Rock Mech Rock Engng (2009) 42: 117–127
DOI 10.1007/s00603-008-0167-x
Printed in The Netherlands

Rock Mechanics and Rock Engineering

Technical Note

Predicting the uniaxial compressive strength and elastic modulus of a fault breccia from texture coefficient

By

M. Alber[1], S. Kahraman[2]

[1] Institute for Geology, Mineralogy and Geophysics, Ruhr-University, Bochum, Germany
[2] Mining Engineering Department, Nigde University, Nigde, Turkey

Received June 29 2006; Accepted January 23 2008; Published online January 28 2009

Keywords: Fault breccia, uniaxial compressive strength, elastic modulus, texture coefficient, image analysis

1. Introduction

Fault rocks can be divided into six types: fault cataclastic rocks, fault block rocks, unindurated fault breccias, fault gouge, fault breccias and mylonites. These fault rocks always have very poor engineering properties and fall within the category of weak or soft rocks. Weak rocks usually cause problems, not only in construction works, but also in slopes, or in underground works. For this reason, knowing the mechanical and elastic properties of fault breccia is very important in rock engineering. However, no published material on the geomechanical properties of fault breccias was encountered.

Several researchers (Chester and Logan, 1986; Lindquist and Goodman, 1994; Medley, 1994, 2001, 2002; Medley and Goodman, 1994; Ehrbar and Pfenniger, 1999; Goodman and Ahlgren, 2000; Burgi et al., 2001; Habimana et al., 2002; Laws et al., 2003; Sonmez et al., 2004, 2006) have investigated the properties of complex geo-materials such as melanges, sheared serpentinites, coarse pyroclastic rocks and fault rocks. However, none of them has investigated the properties of fault

Correspondence: Dr. S. Kahraman, Mining Engineering Department, University of Nigde, 51100 Nigde, Turkey
e-mail: sairkahraman@yahoo.com

breccia. In an accompanying paper, the results of these studies were summarised by Kahraman and Alber (2006). They correlated the Volumetric Block Proportion (VBP) with the Uniaxial Compressive Strength (UCS) and the Elastic modulus (E) values of the fault breccia tested in this study and found strong correlation between UCS and VBP.

Determination of the rock properties from direct methods requires a large number of shaped, regular specimens. However, weak rocks are usually not suitable for preparing smooth specimens or the preparation of such specimens is tedious, time consuming and expensive. For this reason, estimating the strength properties of fault breccia from indirect methods such as textural properties is essential. Numerous researchers, such as Olsson (1974), Bell (1978), Hugman and Friedman (1979), Onodera and Asoka Kumara (1980), Howarth and Rowlands (1987), Ulusay et al. (1994), Azzoni et al. (1996), Jeng et al. (2004), have investigated the correlations between textural properties and physico-mechanical rock properties for various rocks, and found strong relations between rock properties and textural properties. The rocks used in the previous studies were generally fine grained. Burgi et al. (2001) developed a new quantitative method for the characterization of weak cataclastic fault rocks. They developed an index called MSI (Mineralogical and Structural Index) using the mean weighted Vickers hardness, the Texture Coefficient (TC) developed by Howarth and Rowlands (1987) and the matrix coefficient derived by themselves in thin sections, and found good correlation between MSI and major principal stress.

The studies summarised above were carried out on the bimrocks, i.e. a mixture of rocks composed of geotechnically significant blocks within a bonded matrix of finers. However, the breccia tested in this study has blocks weaker than the matrix, which is unusual and the blocks and matrix are cemented together. The diameters of shale blocks in the available 101.3 mm-diameter-cores range from very small (<1 mm) to 11.7 cm. In this study, predictability of UCS and E of a fault breccia from the TC developed by Howarth and Rowlands (1987) was investigated. Since there is no outcrop of the fault breccia, the research was conducted using the limited available core samples.

2. Geology and sampling

101.3 mm-diameter-cores were taken from the Ahauser dam near Attendorn in Northrhine-Westfalia, Germany. The Devonian (Givet) strata consist of reddish, greyish and brownish shale, fine-grained sandstone with varying content of calcite, with massive limestone in reef facies on top. Cemented tectonic breccia consists of slate components (Newberrien) of various dimensions. Those components are partly weathered and/or altered by Fe-rich fluids. They show reddish-brown reaction rims or are totally altered to reddish brown slate. The calcareous cement of the breccia comes from the fluids which are saturated with $CaCO_3$. Fluids come from the underlying reef limestone (Slatalla, 2004). It was seen from the thin section of the cement material (matrix) that the matrix consists of recrystalized limestone and its fractures were filled with secondary calcite crystals.

Twelve core samples among the stored samples were taken for the study. The length of cores ranges from 15 to 29 cm. In the laboratory, for the strength tests, in addition to the two 101.3 mm-diameter-cores, only 22 samples having diameters of

Fig. 1. Tested samples

7.6–73.0 mm could be cored from eight 101.3 mm-diameter-cores to obtain the samples having different TC (Fig. 1).

3. Determination of texture coefficient

Howarth and Rowlands (1987) developed a dimensionless quantitative measure of rock texture. The procedure can be formulated as follows:

$$\mathrm{TC} = \mathrm{AW}\left[\left(\frac{N_0}{N_0 + N_1} \times \frac{1}{\mathrm{FF}_0}\right) + \left(\frac{N_1}{N_0 + N_1} \times \mathrm{AR}_1 \times \mathrm{AF}_1\right)\right] \tag{1}$$

where TC is the texture coefficient, AW is the grain packing weighting, N_0 is the number of grains whose aspect ratio is below a pre-set discrimination level, N_1 is the number of grains whose aspect ratio is above a pre-set discrimination level, FF_0 is the arithmetic mean of discriminated form-factors, AR_1 is the arithmetic mean of discriminated aspect ratios, and AF_1 is the angle factor, quantifying grain orientation.

Howarth and Rowlands (1987) obtained the data for the model by image analysis of thin sections. Their method was adapted to fault breccia supposing the rock blocks (clasts) as a grain. The image analyses were carried out on the scanned images of the circumferential surfaces of the cores.

Medley and Lindquist (1995) suggested the block/matrix threshold as 5% of a characteristic engineering dimension, such as tunnel diameter, landslide height or core diameter. The blocks smaller than the block/matrix threshold dimension can be accepted as matrix, and have negligible effect on the rock strength. In this study, the core diameters were selected as characteristic engineering dimension.

Circumferential surfaces of the cores were scanned by DMT (Deutsche Montan Technologie GmbH) CoreScan® II-Digital Core Imaging System. Scanned images were analysed using SigmaScan Pro 5 software. Since the blocks are moderately

Table 1. The summarised derivations of TCs

Sample no.	Sample diameter (mm)	No. of counted block	AW	$\frac{N_0}{N_0+N_1}$	$\frac{1}{FF_0}$	$\frac{N_1}{N_0+N_1}$	AR1	AF1	Weighted TC
1	101.3	131	0.70	0.50	1.47	0.50	3.47	0.03	0.555
2	101.3	170	0.75	0.54	1.59	0.46	3.42	0.03	0.669
3	73.0	289	0.77	0.42	1.47	0.58	3.23	0.01	0.483
4	73.0	116	0.77	0.34	1.82	0.66	3.83	0.03	0.529
5	62.6	93	0.55	0.82	1.61	0.18	3.44	0.07	0.742
6	43.6	122	0.71	0.43	1.54	0.57	3.29	0.02	0.499
7	40.5	20	0.94	0.30	1.96	0.70	3.89	0.10	0.815
8	37.8	25	0.68	0.52	1.39	0.48	2.79	0.19	0.667
9	30.1	60	0.75	0.57	1.47	0.43	2.75	0.09	0.702
10	30.1	72	0.50	0.38	1.30	0.63	3.18	0.02	0.265
11	30.1	27	0.78	0.19	1.92	0.81	2.44	0.07	0.384
12	30.1	64	0.76	0.39	1.69	0.61	3.32	0.04	0.570
13	24.4	32	0.56	0.31	1.64	0.69	4.02	0.06	0.380
14	24.4	58	0.23	0.29	2.13	0.71	3.49	0.65	0.514
15	24.4	35	0.88	0.46	1.72	0.54	2.94	0.08	0.809
16	24.4	17	0.97	0.24	2.08	0.76	3.39	0.09	0.704
17	24.4	7	0.23	0.29	3.23	0.71	3.29	0.26	0.349
18	24.4	37	0.29	0.41	1.69	0.59	4.27	0.07	0.244
19	14.5	20	0.24	0.45	1.45	0.55	2.83	0.20	0.229
20	14.5	14	0.18	0.71	1.47	0.29	2.92	0.47	0.263
21	7.6	6	0.08	0.17	1.79	0.83	3.95	0.54	0.162
22	7.6	12	0.07	0.58	1.49	0.42	2.84	0.60	0.114
23	7.6	5	0.11	0.60	1.35	0.40	2.69	2.00	0.314
24	7.6	12	0.09	0.67	1.33	0.33	2.64	0.73	0.130

weathered, they generally show a mixture of light brown and dark brown colours or a mixture of grey/brown and green colours. Due to the poor tonal discrimination, blocks could not be selected automatically and block boundaries were outlined semi-automatically. When outlining the block boundaries, area, length, breadth, form factor and orientation of each grain were calculated by the software.

Firstly, the TCs of the available twelve 101.3 mm-diameter-cores were calculated. The TCs of these cores range from 0.530 to 0.669 with an overall average of 0.572 ± 0.056. To obtain additional samples having different TC and to observe the scale effect on the strength and elastic properties, 22 smaller samples were cored from 101.3 mm-diameter-cores in different diameters, ranging from 7.6 to 73.0 mm. A total of 24 samples were prepared for image processing and the other tests. The summarised derivations of TCs of all samples are indicated in Table 1. As shown in the table, TC values range from 0.114 to 0.815. In addition, VBP values of the same samples were estimated from the areal block proportions as explained in an accompanying paper (Kahraman and Alber, 2006).

4. Laboratory studies

4.1 Physico-mechanical tests on the components of fault breccia

The physico-mechanical properties of the components of the fault breccia were determined in a previous study (Kahraman and Alber, 2006). As explained in this study, the individual UCS values of the components of the fault breccia range from 32.6 to 89.3 MPa. The average UCS value of matrix is 70.1 MPa. This value is higher than the UCS values of blocks except for the brownish shale blocks. For this reason, the breccia is not a conventional bimrock, which requires some strength contrast between block and matrix as well as consisting of blocks stronger than the matrix.

4.2 Compressive strength tests on the fault breccia

Twenty five core samples having different diameters, ranging from 7.6 to 101.3 mm, were used for the compressive strength tests. The two samples were original 101.3 mm cores. Twenty-two smaller samples were cored from original 101.3 mm cores. ISRM (1981) suggests that the diameter of cores should be about 10 times the maximum grain size in each sample and not smaller than NX size (about 54 mm). However, it is not possible to satisfy this condition for breccias or other bimrocks. In addition, measured rock strength decreases with increasing height to diameter ratio. However, rock strength is approximately the same above a height to diameter ratio of about 2. USBM (1974) suggests 2, ISRM (1981) suggests 2.5–3.0 for the height to diameter ratio. Most of the cores had a height to diameter ratio of 2–2.5. A good number of cores could not be prepared in standard dimensions because of core breakage due to weak structure of the breccia. The UCS values of the samples having a height to diameter ratio of less than 2 were corrected using the following formula suggested by Protodyakonov (1969):

$$\mathrm{UCS} = \frac{8\mathrm{UCS}_1}{7 + 2d/h} \tag{2}$$

where UCS is the standard uniaxial compressive strength (MPa), UCS_1 is the measured uniaxial compressive strength (MPa), d is the core diameter (mm), and h is the core height (mm).

After trimming the end surfaces of the cores, uniaxial compression tests were performed using an electro-hydraulic servo-controlled stiff testing machine (MTS). In the tests failure planes passed around the block boundaries in some samples which have strong blocks. Failures through blocks were commonly observed in the samples having high TC and high VBP or having large blocks. Dominant matrix failures were seen in the samples having low TC and low VBP.

The uniaxial compressive strength test results are shown in Table 2. UCS values indicate a wide range (from 9.8 to 86.6 MPa).

4.3 Elastic modulus tests on the fault breccia

During the uniaxial compressive strength tests, deformation measurements were carried out using high resolution LVDTs and stress-strain curves were plotted. Tangent Young's modulus values were obtained from stress-strain curves at a stress level equal to 50% of the ultimate uniaxial compressive strength. The E values range from 3.0 to 16.8 GPa (Table 2). It should be noted that the sensitivity of E measurement is less in small samples.

Table 2. Compressive strength and elastic modulus values

Sample no.	Sample diameter (mm)	Volumetric block proportion (%)	Compressive strength (MPa)	Elastic modulus (GPa)
1	101.3	70.0	12.1	16.8
2	101.3	75.0	16.1	10.8
3	73.0	76.7	20.6	10.6
4	73.0	77.0	15.5	5.2
5	62.6	54.5	13.1	4.6
6	43.6	70.7	17.7	9.4
7	40.5	94.4	15.1	7.1
8	37.8	68.3	13.5	6.4
9	30.1	74.6	11.5	5.9
10	30.1	50.4	47.2	9.1
11	30.1	77.6	41.1	12.3
12	30.1	76.3	9.8	3.0
13	24.4	56.0	33.8	8.5
14	24.4	23.1	26.0	5.1
15	24.4	88.2	11.9	5.9
16	24.4	96.6	23.5	14.2
17	24.4	22.8	34.8	10.3
18	24.4	28.5	34.6	12.3
19	14.5	23.8	43.4	10.1
20	14.5	18.2	70.1	15.8
21	7.6	7.8	77.2	10.4
22	7.6	7.2	63.8	14.2
23	7.6	10.6	47.1	9.7
24	7.6	8.5	86.6	11.6

5. Results and discussion

The scale effect on the UCS of the fault breccia was graphically investigated. The plot of UCS versus core diameter was examined and it was shown that the data points are scattered below the approximately 40 mm-core-diameter. That the samples are not standard size may be a reason for scattering. Although it seems to be a descending trend in this area, it is expected that increasing data points increases the scattering. When the plot is examined, it is seen that samples having the same diameters show a wide range. Small diameter cores are only possible in relatively homogeneous component material. High UCS for the small diameters reflects bias to successfully sampling component because breccia would full apart. For example, UCS values for the 30.1 mm-diameter-cores range from 9.8 to 47.2 MPa; apparently small samples, randomly cored, may include an intact rock or a mixed rock and may thus show a range of TC and VBP. If a small sample, for example, belongs to the matrix, its strength will be high. Above approximately the 40 mm-core-diameter, the UCS values are almost the same. This is due to the fact that the samples having diameters higher than 40 mm have nearly the same VBP (Kahraman and Alber, 2006) and have a narrow range of TC (0.483–0.742).

An inverse logarithmic relation between UCS and TC (Fig. 2) was found. UCS values decreases with increasing TC. The equation of the curve is

$$\mathrm{UCS} = -35.89 \ln \mathrm{TC} + 0.123 \quad R^2 = 0.83 \tag{3}$$

where UCS is the uniaxial compressive strength (MPa) and TC is the texture coefficient.

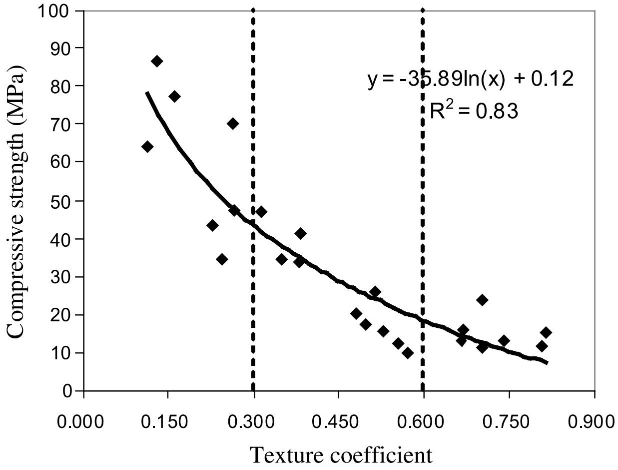

Fig. 2. Texture coefficient versus uniaxial compressive strength

Burgi et al. (2001) developed an index called Mineralogical and Structural Index (MSI) using the mean weighted Vickers hardness, the texture coefficient and the matrix coefficient derived by themselves in thin sections, and found good correlation between MSI and major principle stress for the weak cataclastic fault rocks. Major principle stress increases with increasing MSI. In this study, it was found that UCS values decrease with increasing TC. The difference between the two studies is probably due to the different matrix type. The rocks tested by Burgi et al. (2001) have weak matrixes. However, the breccia tested in this study has a strong matrix as explained in Sect. 4.1. This clearly shows that the UCS of low strength rocks consisting of block and matrix is mainly dependent on the strength of the matrix.

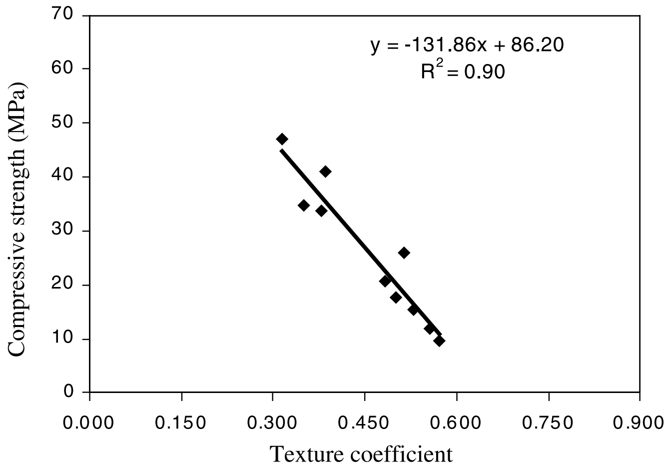

Fig. 3. Texture coefficient versus uniaxial compressive strength for values of texture coefficient between 0.300 and 0.600

As shown in Fig. 4, data are scattered below about 0.300 TC and data are approximately the same above about 0.600 TC. For about 0.300 and 0.600 TC, Fig. 2 was re-plotted and linear regression analysis was executed. As indicated in Fig. 3, the correlation coefficient increased to 0.90 comparing to Eq. (3). The equation of the line is

$$\mathrm{UCS} = -131.86\mathrm{TC} + 86.20 \quad R^2 = 0.90 \tag{4}$$

Lindquist and Goodman (1994) and Lindquist (1994) identified a conservative relation between strength and VBP for melange bimrocks. The strength of a melange is that of the matrix below about 25% VBP. The friction angle of the melange proportionally increases with increasing VBP between about 25 and 75% VBP. Above 75% VBP, the blocks tend to touch and there is no further increase in melange strength. Below about 0.300 TC does not correspond to below about 25% VBP and above about 0.600 TC does not correspond to above 75% VBP as indicated in Fig. 4.

Equations (3) and (4) have higher correlation coefficient than the correlation between UCS and VBP derived in an accompanying paper (Kahraman and Alber, 2006). This is due to the fact that, samples having approximately the same VBP may have different strength values. This is because of the texture differences. As shown in Fig. 4, samples having about the same VBP may have different TC, and therefore have different UCS. For example, the TC*s* of the samples having between 74.6 and 77.6% VBP range from 0.384 to 0.702.

There is a weak correlation between *E* and TC as shown in Fig. 5. The data above about 0.550 TC are highly scattered. Fig. 5 was re-plotted for about 0.250 and 0.550 TC. As shown in Fig. 6, the data are less scattered comparing to Fig. 5. However, the relation requires further investigation.

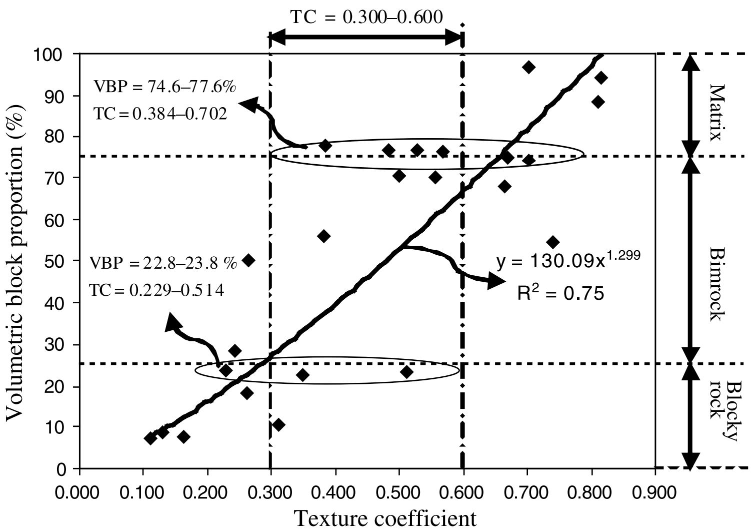

Fig. 4. Volumetric block proportion versus texture coefficient (Matrix, bimrock and blocky rock areas are shown according to Medley (1994))

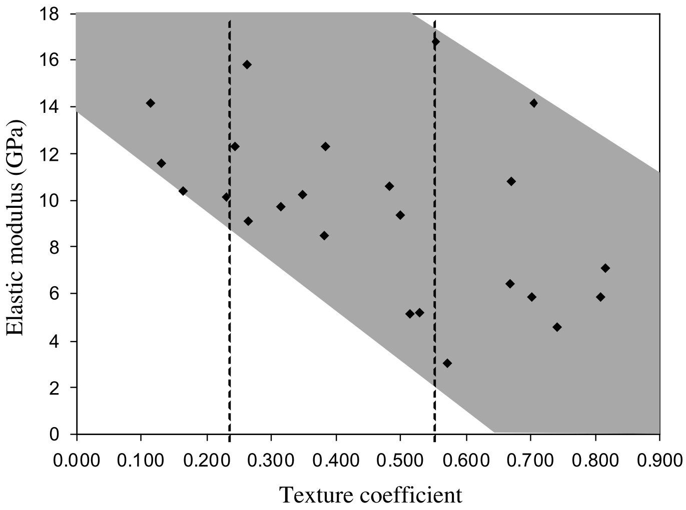

Fig. 5. Texture coefficient versus elastic modulus

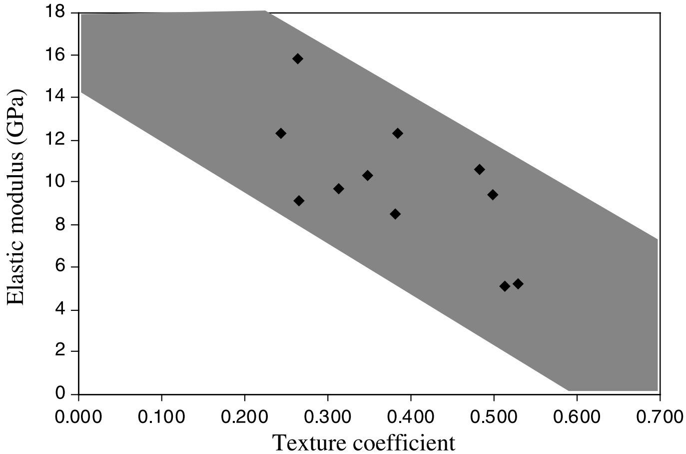

Fig. 6. Texture coefficient versus elastic modulus for about 0.250 and 0.550 texture coefficient

6. Conclusions

TC values were correlated with the UCS and E of a fault breccia to develop some estimation models. A strong correlation between UCS and TC was found. It was seen that the correlation coefficient was increased for about 0.300 and 0.600 TC. The relation between E and TC is weak. However, the correlation coefficient was increased for about 0.250 and 0.550 TC.

Another conclusion is that although there is a correlation between VBP and TC, samples having approximately the same VBP may have different TC values, indicating different strength values.

Concluding remark is that the UCS of the tested breccia can be estimated from TC. Further research is necessary to check the validity of the results and the derived equations for other breccia types where matrix is stronger than blocks. In addition, the dependence between *E* and TC needs further research.

Acknowledgement

This study was supported by Alexander von Humboldt Foundation. Authors thank to Dr. G. Rafat from DMT for the scanning of the cores.

References

Azzoni A, Bailo F, Rondena E, Zaninetti A (1996) Assessment of texture coefficient for different rock types and correlation with uniaxial compressive strength and rock weathering. Rock Mech Rock Engng 29: 36–46

Bell FG (1978) The physical and mechanical properties of the Fell Sandstones, Northumberland. England Engng Geol 12: 1–29

Burgi C, Parriaux A, Franciosi G (2001) Geological characterization of weak cataclastic fault rocks with regards to the assessment of their geomechanical properties. Q J Engng Geol Hdyrogeol 34: 225–232

Chester FM, Logan JM (1986) Implications for mechanical properties of brittle faults from observations of the Punchbowl Fault Zone, California. Pure Appl Geophys 124: 79–106

Ehrbar H, Pfenniger I (1999) Umsetzung der Geologie in technische Massnahmen im Tavetscher Zwischenmassive Nord. In: Loew S, Wyss R (eds) Vorerkundung und Prognose der Basistunnels am Gotthard und am Lötschberg. Balkema, Rotterdam, pp 381–394

Goodman RE, Ahlgren CS (2000) Evaluating safety of concrete gravity dam on weak rock: Scott Dam. J Geotech Geoenvir Engng 126(5): 429–442

Habimana J, Labiouse V, Descoeudres F (2002) Geomechanical characterisation of cataclastic rocks: experience from the Cleuson-Dixence project. Int J Rock Mech Min Sci 39(6): 677–693

Howarth DF, Rowlands JC (1987) Quantitative assessment of rock texture and correlation with drillability and strength properties. Rock Mech Rock Engng 20: 57–85

Hugman RH, Friedman M (1979) Effects of texture and composition on mechanical behaviour of experimentally deformed carbonate rocks. Am Assoc Pet Geol Bull 63: 1478–1489

ISRM (1981) In: Brown ET (ed) ISRM Suggested methods. Pergamon Press, Oxford

Jeng FS, Weng MC, Lin ML, Huang TH (2004) Influence of petrographic parameters on geotechnical properties of tertiary sandstones from Taiwan. Engng Geol 73: 71–91

Kahraman S, Alber M (2006) Estimating the unconfined compressive strength and elastic modulus of a fault breccia mixture of weak rocks and strong matrix. Int J Rock Mech Min Sci 43: 1277–1287

Laws S, Eberhardt E, Loew S, Descoeudres F (2003) Geomechanical properties of shear zones in the Eastern Aar Massif, Switzerland and their implication on tunnelling. Rock Mech Rock Engng 36(4): 271–303

Lindquist ES (1994) The strength and deformation properties of melange. Ph.D. Dissertation, University of California at Berkeley, California. UMI Inc., Ann Arbor, MI

Lindquist ES, Goodman RE (1994) Strength and deformation properties of a physical model melange. In: Nelson PP, Laubach SE (eds) Proceedings of the 1st North American Rock Mechanics Symposium, Balkema, Rotterdam, pp 843–850

Medley EW (1994) The engineering characterization of melanges and similar block-in-matrix rocks (bimrocks). Ph.D. Dissertation. University of California at Berkeley, California. UMI Inc., Ann Arbor, MI

Medley EW (2001) Orderly characterization of chaotic Franciscan Melanges. Felsbau-Rock and Soil Engng 19: 20–33

Medley EW (2002) Estimating block size distribution of melanges and similar block-in-matrix rocks (bimrocks). In: Hammah R, Bawden W, Curran J, Telesnicki M (eds) Proc. 5th North American Rock Mech. Symp. University of Toronto Press, Toronto, Canada, pp 509–516
Medley EW, Goodman RE (1994) Estimating the block volumetric proportions of melanges and similar block-in-matrix rocks (bimrocks). In: Nelson PP, Laubach SE (eds) Proc. 1st North American Rock Mech. Symp. Balkema, Rotterdam, pp 851–858
Medley EW, Lindquist ES (1995) The engineering significance of the scale-independence of some Franciscan melanges in California. In: Daemen JK, Schultz RA (eds) Proc. 35th US Rock Mech. Symp. Balkema, Rotterdam, pp 907–914
Olsson WA (1974) Grain size dependence of yield stress in marble. J Geophys Res 79: 4859–4861
Onodera TF, Asoka Kumara HM (1980) Relation between texture and mechanical properties of crystalline rocks. Bull Int Assoc Engng Geol 22: 173–177
Protodyakonov MM (1969) Method of determining the strength of rocks under uniaxial compression. In: Protodyakonov MM et al. (eds) Mechanical properties of rocks. Translated from Russian, Israel Program for Scientific Translations, Jerusalem
Slatalla N (2004) Geological mapping at the Ahauser reservoir. Unpublished BSc Thesis, Institute of Geology, Mineralogy Geophysics, Ruhr University Bochum (in German)
Sonmez H, Gokceoglu C, Medley EW, Tuncay E, Nefeslioglu HA (2006) Estimating the uniaxial compressive strength of a volcanic bimrock. Int J Rock Mech Min Sci 43: 554–561
Sonmez H, Gokceoglu C, Tuncay E, Medley EW, Nefeslioglu HA (2004) Relationship between volumetric block proportion and overall UCS of a volcanic bimrock. Felsbau-Rock Soil Engng 22: 27–34
Ulusay R, Tureli K, Ider MH (1994) Prediction of engineering properties of selected litharenite sandstone from its petrographic characteristics using correlation and multivariate statistical techniques. Engng Geol 37: 135–157
USBM (1974) Bureau of mines (USBM) test procedures for rocks. In: Lewis WE, Tandanand S (eds) Information circular, 8628