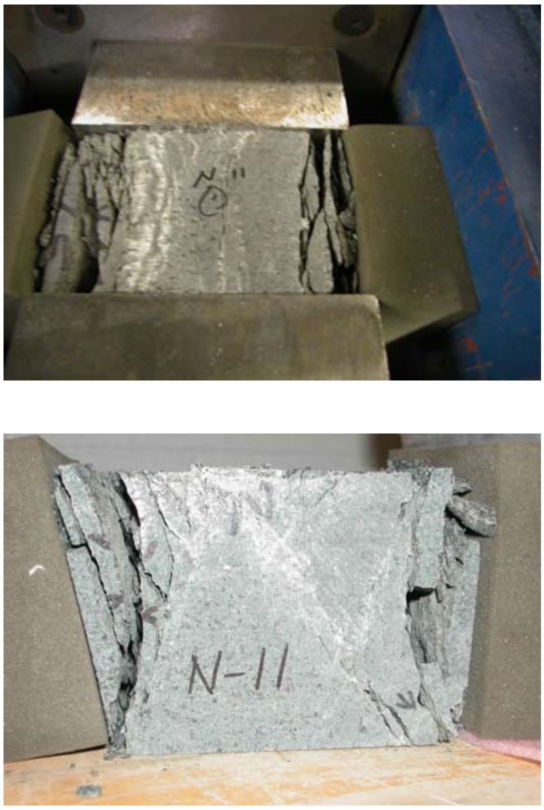

Figure 7. Top and side views, failure mode, 52.3 MPa confinement test, 0.75 MPa/sec loading rate.

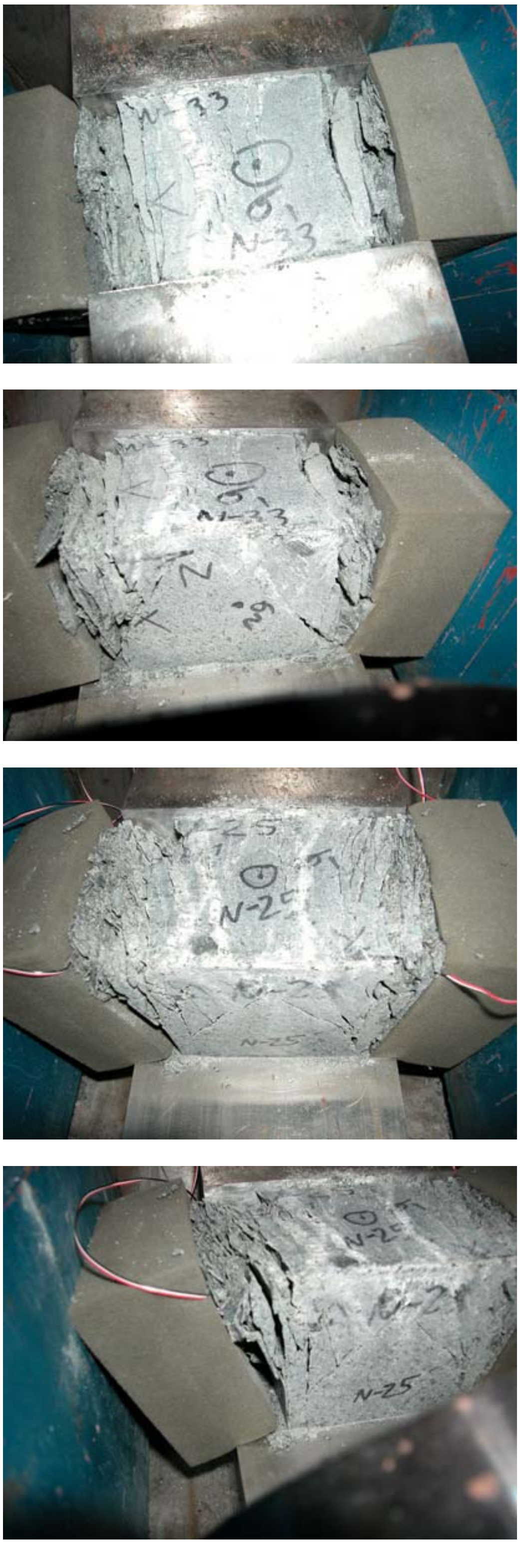

Figure 9. Top and side views, failure mode, 150.6 MPa confinement test, 0.75 MPa/sec loading rate.

Figure 10. Top and side views, failure mode, 169.9 MPa confinement test, 0.75 MPa/sec loading rate

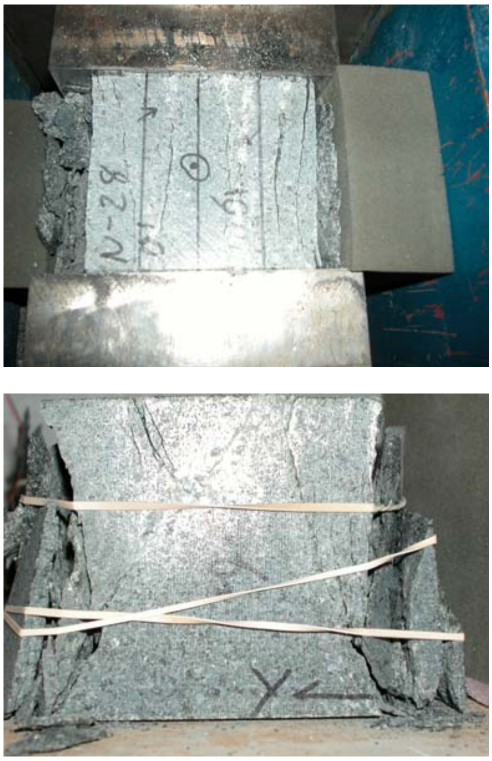

Figure 11. Top and side views, failure mode, 51.3 MPa confinement test, 2.25 MPa/sec loading rate.

Figure 12. Top and side views, failure mode, 101.6 MPa confinement test, 2.25 MPa/sec loading rate.

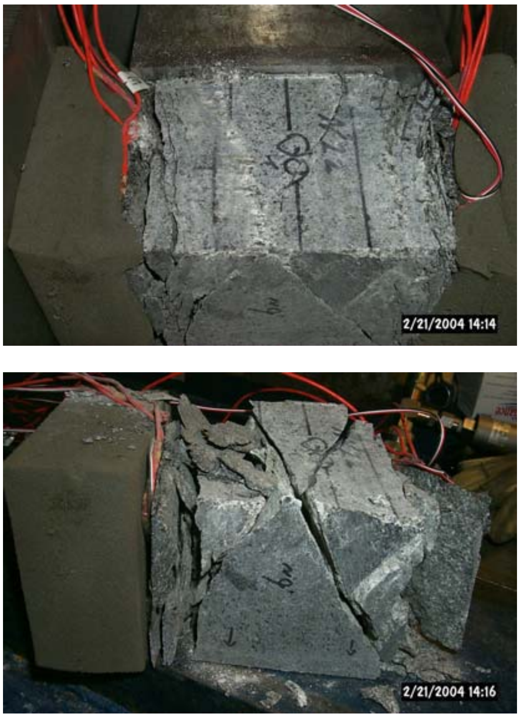

Figure 13. Top and side views, failure mode, 150.7 MPa confinement test, 2.25 MPa/sec loading rate.

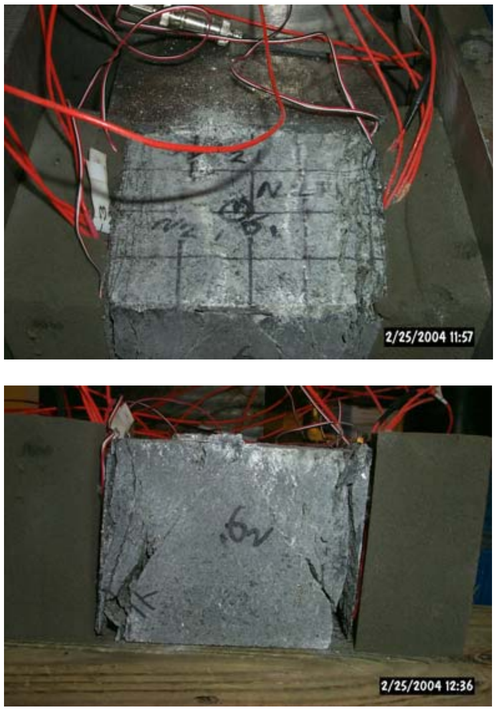

Figure 14. Top and side views, failure mode, 170.5 MPa confinement test, 2.25 MPa/sec loading rate.

- Shearing on the spalling surfaces increases with confinement as seen by the thickness of finely ground material occurring on these
- Spalling plate curvature increases with confinement

Furthermore, the 2.25 MPa/sec laoding rate imposes the following trends:

- For the same level of confinement at these two loading rates, the volume of the sample affected by the spalling is less for the faster loading rate
- The thickness of the spalled plates does not decrease significantly with an increase in confinement for the faster lading rate versus the slower rate.

4. DISCUSSION

The following points address the strength and failure mechanism trends associated with biaxial testing of this brittle rock.

- Due to lateral confinement, biaxial failure strength in the vertical direction is significantly higher than the uxiaxial one. The average biaxial-to-uniaxial strength ratio for the applied confinements ranges from 1.62 to 2.16. The highest strength was not attained due to the confinement system limit.
- Failure of norite under uniaxial and biaxial loading is of brittle, violent nature and is controlled by shear failure in the Φ_1-Φ_3 plane.

- Tensile rock spalling occurs before sample failure at lower confinement levels, but decreases in importance with level of confinement. Shear spalling increases in importance with level of confinement.

  This agrees well with field observations that mining-induced extension fractures form at or very near the stope face and are face–parallel (Anon, 1988) and that such spalling is common in civil engineering tunnels when peripheral stress is sufficiently high (Myrvang and Grimstad 1983)(Broch and Sorheim 1984)(Dowding and Andersson 1986)(LeBel et al. 1987)

  Furthermore, the high intensity of shearing occurring at higher confinements is identical to the field observations (Figure 1) reported by Morrison (1976).
- A faster loading rate delays the onset of intense shearing until a higher confinement level is reached.
- Spalling from all sides is exhibited in the uniaxial sample but without exception, the dominant spalling direction and shear failure mechanism occurs in the Φ_1-Φ_3 plane (Φ_1=0).
- More test results are required to indicate the benefit of very high confinements (i.e. at a level close to $\Phi_1=\Phi_2$).

5. CONCLUSIONS

A clear gain in biaxial strength with lateral confinement is evident from the laboratory results. Testing is required to indicate if there are benefits at very high confinements (using a higher capacity confinement system).

Spalling of thin plates before peak strength is reached, and the final shear failure of the sample, occur in the Φ_1-Φ_3 plane. Spallings effects are clearly defined. A limited portion of the sample periphery is subject to extension spalling, producing plates several millimeters thick, at low confinements. With higher confinement, spalling is created by intense localized shearing, leading to the formation of very thin, rock grain-thick plates that are not forcefully ejected by the time totall sample failure on two shear planes occurs.

This mirrors field behaviour of highly stressed openings where shearing and progressive closure of the opening periphery is in effect prior to rockbursting with increasing applied peripheral stress.

The delay in the onset of intense shearing as a result of a higher stress loading rate has a practical application: a higher rock mass extraction rate would have for effect of reducing the onset of rock mass shearing as a pre-cursor to rockbursting, i.e. the periphery of the rock would be subject to limited shearing after tensile spalling occurs, leading more rapidly to rockbursting.
Further testing is required to better define brittle rock behaviour (commonly with rockbursting potential) under biaxial testing as a valid representation of field behaviour. The effect of loading rate on the development of failure as well as strength effects is also important.

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