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 = εr/εt
where εr is the reversible strain and εt is the total strain, determined from the stress-strain curve in a UCS test

B2 = Wr/Wt
Where Wr is the reversible energy and Wt is the total energy, determined from the UCS stress-strain curve

B3 = (UCS - σ_T)/(UCS + σ_T)
where σ_T is the tensile strength.

And more:

B5 = q x UCS
where q is the percentage of fines formed in the Protodyakonov impact test

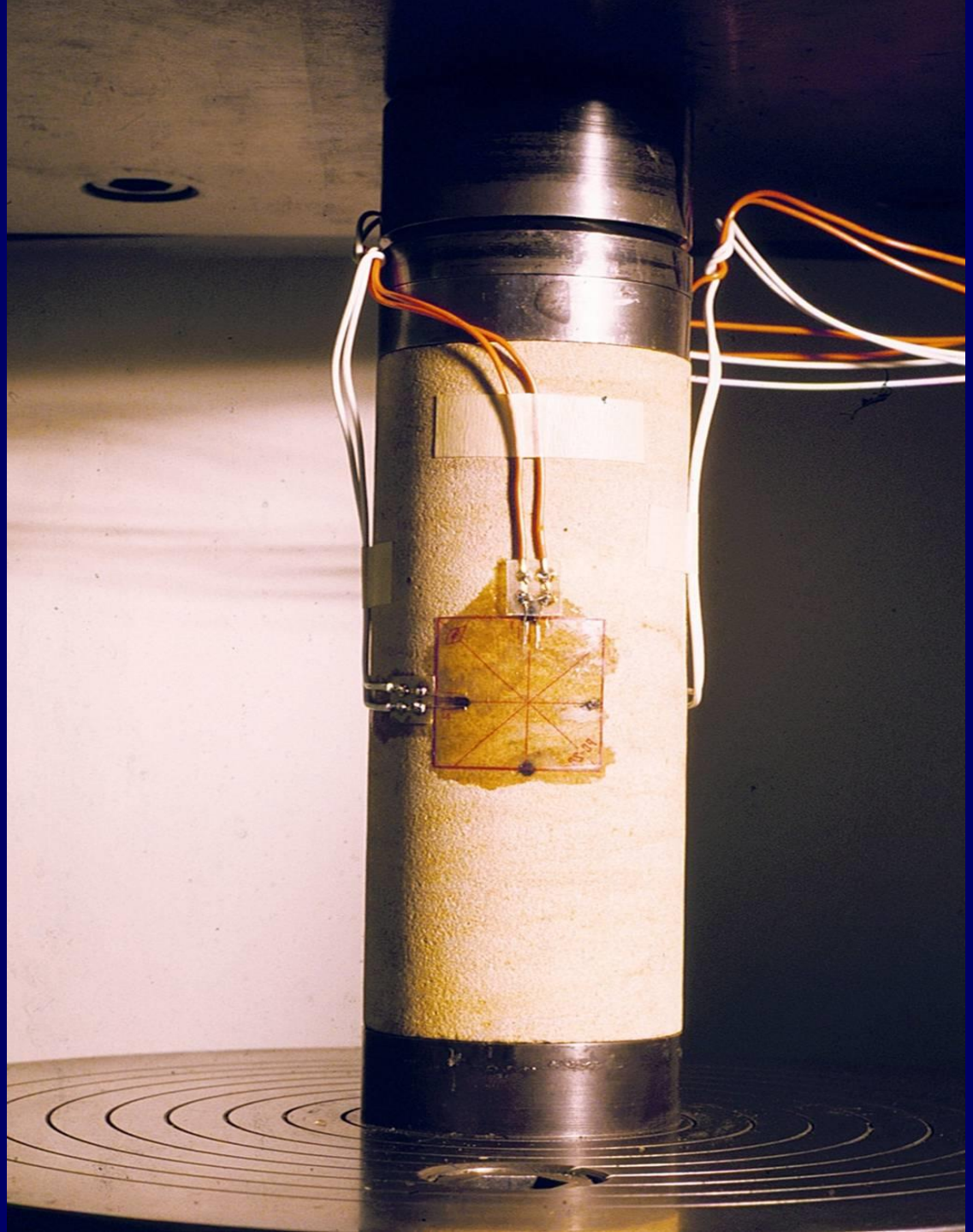
B6 = (Hμ – H)/K
where Hμ is the micro-indentation hardness and H is the macro-indentation hardness.

B8 = UCS/σ_T

B9 = (UCS x σ_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



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- 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", ie 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

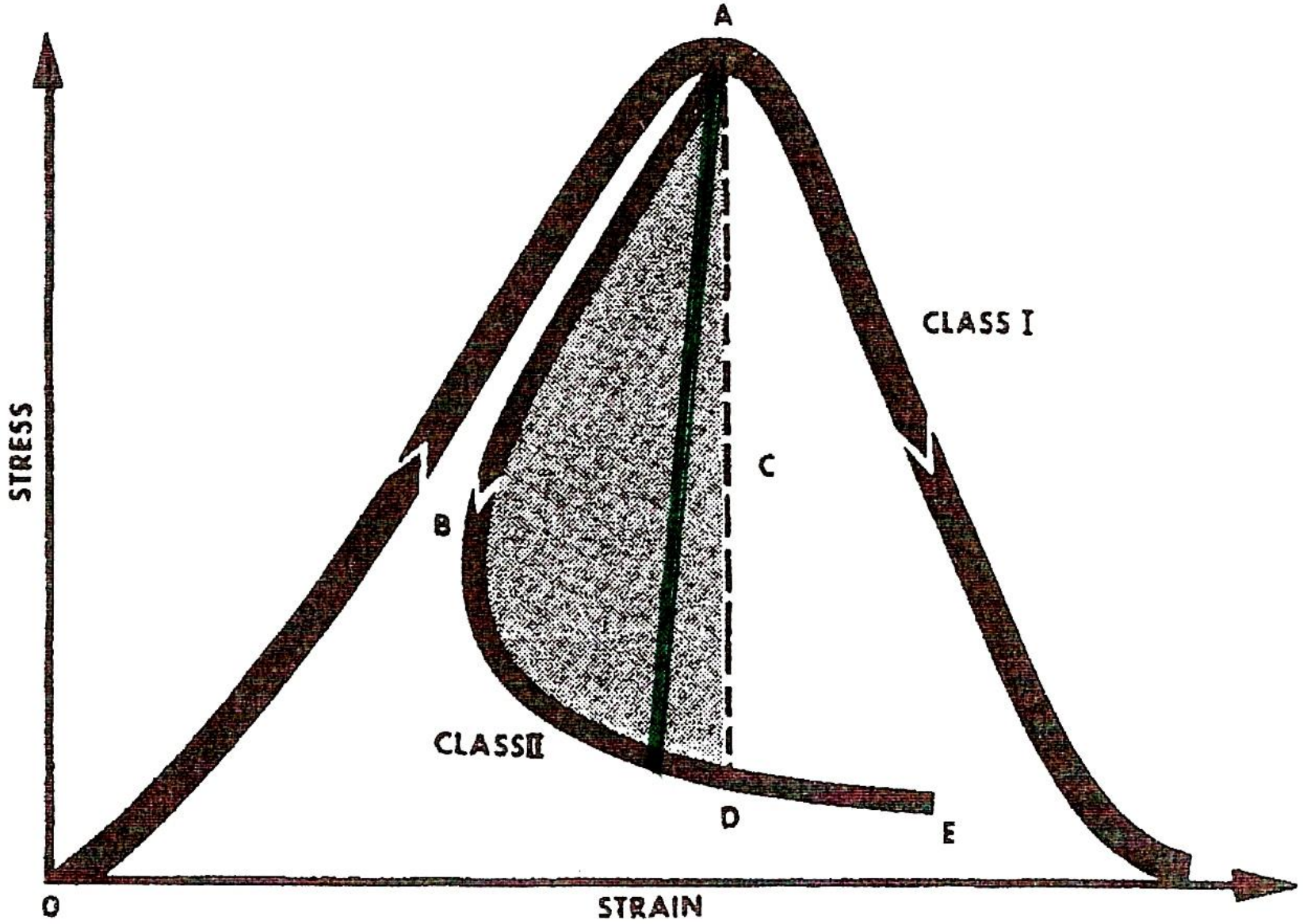


Fig. 1. Classification of class I and class II behavior of rock failure in uniaxial compression [4].

- 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

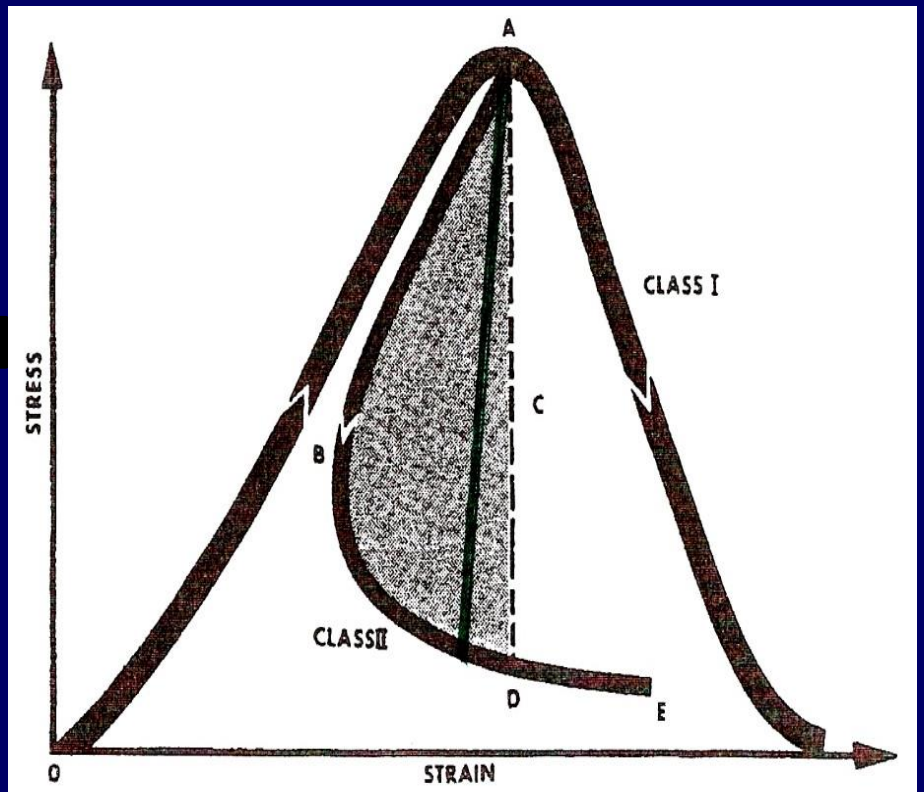
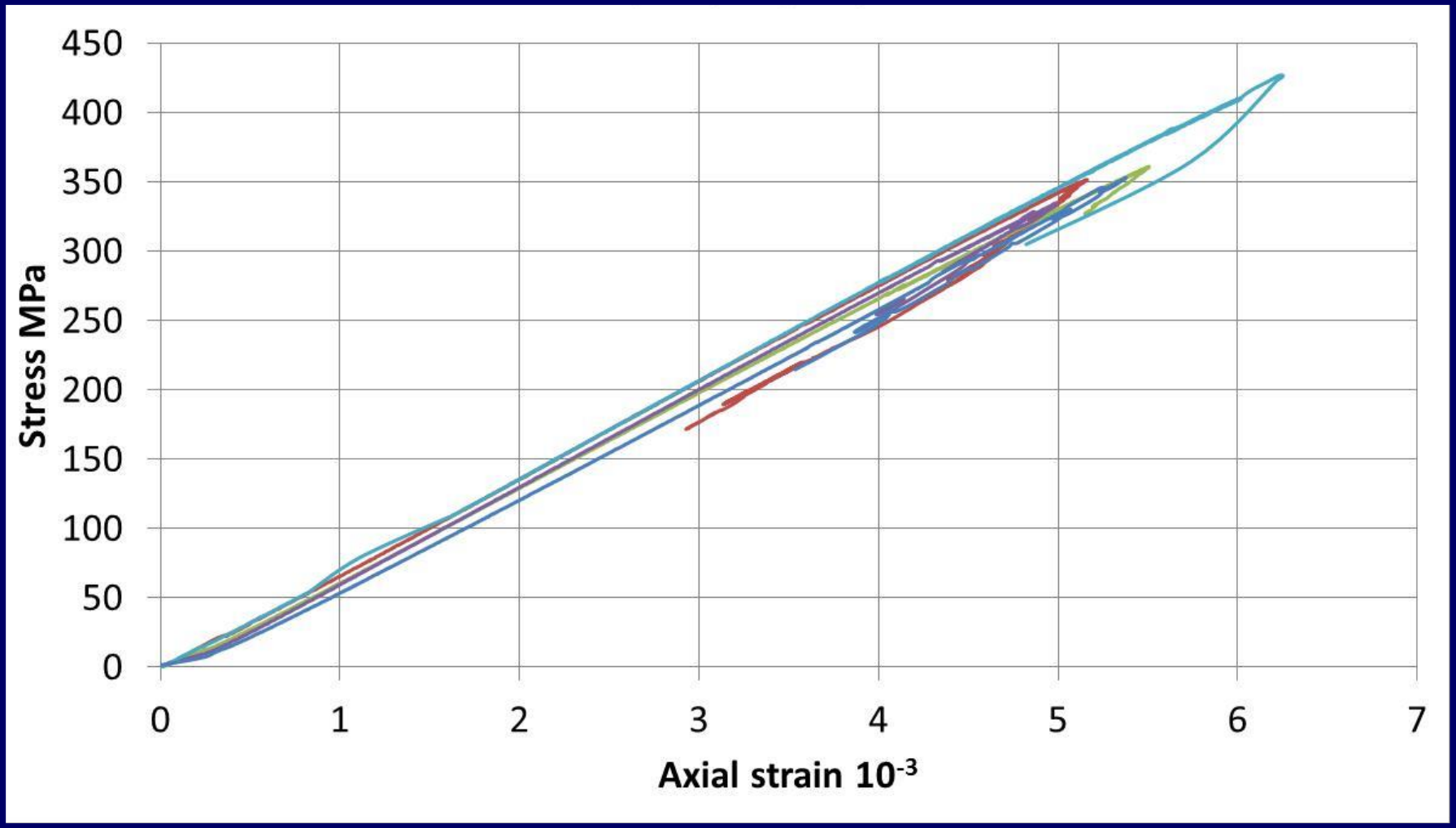


Fig. 1. Classification of class I and class II behavior of rock failure in uniaxial compression [4].

"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:

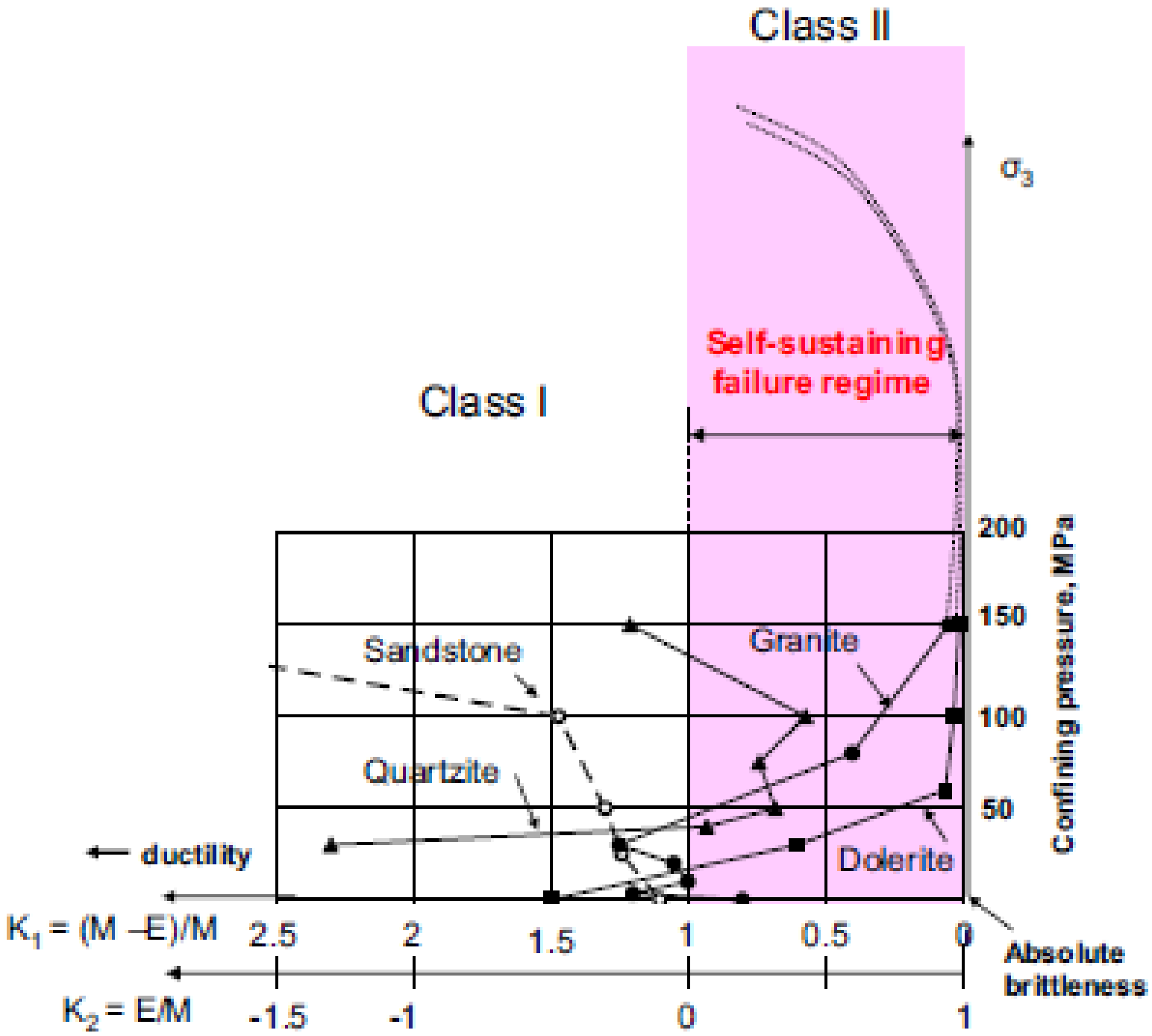
K1 = (M-E)/M

K2 = E/M

Another: K = (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, K1 and K approach zero, described by Tarasov as absolute brittleness

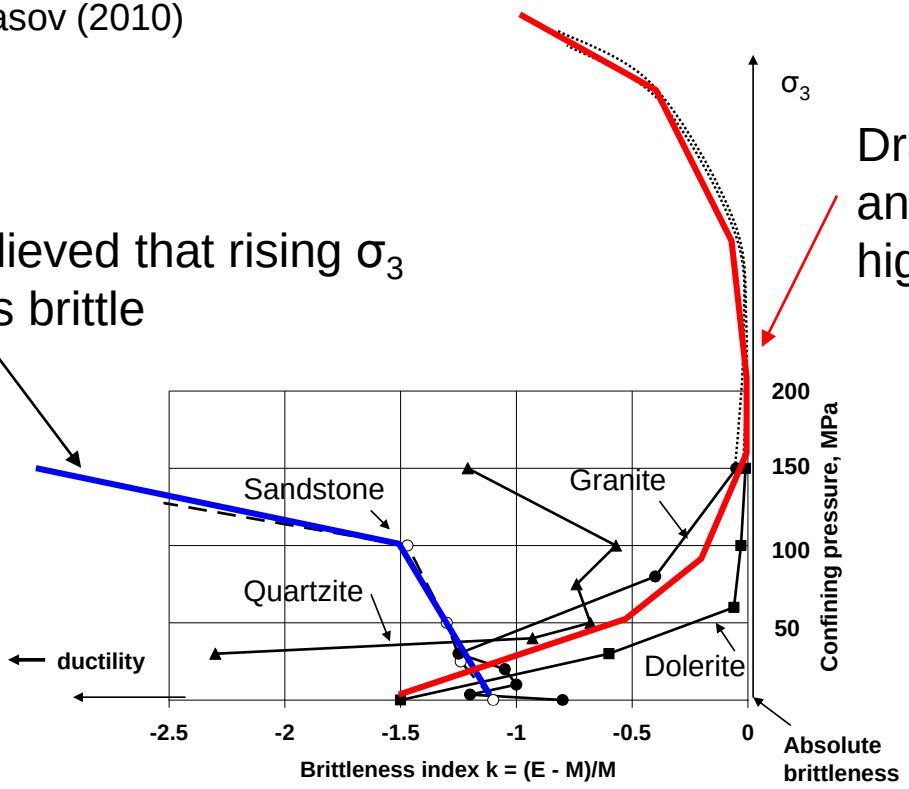

Class II
Class I
Self-sustaining failure regime
σ_3
Confining pressure, MPa
200
150
100
50
Sandstone
Granite
Quartzite
Dolerite
ductility
$K_1 = (M - E)/M$
2.5
2
1.5
1
0.5
0
Absolute brittleness
$K_2 = E/M$
-1.5
-1
0
1

Brittleness variation with rising confining pressure for rocks of different hardness

From Tarasov (2010)

It is generally believed that rising σ_3 makes rocks less brittle

Dramatic rock embrittlement and superbrittle behavior at high σ_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

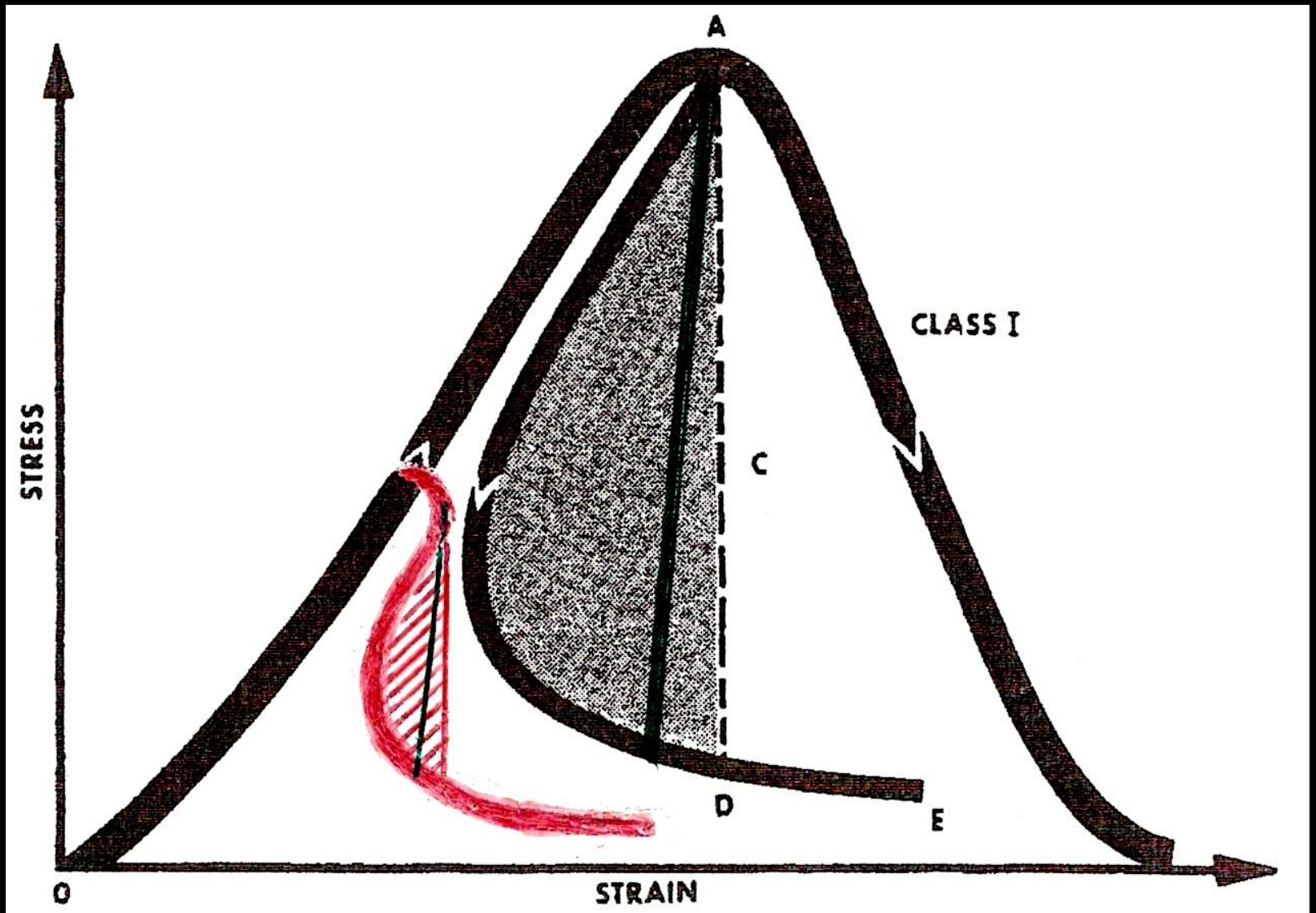


Fig. 1. Classification of class I and class II behavior of rock failure in uniaxial compression [4].

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)***

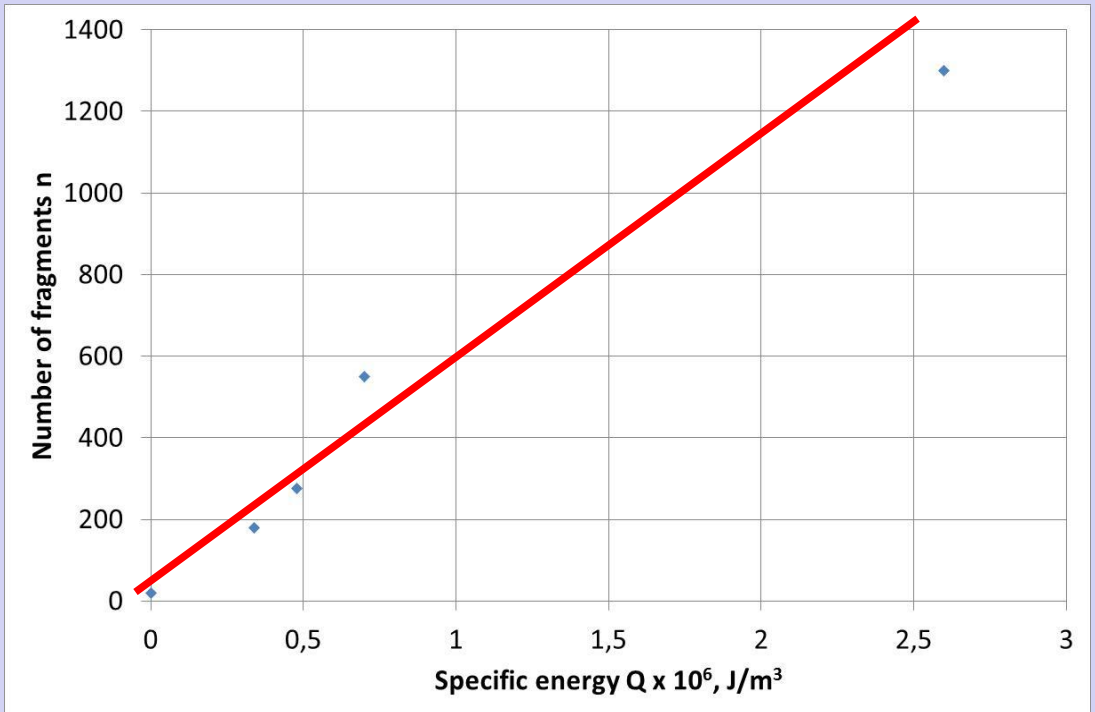
σ_A = 220 MPa

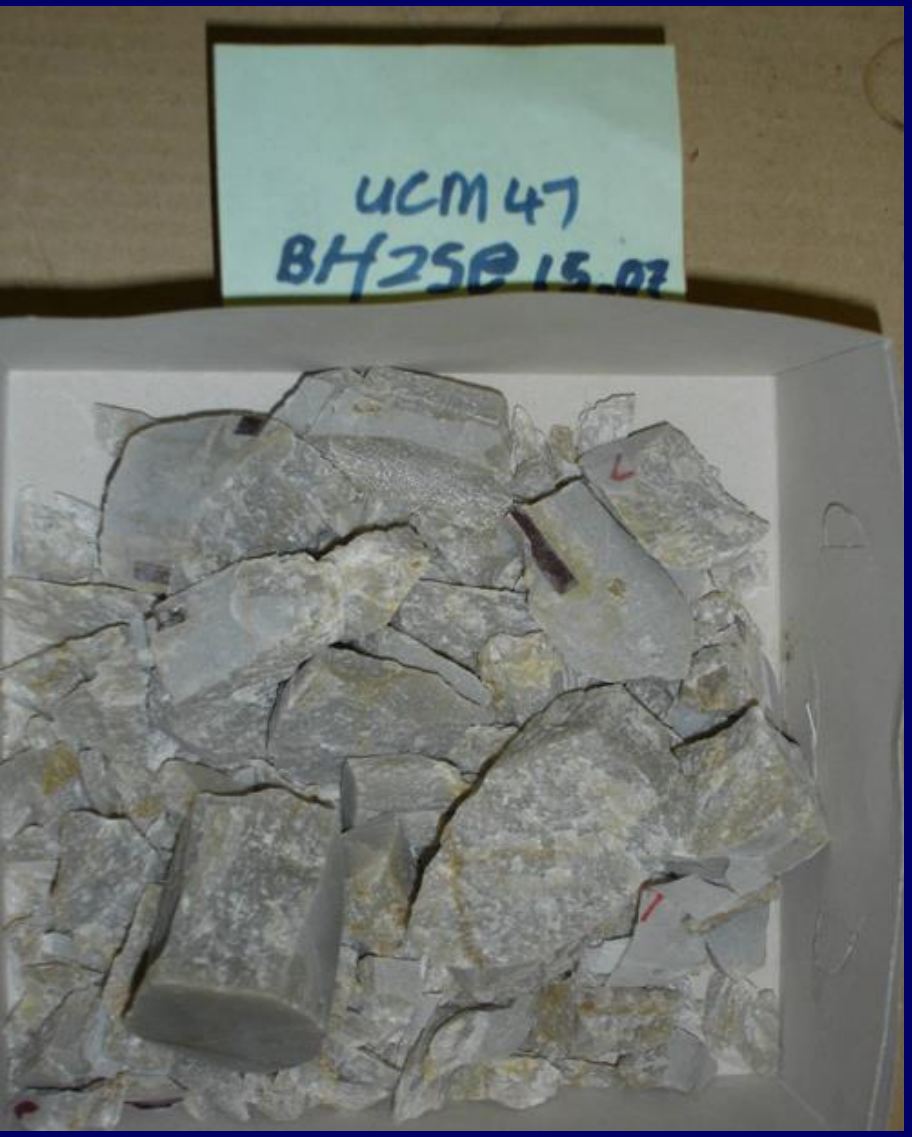
σ_A = 260 MPa

σ_A = 310 MPa

σ_A = 600 MPa

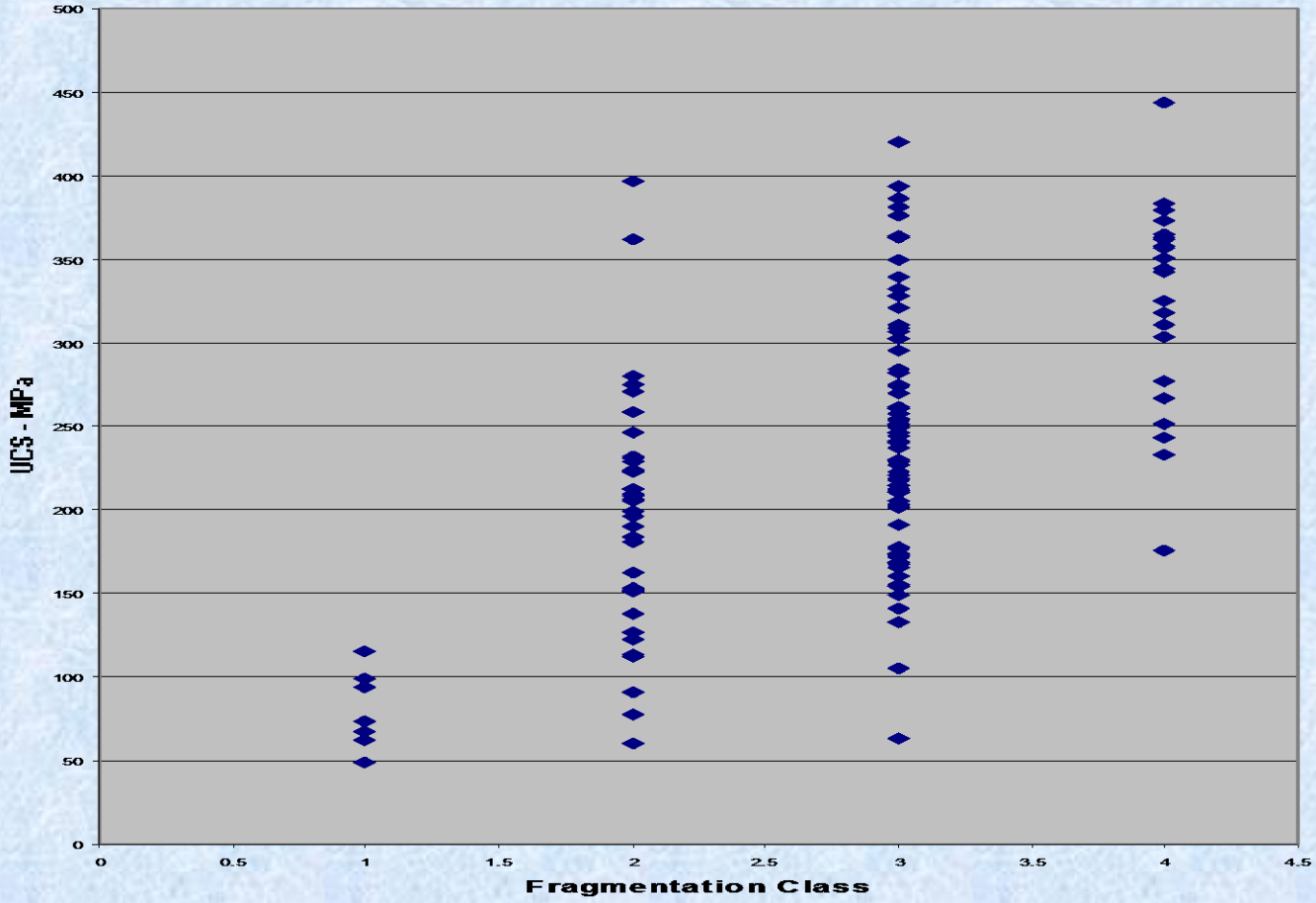
b)



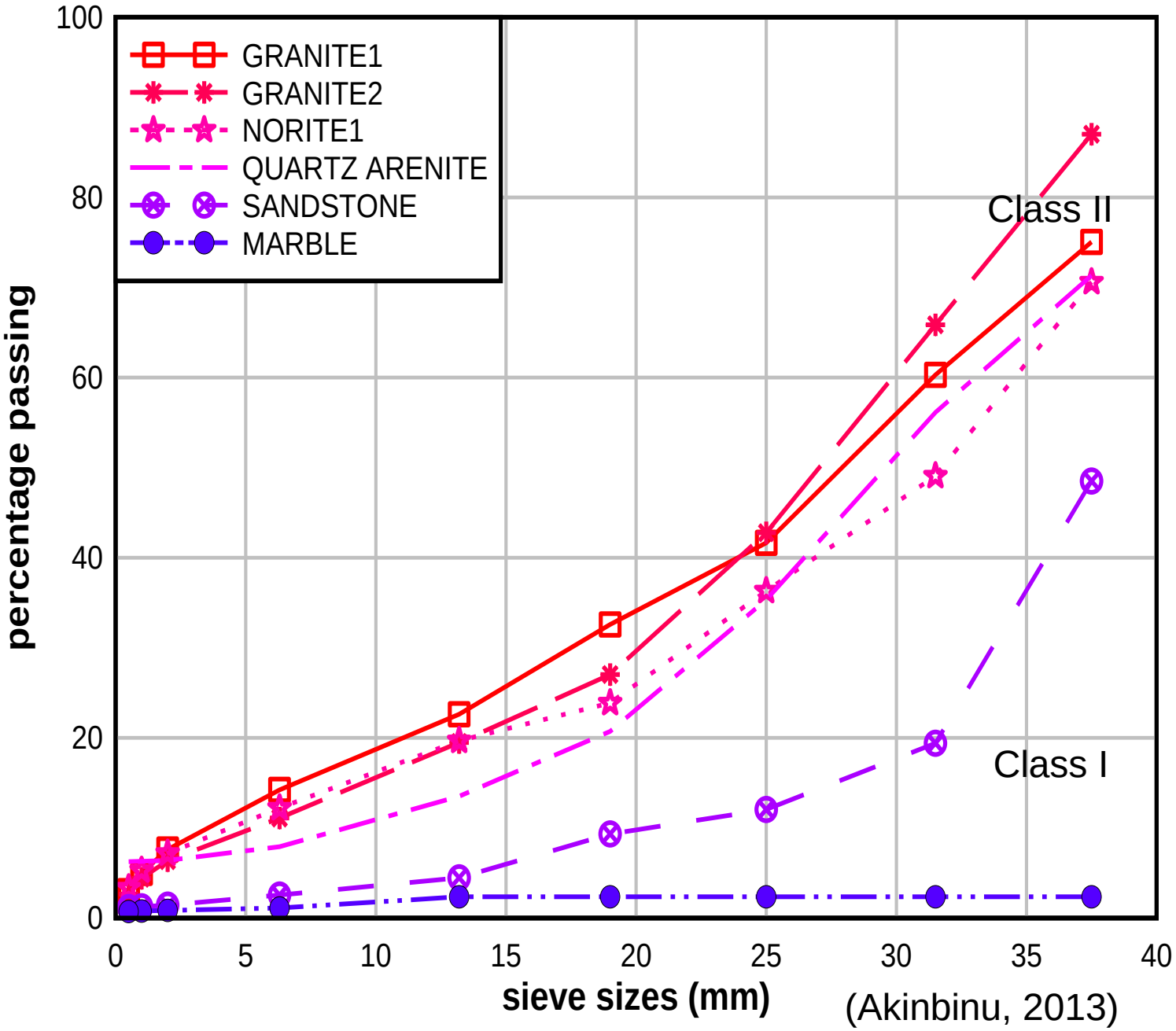

UCM 47

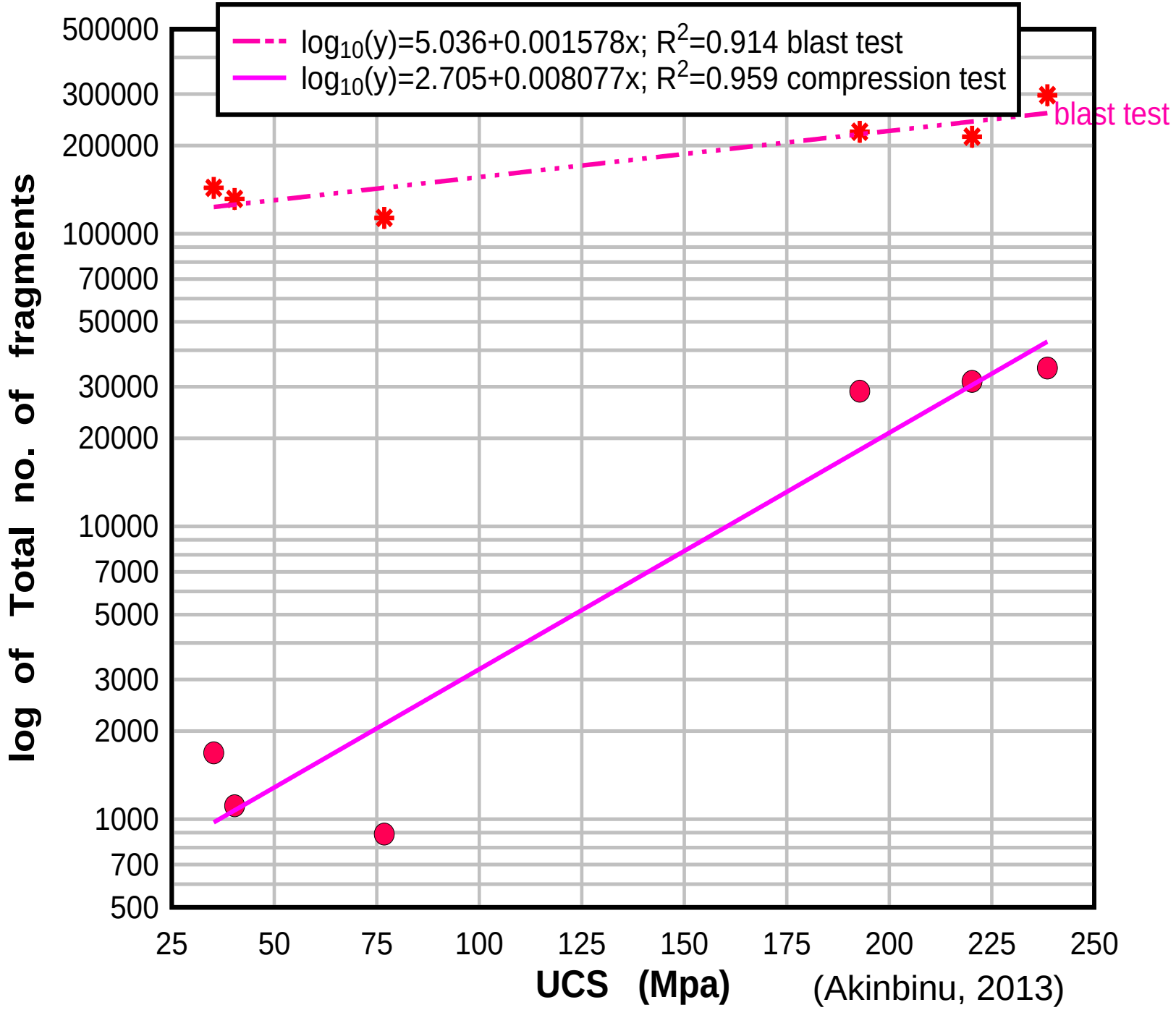
UCM 61
BH27 09.28.

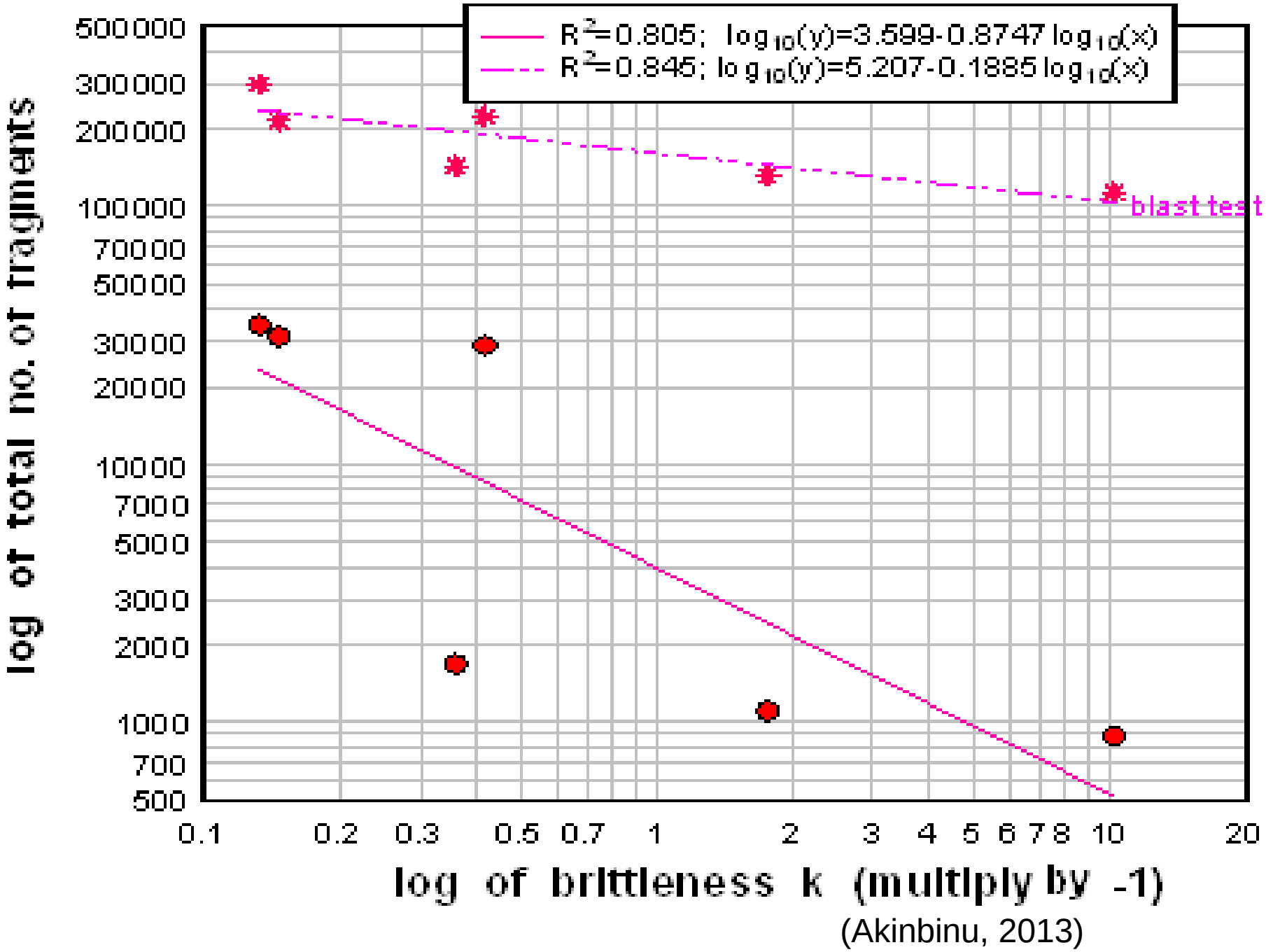
Fragmentation (4)
Results: UCS vs Class



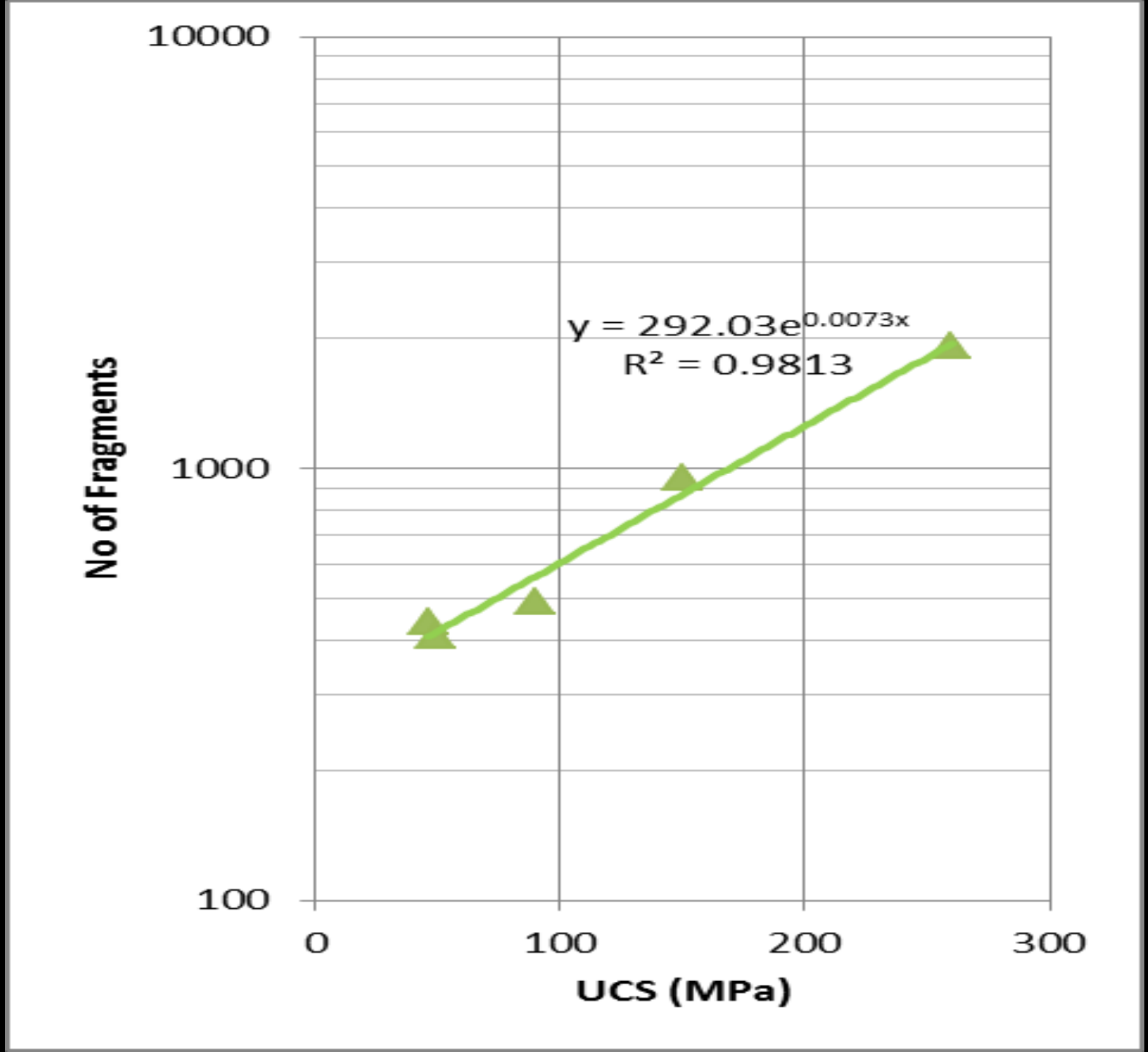
RAI


GRANITE1
GRANITE2
NORITE1
QUARTZ ARENITE
SANDSTONE
MARBLE
Class II
Class I
percentage passing
sieve sizes (mm)
0
20
40
60
80
100
0
5
10
15
20
25
30
35
40
(Akinbinu, 2013)


log10(y)=5.036+0.001578x; R2=0.914 blast test
log10(y)=2.705+0.008077x; R2=0.959 compression test
blast test
log of Total no. of fragments
500000
300000
200000
100000
70000
50000
30000
20000
10000
7000
5000
3000
2000
1000
700
500
25
50
75
100
125
150
175
200
225
250
UCS (Mpa)
(Akinbinu, 2013)



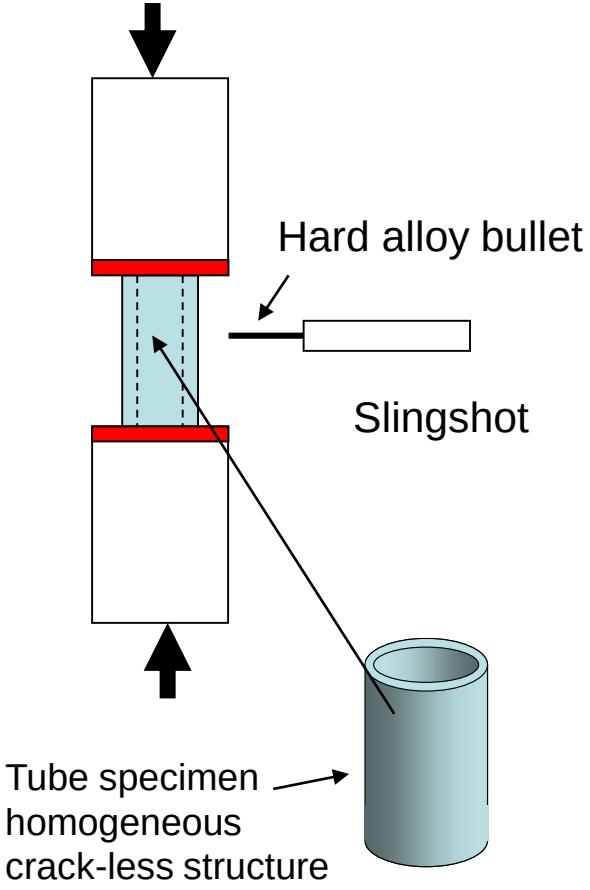
(Akinbinu, 2013)


10000
1000
100
No of Fragments
y = 292.03e0.0073x
R² = 0.9813
0
100
200
300
UCS (MPa)

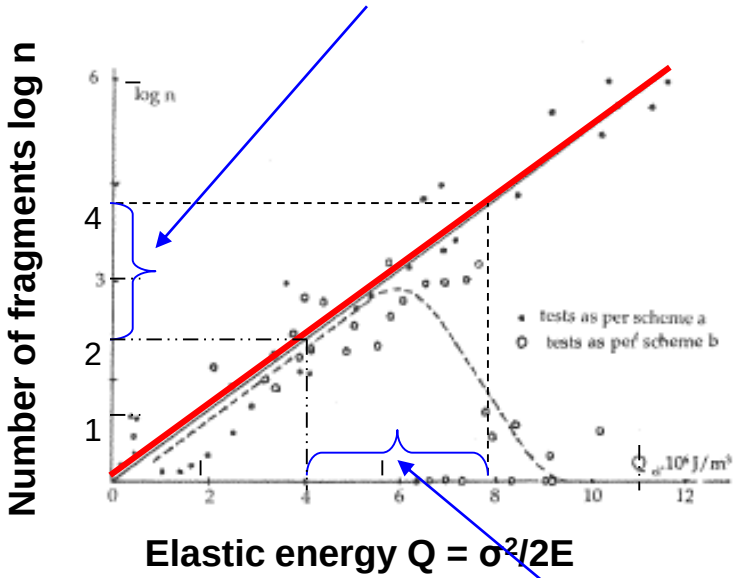
Fragmentation of stressed glass tubes

(acoustically **non-transparent** interfaces)

From Stavrogin and Tarasov



Increase in number of fragments by 100 times



Elastic energy $Q = \sigma^2/2E$

Increase in accumulated energy by 2 times

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.