ROCK STRENGTH, ROCK BRITTLENESS AND BLAST FRAGMENTATION

Presenter: Professor Dick Stacey
It is logical to expect that the more brittle a material, the greater will be the extent of fragmentation when it breaks.
Mundane example:

- Glass jar
- China jar
- Unfired clay jar
- All the same size and shape, and same mass
- Dropped on a stone floor, same energy input, but completely different failure behaviour
- Function of the material characteristics: the glass jar will shatter

What is brittleness? How is it defined?
Several brittleness concepts:

B1 = $\varepsilon_r / \varepsilon_t$
where $\varepsilon_r$ is the reversible strain and $\varepsilon_t$ is the total strain, determined from the stress-strain curve in a UCS test

B2 = $W_r / W_t$
Where $W_r$ is the reversible energy and $W_t$ is the total energy, determined from the UCS stress-strain curve

B3 = $(\text{UCS} - \sigma_T)/(\text{UCS} + \sigma_T)$
where $\sigma_T$ is the tensile strength.
And more:

\[ B_5 = q \times \text{UCS} \]

where \( q \) is the percentage of fines formed in the Protodyakonov impact test

\[ B_6 = (H_\mu - H)/K \]

where \( H_\mu \) is the micro-indentation hardness and \( H \) is the macro-indentation hardness.

\[ B_8 = \frac{\text{UCS}}{\sigma_T} \]

\[ B_9 = \frac{(\text{UCS} \times \sigma_T)}{2} \]
There are about 30 different formulae for the calculation of a “brittleness”, and I want to ignore all those that I have shown, and introduce a concept that is related to a special type of rock testing called “stiff testing”

An introduction to compressive strength testing of rock
Equipment for Uniaxial Tests (with deformation measurement)
- In common rock strength testing, most “hard” rock specimens “blow apart” when the UCS is reached.
- This is due to the energy stored in the testing machine and in the rock specimen itself.
- Standard or commonly used testing machines are “soft”, i.e., they can store a lot of energy.
- The full stress-strain behaviour of brittle rock samples (ie no “blow apart”) can be determined using “stiff” testing machines
- Special servo-controlled machines are used for stiff testing nowadays
- Sensors detect when failure is imminent, and energy is then extracted very rapidly from the system before “blow apart” occurs
- This sequential loading and then rapid extraction of energy allows the full load-deformation, or stress-strain behaviour to be recorded
Fig. 1. Classification of class I and class II behavior of rock failure in uniaxial compression [4].
- Infinite stiffness, line AD
- Class I and Class II classification
- Energy input is required for Class I, but available for Class II. The shaded area in the graph is “the surplus energy which would be supplied by a rigid machine with infinite modulus ... leading to uncontrolled failure” (self-sustained failure)
- Negative slope for Class I, positive slope for Class II
- Stiffness artificially greater than infinite stiffness

Fig. 1. Classification of class I and class II behavior of rock failure in uniaxial compression [4].
“Cylindrical specimens that exhibit Class I behavior tend to be somewhat ductile in nature when loaded axially; whereas specimens that exhibit Class II behavior tend to respond in a brittle fashion to axial loading ...” *(quote from ISRM SM)*

The closer the slope of the positive post-peak curve is to the pre-peak curve (ie the further from the vertical infinite stiffness line), the more the energy stored and the more brittle the rock.
Examples of partial complete stress-strain curves for an extraordinarily brittle rock.
Tarasov and Potvin (2013) introduced several brittleness concepts, based on the complete stress-strain behaviour of rock in a compressive test determined using a servo-controlled testing machine:

\[ K_1 = \frac{(M-E)}{M} \]

\[ K_2 = \frac{E}{M} \]

Another: \[ K = \frac{(E-M)}{M} \]

Where \( E \) is the elastic modulus (unloading)
\( M \) is the post-peak modulus

Note that when \( E \) and \( M \) are nearly equal, \( K_1 \) and \( K \) approach zero, described by Tarasov as absolute brittleness
Brittleness variation with rising confining pressure for rocks of different hardness

It is generally believed that rising $\sigma_3$ makes rocks less brittle.

Dramatic rock embrittlement and superbrittle behavior at high $\sigma_3$

The harder and stronger the rock the greater effect of embrittlement is.
- Energy stored in the rock specimen depends on rock strength and rock brittleness
- The higher the UCS, the greater the energy available for “blowing apart”
- Violence of the event depends on the amount of energy stored - stiffness of the testing machine, UCS of rock and brittleness of the rock
Fig. 1. Classification of class I and class II behavior of rock failure in uniaxial compression [4].
The shaded area in the graph is “the surplus energy which would be supplied by a rigid machine with infinite modulus ... leading to uncontrolled failure.” (quote from ISRM SM)

“... Failure for class II rock behavior is self-sustaining, ie the elastic strain energy stored in the sample when the applied stress equals the compressive strength is sufficient to maintain fracture propagation until the specimen has lost virtually all strength”

“Obviously, class II behavior cannot be established by way of stiffening the testing machine alone because fracture would proceed even if the machine stiffness were infinite” (quotes from Wawersik and Fairhurst, 1970)
\[ \sigma_A = 220 \text{ MPa} \quad \sigma_A = 260 \text{ MPa} \quad \sigma_A = 310 \text{ MPa} \quad \sigma_A = 600 \text{ MPa} \]
Fragmentation (4)
Results: UCS vs Class
Class I
Class II

(Akinbinu, 2013)
log$_{10}(y)=5.036+0.001578x; \quad R^2=0.914$ blast test

log$_{10}(y)=2.705+0.008077x; \quad R^2=0.959$ compression test

(Akinbinu, 2013)
$y = 292.03e^{0.0073x}$

$R^2 = 0.9813$
Fragmentation of stressed glass tubes
(acoustically non-transparent interfaces)

From Stavrogin and Tarasov

Experimental results obtained on structure-less brittle material (glass) reveal the relation between elastic energy accumulated within the material before failure and fragmentation. Increase in stress leads to excessive fragmentation.
RESEARCH QUESTION

The empirical results show clear correlations between rock strength and fragmentation and between rock brittleness and fragmentation. The research question is whether these relationships can be supported by theory, so that brittleness, in combination with strength, can be taken into account in the prediction of fragmentation in blasting.