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# Scale effects in rock strength properties.

## Part 1: Unconfined compressive test and Brazilian test

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**ABSTRACT:** Performing a testing program to evaluate the impact of shape and size on common rock properties, some surprising results were encountered. Firstly, the shape effect had the greatest impact on rock strength properties. In the typical range of length/diameter ratios varying from 1 to 3, the influence on destruction work, modulus of elasticity and tensile strength is quite significant. In comparison, the effect on unconfined compressive strength is much lower. Depending on the measuring technique used for longitudinal displacement along the core sample, the modulus of elasticity increases and the strain destruction work decreases with core length. Size, very often considered to have a controlling influence on strength, in contrast to shape only had a marginal effect within the tested diameter range from 50 to 110 mm. Such testing results should be considered when the suggested methods for determining the uniaxial compressive strength, deformability of rock materials and the tensile strength are revised.

### 1 SCOPE

In rock mechanics and engineering geology, the unconfined compressive test and the Brazilian test are considered to be the most wide spread methods to obtain rock strength properties. Well known is the scale effect concerning the unconfined compressive strength but little data has been published since the early 1980s (with the exception of Hoek & Brown 1980, Hawkins 1998) and even less when considering other important rock properties.

Since modern testing devices today allow sophisticated servo-controlled stress-strain paths and PC-based monitoring to obtain all data, a state-of-the-art approach would be favourable. Now, the results of the classic testing methods can be updated as well as the determination of properties not yet included. Strong efforts have led to a research program studying the principles of rock strength properties in different rock types such as metamorphic, igneous and sedimentary rock (Schütz 1995, Zäh 1999). In this contribution emphasis is placed on scale effects of

- unconfined compressive strength
- modulus of elasticity (Young's modulus)
- destruction work (strain energy; defined as the integral of the stress-strain curve)
- and tensile strength

The tests were performed using core diameters between 50 and 110 mm, since most of the core samples taken during typical site investigations are

of this size. In this context, the so-called “scale effect” is split up into two categories: shape and size.

- 1 The shape effect describes the impact of variation of the length/diameter ratio of a cylindrical specimen (“core”) on rock strength properties.
- 2 The size effect is defined by the influence of the absolute size (i.e. diameter) of the core sample where the length/diameter ratio is left constant.

### 2 CORE TESTING

#### 2.1 Unconfined compressive test

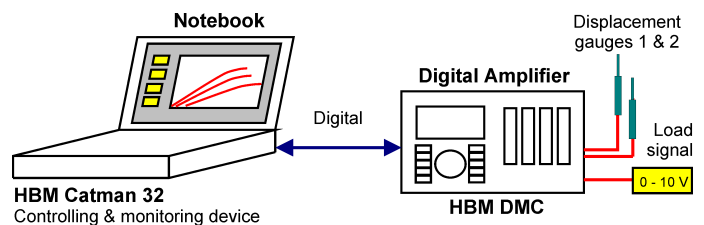


Figure 1. PC-based testing arrangement for determining complete stress-strain curves during unconfined compressive tests with a digital monitoring equipment.

The unconfined compressive tests were performed using a servo-controlled testing machine with a stiff frame and a digital monitoring device (Figure 1). Figure 2 shows the core specimen during loading, calculating strain along the entire length of the core

following the ISRM (1978a) suggested methods and those of Fairhurst & Hudson 1999. In addition to the standard values of unconfined compressive strength (UCS) and modulus of elasticity (Young's modulus;  $E$ , Figure 3), the complete stress-strain curve was measured. The value defined as the integral of the curve was calculated, an termed the "specific destruction work"  $W$  [ $\text{kJ}/\text{m}^3$ ], in short: destruction work (after Thuro & Spaun 1996a, b, Thuro 1997, Figure 3). This parameter is sometimes also described as "strain energy" by other authors.

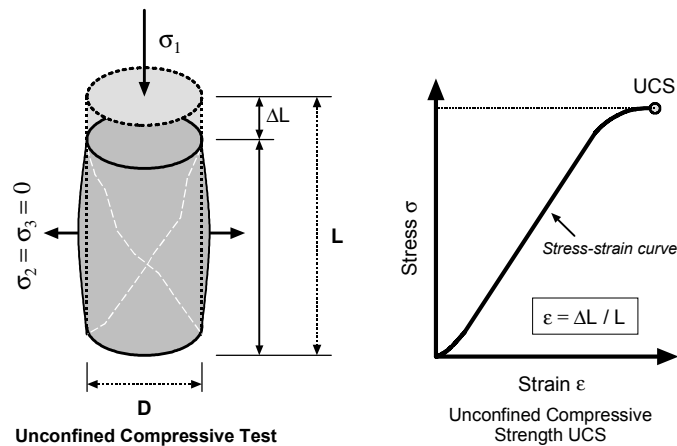


Figure 2. Unconfined compressive test – core specimen with failure under unconfined compression. Terms and abbreviations.

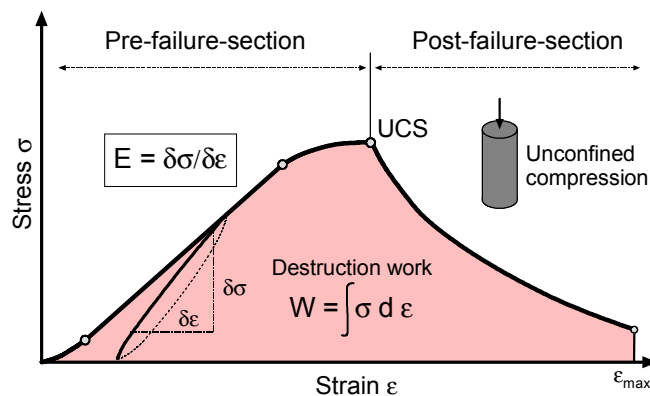


Figure 3. Unconfined compressive test – complete stress-strain curve and determining modulus of elasticity (Young's modulus  $E$ ) and specific destruction work  $W$  (strain energy).

As can be observed, the integral of the envelope curve is an energy (or work) related to the volume, required for destruction of the rock sample. As a product of both stress and strain, destruction work represents the work of deformation including the post-peak section. Whereas the modulus of elasticity submits the gradient (derivation) of the linear section, the destruction work is estimated out of the area (integral) under the stress-strain-envelope.

The value of the maximum strain  $\epsilon_{\text{max}}$  taken for determining destruction work is the one strain value

which is still associated with failure. The strength of a more or less fractured rock sample, which only reacts upon friction with an increase of strength, is excluded in the determination of destruction work.

## 2.2 Brazilian test

The Brazilian test was performed to determine the indirect tensile strength according to ISRM (1978b) suggested methods. The same testing equipment was used as that for the unconfined compressive tests using  $5 \times 20$  mm hard fibre stripes for load distribution of the diametrically tested specimen (Figure 4).

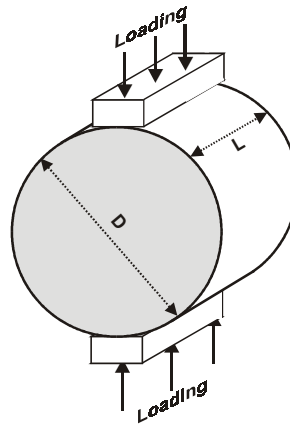


Figure 4. Brazilian testing arrangement for determining indirect tensile strength. Core specimen and abbreviations.

## 2.3 Testing setup

Three rock types were tested which could be obtained in high quality out of quarries, meaning that emphasis has been placed on homogeneity and isotropy of the samples:

- A coarse-grained two-mica granite of the Bavarian forest near Passau, Germany.
- A fine-grained, pyroxen- and amphibole-rich kerantite (a type of mafic dyke) of the south Bohemian massif near Vienna, Austria.
- A fine- to medium-grained clastic limestone of the northern alps near Salzburg, Austria.

The following testing program was performed:

- 1 For the shape effect during unconfined compression, common length-diameter ratios between 1 and 3 in steps of  $\frac{1}{4}$  were drilled out of  $\varnothing 50$  mm cores, and a mean value was calculated from 3-5 samples for each step.
- 2 For the shape effect during the Brazilian test, common length-diameter ratios between 0.5 and 2 in steps of  $\frac{1}{4}$  were cut out of  $\varnothing 70$  mm cores, calculating a mean value from 3-4 samples for each step.
- 3 For the size effect under unconfined compression, the diameter of the cores was varied between 45 and 80 mm with an exception of 110 mm for the granite. This resulted in length-diameter ratios

constant with 2.0. Mean values were calculated from 3-5 samples for each diameter. In our experience these core diameters represent typical core sizes in geotechnical testing practice.

- For the size effect during the Brazilian test, the diameter of the cores was varied between 45 and 80 mm leaving the length-diameter ratio constant with 1.0 and calculating a mean value out of 4 samples for each diameter.

### 3 RESULTS

#### 3.1 Shape effect

Various results from the performed testing program can be seen in the Figures 5 to 8. The mean values of the rock properties are plotted against the length/diameter ratio together with their maximum and minimum. Since the interesting point is the variation of the received values, the right hand scale is normalized for a  $L/D=2.0$  equals 1 (compression tests) and  $L/D=1.0$  equals 1 (Brazilian tests). For all the diagrams a logarithmic regression function has been chosen in the common form  $f(x) = a + b \ln(x)$  where  $x = L/D$ . The relationship found for all three rock types resemble one another very closely, suggesting a geometrical factor for the correlation.

Surprisingly, the influence on the destruction work (Figure 6), the modulus of elasticity (Figure 7) and the tensile strength (Figure 8) is quite significant with a standardizing factor between app. 0.7 and 1.3 meaning about 30% variation. In comparison, the effect on unconfined compressive strength is much lower with a standardizing factor between approx. 0.95 and 1.05 meaning only 5% variation.

Remarkably the modulus of elasticity increases and the destruction work decreases with core length, which will be discussed in section 4. Also the indirect tensile strength is strongly dependent on the variation of the length to diameter ratio.

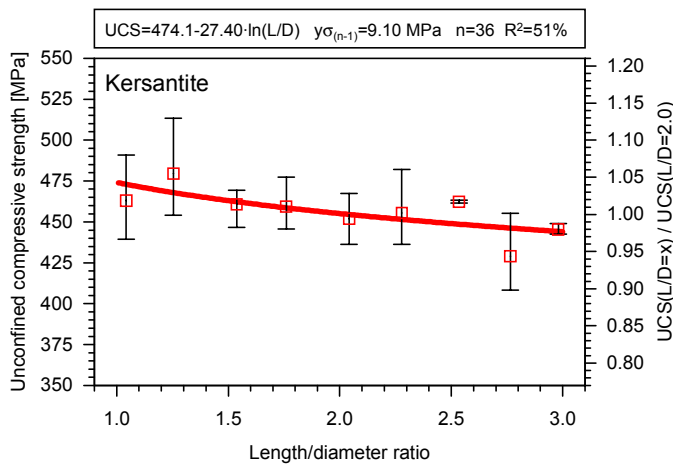


Figure 5. Unconfined compressive strength of the kersantite samples in correlation with core shape (length/diameter ratio).

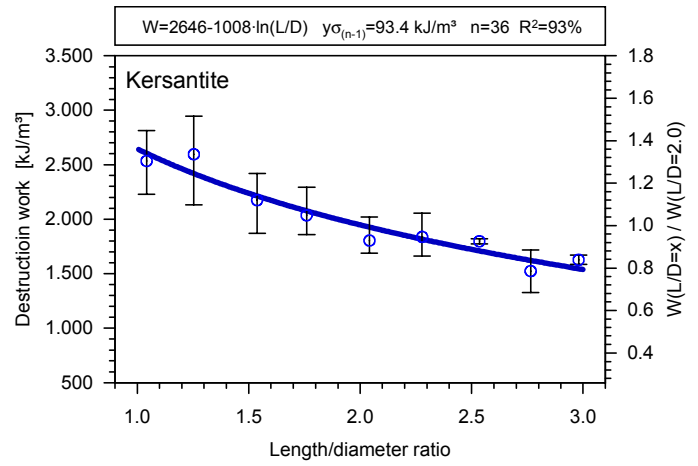


Figure 6. Destruction work of the kersantite samples in correlation with core shape (length/diameter ratio).

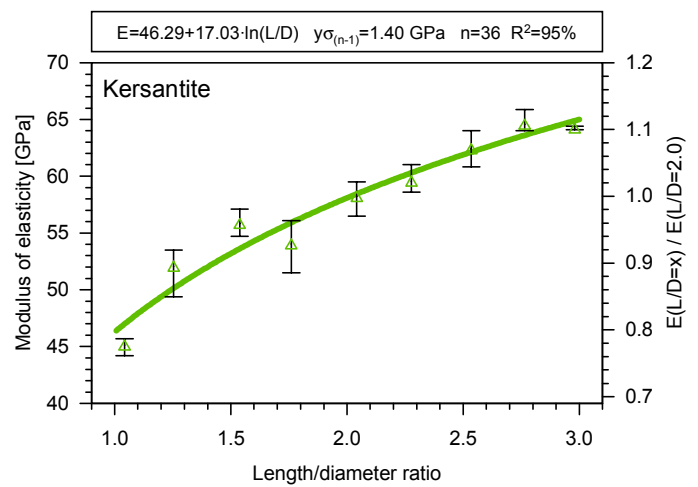


Figure 7. Modulus of elasticity of the kersantite samples in correlation with core shape (length/diameter ratio).

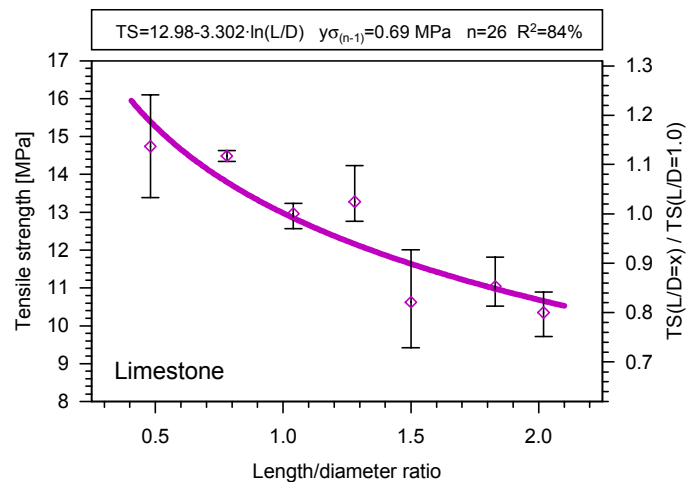


Figure 8. Indirect tensile strength of the limestone samples in correlation with core shape (length/diameter ratio).

#### 3.2 Size effect

Results of the performed testing program can be seen in the Figures 9 to 13. The mean values of the

rock properties are plotted against the diameter together with their maximum and minimum. Since the interesting point is the variation of the received values, the right hand scale is normalized against a  $D=50\text{mm}$  (equals 1). As for the shape, for all the diagrams a logarithmic regression function has been chosen in the standard form  $f(x) = a + b \ln(x)$  where  $x = D$ . The relationships found for all three rock types closely resemble one another, suggesting a geometrical correlation.

The interesting result is that size, normally considered to have a significant influence on all strength properties, in contrast to shape only has a marginal effect in the tested diameter range of the unconfined compressive strength (Figure 9, Figure 10, note the opposite dip of the curves), destruction work (Figure 11), modulus of elasticity (Figure 12) and the indirect tensile strength (Figure 13). The normalized variation (see right hand scale of figures) of less than approx. 5% nearly always stays within the min/max range of the data set. As a conclusion it can be stated, that there was no size effect observed in the tested diameter range.

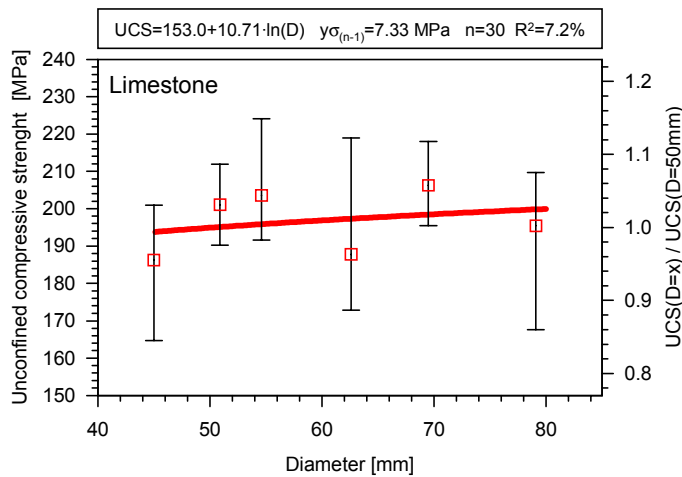


Figure 9. Unconfined compressive strength of the limestone samples in correlation with core diameter.

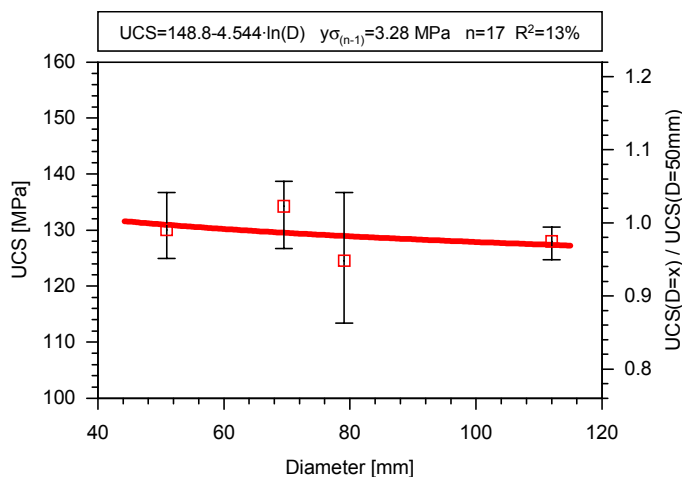


Figure 10. Unconfined compressive strength of the granite samples in correlation with core diameter.

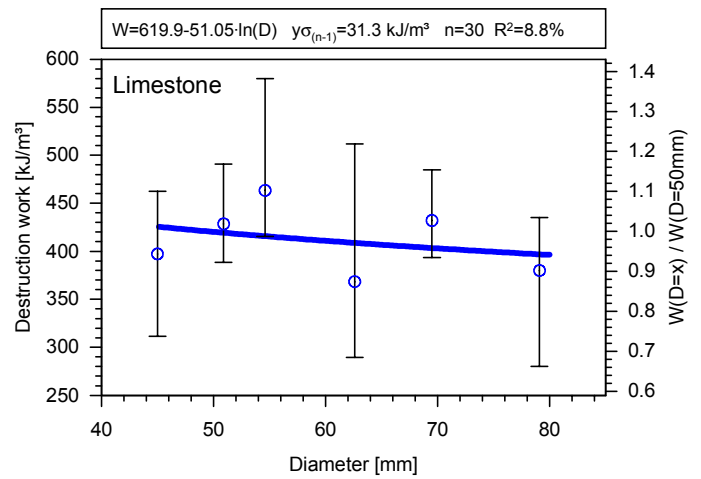


Figure 11. Destruction work of the limestone samples in correlation with core diameter.

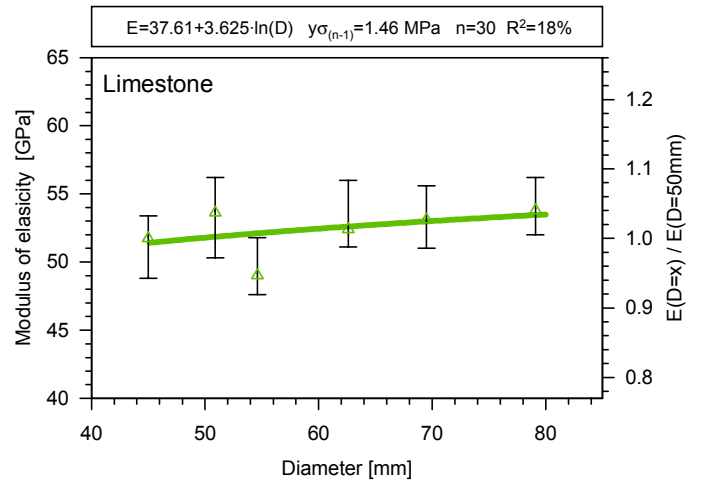


Figure 12. Modulus of elasticity of the limestone samples in correlation with core diameter.

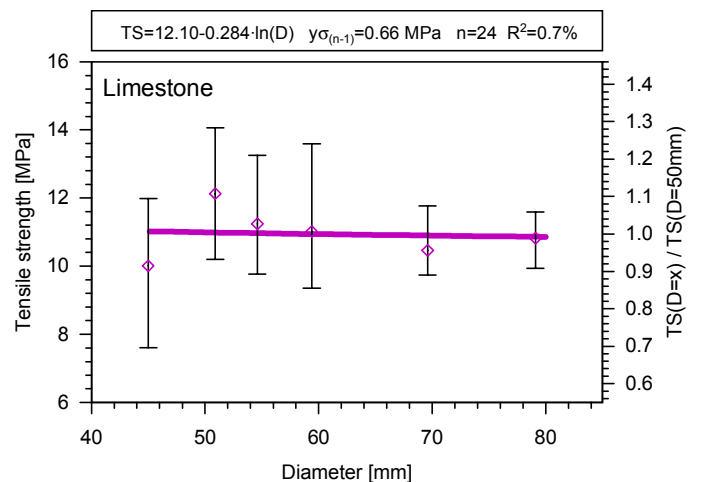


Figure 13. Indirect tensile strength of the limestone samples in correlation with core diameter.

## 4 DISCUSSION & CONCLUSIONS

### 4.1 Shape effect

According to ASTM 1986, the shape correction for the unconfined compressive strength is:

$$C = \frac{C_a}{0.88 + (0.24 \cdot D/L)} \quad (1)$$

where  $C$  = calculated compressive strength of an equivalent 2:1 length/diameter specimen;  $C_a$  = measured compressive strength of the specimen tested;  $D$  = test core diameter;  $L$  = test core height. The variation of  $C$  for a length/diameter ratio between 1 and 3 would be 0.89 to 1.04.

Using the diagram of Figure 14, the variation for the data presented in this contribution is 0.96 to 1.03 which is less, but quite close to ASTM. In addition, correction curves for the modulus of elasticity and the destruction work are proposed. The functions are simplified from the ones presented in the chapter before for convenience but without losing accuracy. Notice that the  $E$  correction is only valid when strain (or displacement) is measured between the load platens!

To obtain a correction curve for the indirect tensile strength, Figure 8 may be taken as an approximation. But more testing must be performed to validate the function parameters found.

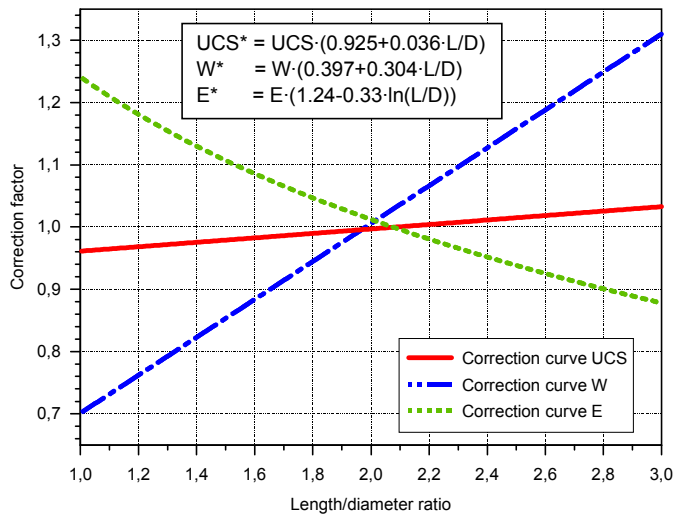


Figure 14. Shape correction curves for unconfined compressive strength UCS, destruction work  $W$  and modulus of elasticity  $E$ .

The final question to be answered is the reason for the significant impact of shape on strain measurement. This can be visualized by Figure 15, where it is suggested that high stresses below the load platens due to friction result in local plastification and higher strain in those regions. If this does occur, it is recommended that the strain (or displacement) measurement for determining the modulus of elasticity should be picked only along the central 2/3 of the

total core length (Figure 16). The influence of shape on the modulus of elasticity should then be minimized. Note that in the case of determining destruction work, the strain measurement must be performed between the load platens (i.e. along the entire core) to gain a value for the entire deformability. Therefore, such testing must be carried out on cores with a  $L/D \geq 2$ .

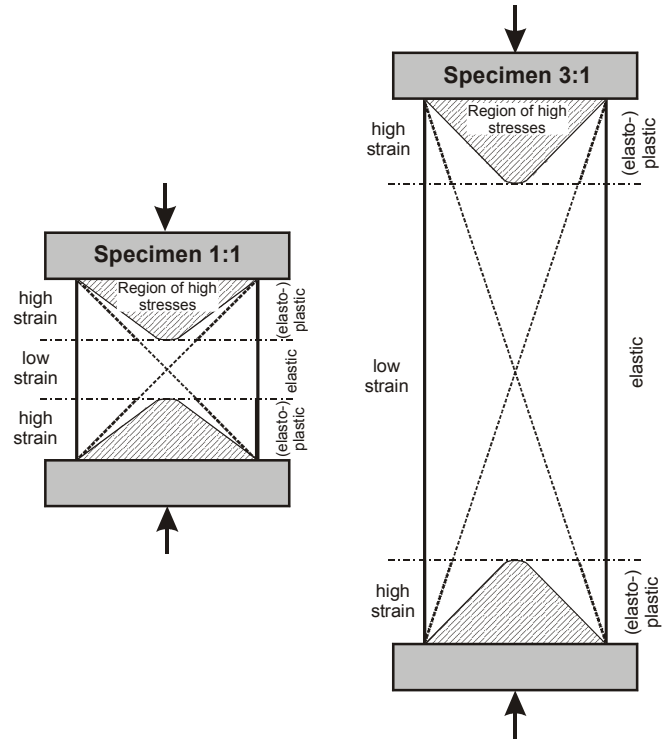


Figure 15. Conceptual explanation for the relationship between shape effect and strain measurement.

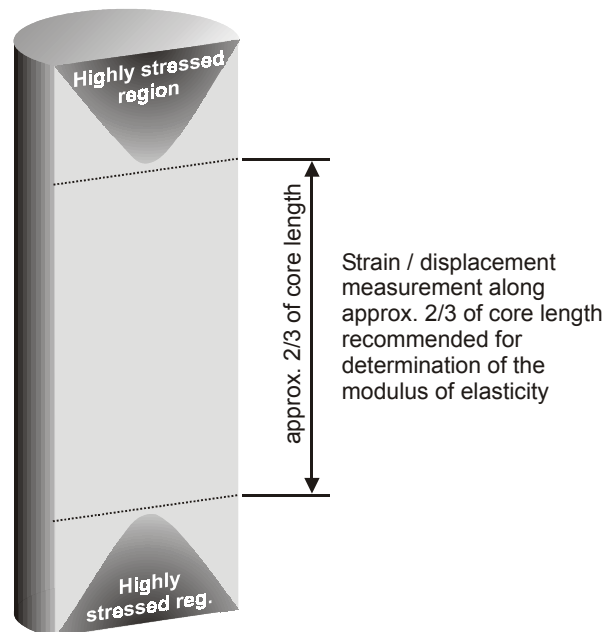


Figure 16. Recommendation for the strain measurement along approx. 2/3 of the specimen length during unconfined compression testing.

## 4.2 Size effect

For comparison, the obtained data range has been plotted in the published diagrams of Hoek & Brown 1980 (Figure 17) and Hawkins 1998 (Figure 18). Although the tested size range of this contribution is not as wide, in our experience the selected core diameters represent typical core sizes for geotechnical testing practice. Thus, within our tested data range, no size effect could be proved – quite in contrast to the quoted authors!

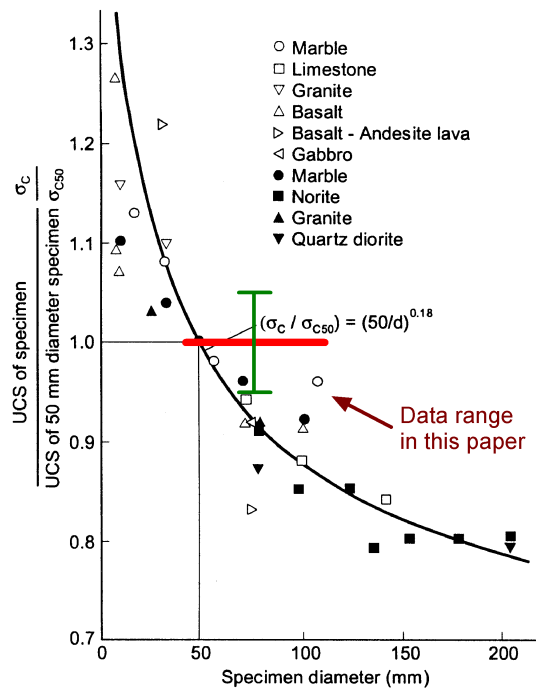


Figure 17. Relationship between UCS and specimen size plotted as dimensionless values (after Hoek & Brown 1980).

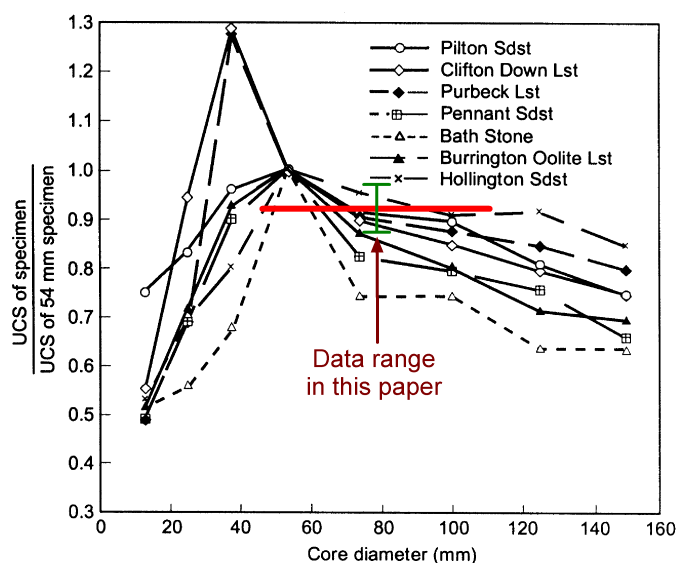


Figure 18. Relationship between UCS and specimen (core) size plotted as dimensionless values (after Hawkins 1998). Note that due to standardization at a core diameter of 54 mm, the data range of this contribution is shifted by a factor of  $50/54=0.93$ !

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