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Technical note

Estimating unconfined compressive strength and elastic modulus of a fault breccia mixture of weak blocks and strong matrix

S. Kahraman*, M. Alber

Ruhr-University, Institute for Geology, Mineralogy and Geophysics, 44780 Bochum, Germany

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1. Introduction

Determination of the compressive strength and elastic modulus of rocks from direct methods requires a large number of regularly shaped specimens. Weak rocks are usually not suitable for preparing smooth specimens, and at best the preparation of such specimens is tedious, time consuming and expensive. Fault breccias have very poor engineering properties, and fall within the category of weak rocks. These rocks usually cause problems, not only in construction works, but also in slopes or in underground works. For this reason, knowing the physical and mechanical properties of fault breccia is very important in rock engineering. However, little published material on the geomechanical properties of fault breccias is available.

Geomechanical characterization of complex geological mixtures of competent blocks and weak matrix (geomaterials) such as melanges, sheared serpentinites, fault rocks, and coarse pyroclastics, is relatively new. The term "block-in-matrix rocks" for complex geo-materials was firstly described by Raymond [1] as "blocks of one lithology enclosed in materials of another lithology". Medley [2] introduced the term "bimrocks", a contraction of the term "block-in-matrix rocks", and defined a bimrock as "a mixture of rocks, composed of geotechnically significant blocks within a bonded matrix of finer". The expression "geotechnically significant" means that there is mechanical contrast between blocks and matrix (such as the ratio $\tan \varnothing_{block}/\tan \varnothing_{matrix} \geqslant 2$), the range in block sizes is between 5% and 75% of the characteristic engineering dimension (the scale of engineering interest such as the diameter of a tunnel or triaxial specimen), and the volumetric block proportion (VBP) (the total volume of blocks divided by the total volume of bimrock mass) is between 25% and 75%. Medley and Goodman [3] and Medley [4] presented some suggestions on how the VBP can be estimated for melanges and similar block-in-matrix rocks (bimrocks). Medley [5] also noted the uncertainty inherent in estimates of VBP. Lindquist and Goodman [6] created a physical model of melanges made up of stronger/stiffer blocks in a weaker/softer matrix to investigate the effect of block proportion and orientation on melange mass strength and deformation properties. Test results showed that increasing the block proportion generally decreases cohesion, and increases internal friction angle and deformation modulus. However, Goodman and Ahlgren [7] inexplicably found that cohesion increased with VBP for Franciscan melange in the foundation of Scott Dam, California. Sonmez et al. [8] investigated the relation between VBP and uniaxial compressive strength (UCS) for Ankara Agglomerate, a volcanic pyroclastic. They correlated equivalent block proportion (a weighted calculation incorporated to the UCS difference between the two or more different block types) with UCS values and stated that there is an apparent dependence between overall compressive strength and individual block strengths in Ankara Agglomerate, which necessitates further investigation. Sonmez et al. [9] recently improved their previous study [8] for Ankara Agglomerate and showed that the UCS depends on both the VBP and the strength contrast between blocks and matrix. They also noted that the

*Corresponding author. Mining Engineering Department, Nigde University, Jeoloji Muh. Bolumu, 51100 Nigde, Turkey. Tel.: +90 388 225 2264; fax: +90 388 225 0112.

E-mail address: sairkahraman@yahoo.com (S. Kahraman).

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welding between pyroclastic matrix and blocks has an important effect on the overall strength of rock.

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 finer. However, the breccia tested in this study has blocks weaker than the matrix, which is unusual, and the blocks and matrix are welded together. In this study, it was aimed to develop predictive models for the UCS and elastic modulus (E) of the fault breccia from VBP obtained from image analysis. Since there is no outcrop of the fault breccia, the research was conducted using the limited available core samples.

2. Geology

Geological details of Ahauser reservoir are based on Ref. [10]. The drilling took place at the Ahauser dam near Attendorn in Northrhine-Westfalia, Germany, in the northern part of the Rheno-Hercynian zone of the Variscan Mountains. The Devonian (Givet) strata consist of reddish, grayish and brownish shale, fine-grained sandstone with varying content of calcite, with massive limestone in reef facies on top. Fig. 1 shows a geologic map of the area and a cross-section. The breccia was recovered from the borehole DH/65°. The drill hole DH /65° is oriented approximately 330°/65° (trend/plunge) and has a length of 40 m. The drillhole comes to lay in a strike-slip fault (strike 330°) which is oriented perpendicular to a thrust fault exhibiting variscan strike (NE–SW). The strata are inverse and the drillhole is in a cemented tectonic breccia within the Newberrian beds.

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.

In addition, thin section was prepared from the cement material (matrix). It was seen that the matrix consists of recrystalized limestone, and its fractures were filled with secondary calcite crystals.

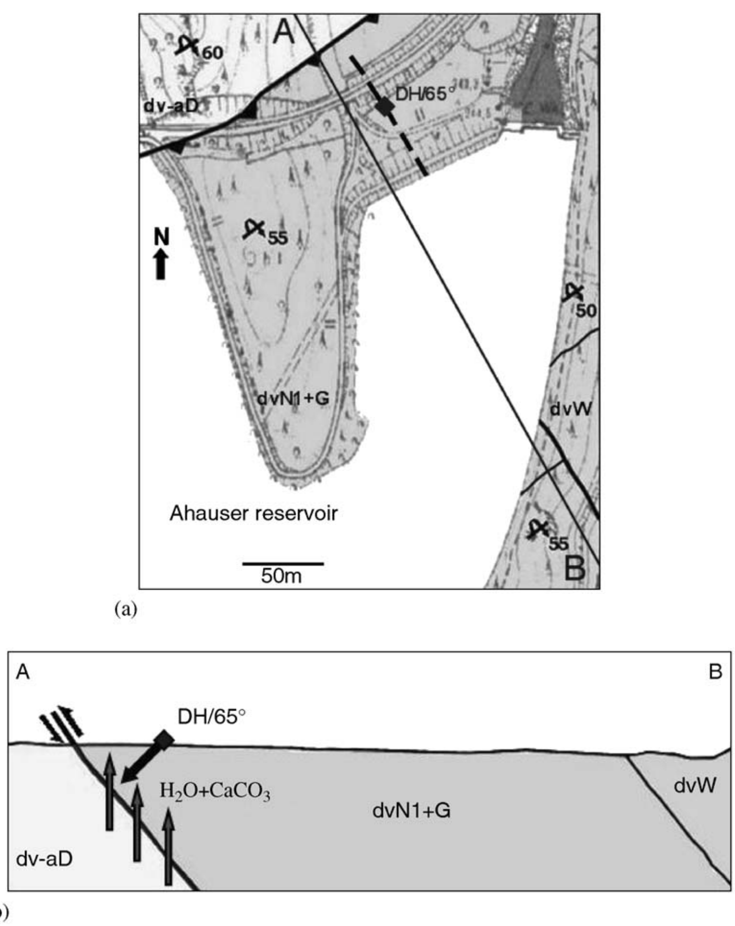

Fig. 1. (a) Geologic map of the area around drillhole DH /65° where the breccia has been recovered. Note the location of the drillhole exactly along the strike-slip fault. (b) A–B cross-section perpendicular to the thrust fault indicating the inclination of the drillhole. (Legend: dv-aD: reef limestone, fine to medium grained , blue-grey , partly dolomitized; dvN1 + G: Newberrien and Grevensteiner beds, silty slate, high mica content, slightly calcareous, grey to green; dvW: Wiedenester beds, slate and siltstone, grey to brown) [10].

3. Sampling

Drill hole DH/65° described in Section 2 was drilled during the geological investigation of the reservoir of the Ahausen dam which is now in use and 101.3 mm-diameter-cores were stored. Diamond drilling was performed featuring a split double-tube core barrel of diameter 110 mm and core recovery was 100%. Twelve core samples among the stored samples were only found and were taken for the study. The length of cores ranged from 15 to 29 cm. Some cores were reserved for the triaxial compressive strength tests.

In the laboratory, a total of 73 small samples having diameter of 15.6 mm were cored from 101.3 mm-diameter-cores to determine the physico-mechanical properties of components of fault breccia. Coring was very difficult, and several cores were disintegrated during coring and cutting their ends. For the strength and deformability tests, in addition to the two 101.3 mm-diameter-cores, only 22 samples having diameters of 7.6–73.0 mm could be cored from eight 101.3 mm-diameter-cores to obtain the samples having different VBP.

4. Estimating VBP

VBP is the total volume of blocks divided by the total volume of the rock mass. VBP can be estimated by one-, two- or three-dimensional methods. Using the measurement of drill core/block intersection lengths (chords) or scanlines on photographs for the estimations are one-dimensional (1-D) methods. Geological mapping and image analysis on scanned images or photographs are examples of two-dimensional (2-D) methods. Sieve analysis is a three-dimensional (3-D) method which is better suited to give an understanding of weight fractions and volume fractions. However, sieve analysis can only be used for the laboratory studies, and separation of blocks from the matrix is very difficult in most situations [4,7,8]. Another method for estimating VBP is to use density of the specimens [11]. If there is any significant density contrast between blocks and matrix, the overall density of the cylindrical specimens will vary directly in proportion to VBP.

Some researchers [3,4] have used scanlines to estimate VBP from 1-D chord length or 2-D image analyses. Medley [4] stated that the uncertainty in estimating 3-D block size distributions from 1-D scanlines/borings is depended on many factors, the most important being block shapes, block volumetric proportions, block orientations, and total length of sampling. Medley also addressed the uncertainty of estimating VBP in [12], and he found that as the total sampling length and/or the total actual volumetric proportion increased, the uncertainty decreased. Haneberg [13] showed the error in assuming that 2-D measurements were equivalent to 3-D values. Recently, Sonmez et al. [8] used image analysis techniques for VBP estimations. They checked the possible uncertainties in the 2-D estimation of VBP using the plot of cumulative frequency distribution of the ratio of the longest to the shortest axis of blocks.

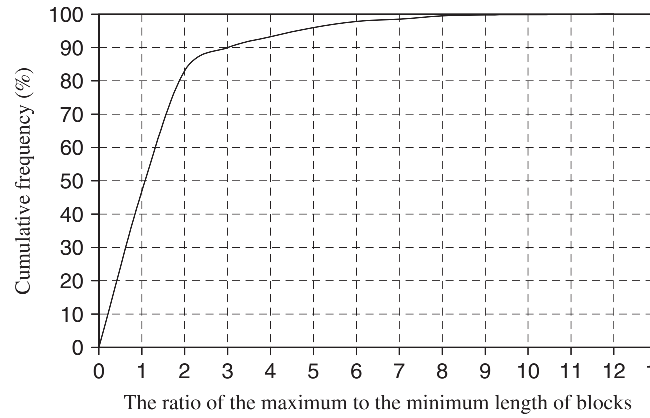

Fig. 2. Cumulative frequency distribution graph of the ratio of the longest to the shortest axis of blocks.

Relatively weaker blocks were embedded within stronger matrix in the fault breccia tested in this study, and the separation of blocks from the matrix was not possible for sieve analysis. For this reason, image analysis on the scanned images of the circumferential surfaces of the cores was used for the estimation of VBP. The uncertainties in the 2-D estimation of VBP were checked by the method of Sonmez et al. [8]. The longest and the shortest axis of blocks were measured on the images of circumferential surfaces of the 101.3 mm-diameter-cores and the cumulative frequency distribution graph of the ratio of the longest to the shortest axis of blocks was plotted. As shown in Fig. 2, 70% of the measured blocks have a ratio less than 1.5. Therefore, it can be accepted that the blocks have approximately same dimension in 2-D and 3-D measurements.

Medley and Lindquist [14] suggested a block/matrix threshold as 5% of a characteristic engineering dimension of the problem at hand, such as a 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 diameter for each sample was selected as the characteristic engineering dimension. For example, the block/matrix threshold for 101.3 mm-diameter-samples is 0.5 cm. Original 101.3 mm-diameter-samples had 5 blocks having average diameters greater than 101.3 mm. However, both 101.3 mm-diameter-samples and smaller-diameter samples used in the tests had not blocks greater than core diameters.

Circumferential surfaces of the cores were scanned by DMT (Deutsche Montan Technologie GmbH) CoreScan® II-Digital Core Imaging System. The system is a portable core-imaging device developed for drill core image acquisition, storage and evaluation. Images of full diameter and slabbed cores can be recorded. Full-diameter cores are rotated 360° around their cylindrical axis while the line-scan camera, positioned parallel to the axis of rotation, records their surface features. A 360° image of a length up to 1 m, recorded in 25-cm sections that are integrated and light calibrated using the DigiCore software provided with the DMT CoreScan System results. Full-diameter-cores are scanned at a rate of ~1 min/m in the unrolled mode and can be stored as BMP, TIF or JPG files. Small cores were scanned by DMT Core-Plug Scanner. Scanning of the very small cores by the Core-Plug Scanner is not possible. Therefore, scanning of the 7.6 and 14.5 mm-diameter cores were covered a transparent film and grain boundaries were manually traced onto the transparent film. Then, the transparent films were scanned by an ordinary scanner. These techniques are inspired by the works of Medley [2] and Lindquist [11].

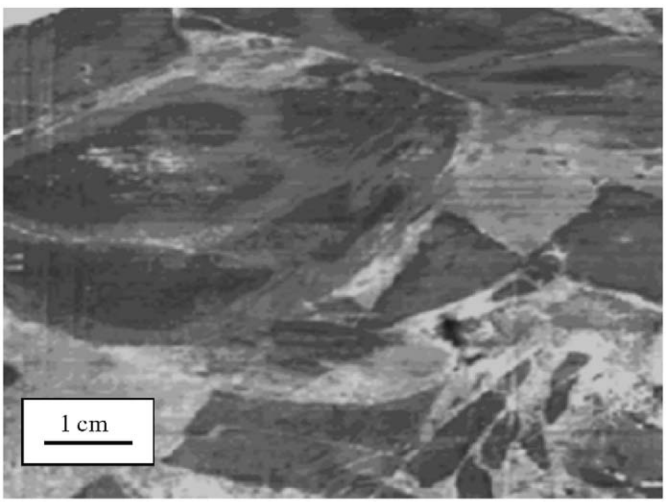

Fig. 3. Weathered block colours.

Scanned images were analysed using SigmaScan Pro 5 software. Since the blocks are moderately weathered (Fig. 3), 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. Block boundaries were outlined semi-automatically, after which block areas and total areas were calculated by the software. Figs. 4 and 5 show the original and processed images of two samples having VBP of 76.3% and 23.1%. As shown in Fig. 4, the samples having high VBP have fragmented pieces of larger blocks separated by infilled joints. These fragmented pieces were identified as separate blocks by the image analysis programme. In Fig. 5(b), several of the blocks have very thin necks. After these blocks were separated into different blocks, image analysis was performed.

Firstly, the VBP values of available twelve 101.3 mm-diameter-cores were estimated. The areal block proportions (ABP) were measured and it is assumed that the ABP is equal to the VBP. The VBP of these cores range from 73% to 91.5%, with an overall average of 80.2 ± 6.5%. Medley [2] limits bimrocks to mixtures between 25% and 75% VBP. Beyond about 70% VBP, blocks start to touch and the rock mass can be considered a "blocky rock mass with infilled joints", and thus can be analysed using conventional rock-engineering approaches. According to Medley [2], the breccia with 80.2% VBP cannot be considered to be a

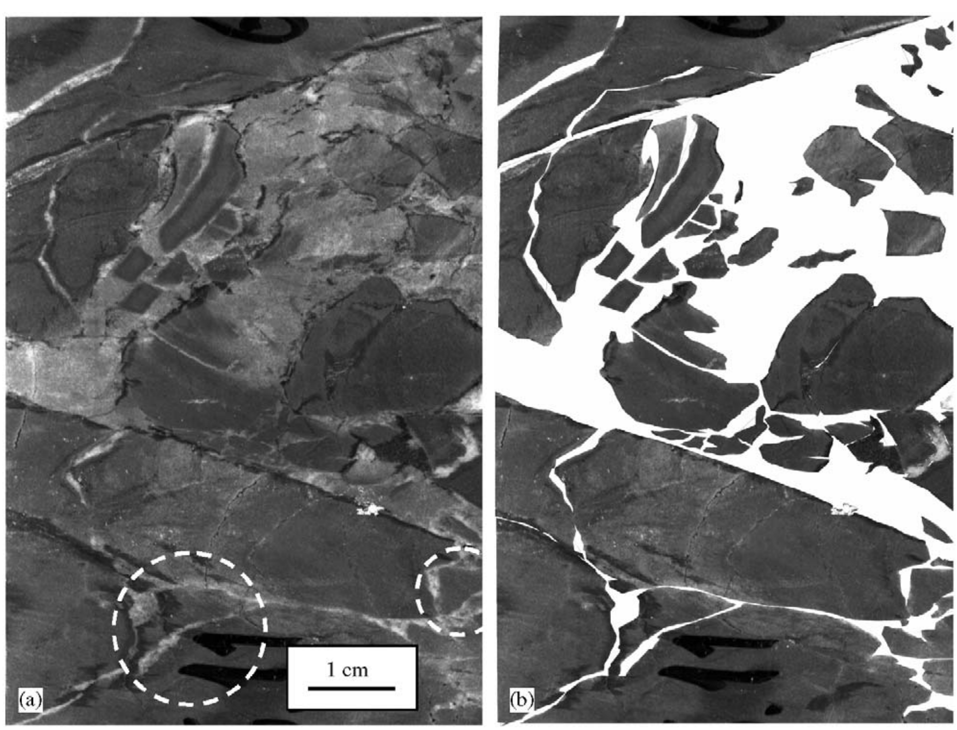

Fig. 4. Original (a) and processed (b) images of a sample having a VBP of 76.3%. The blocks in the circles are the fragmented pieces of larger blocks separated by infilled joints.

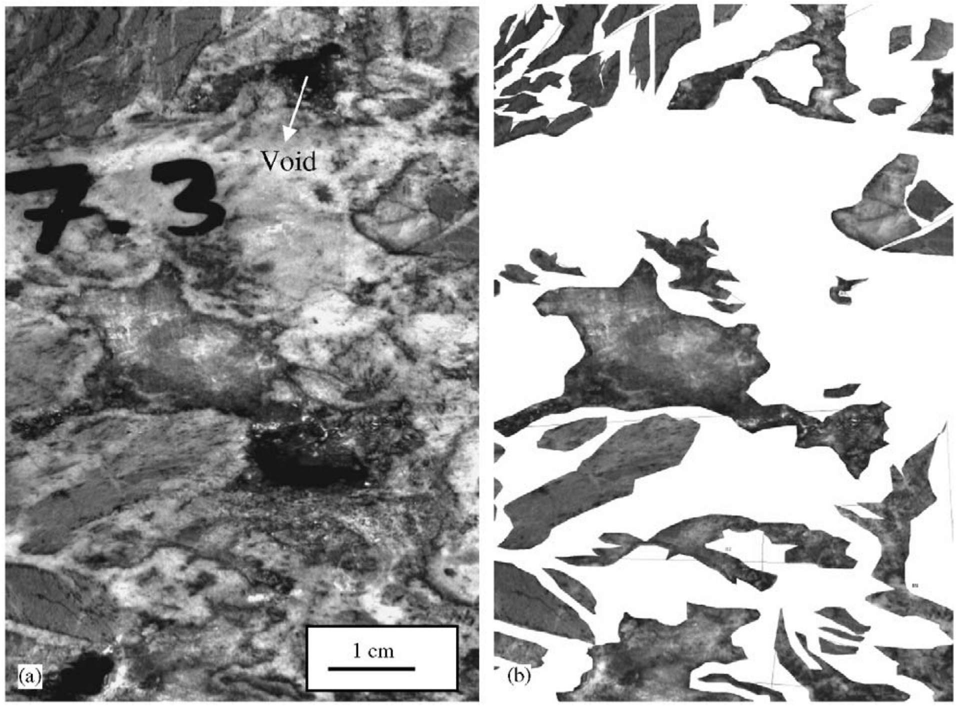

Fig. 5. Original (a) and processed (b) images of a sample having a VBP of 23.1%.

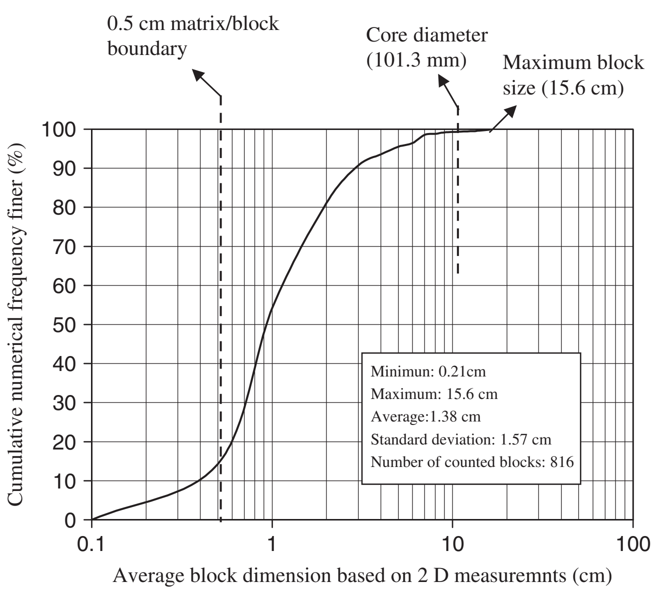

Fig. 6. Block size distribution of the breccia from scanned images of the original twelve 101.3 mm-diameter-cores.

bimrock at the scale of the dam. However, small samples cored from 101.3 mm-diameter-cores can be considered as a bimrock at the scale of laboratory specimens.

To obtain additional samples having different VBPs and to observe the scale effect on the strength and elastic properties, 22 smaller samples were cored from eight 101.3 mm-diameter-cores, with different diameters ranging from 7.6 to 73.0 mm. A total of 24 samples were prepared for image processing and the other tests. Average block sizes were calculated using the maximum and minimum dimensions of blocks in 2-D images from SigmaScan. A graph of block size distribution was plotted using the data measured from the scanned images of 101.3 mm-diameter-cores. As shown in (Fig. 6), the block sizes vary between 0.21 and 15.6 cm with an average value of 1.38 cm.

5. Laboratory studies

5.1. *Physico-mechanical tests on the components of fault breccia*

Greyish and brownish shale blocks, and beige limestone matrix can easily be seen in the breccia. The colours of most blocks are weathered, such as reddish-greyish. Sandstone and limestone blocks were not observed in the specimens.

To determine the physico-mechanical properties of components of fault breccia, 15.6 mm-diameter-samples cored from four 101.3 mm-diameter-cores. 43 samples for UCS and *E* tests, 15 samples for the density tests, and 15 samples for the porosity tests were prepared. UCS, *E*, density and porosity values of the samples were determined in the laboratory according to ISRM [15] standards. The density values were calculated using the calliper and balance readings. Porosity values were determined using saturation and calliper techniques. The average results of the all tests are given in Table 1. The UCS values of blocks 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. In

Table 1
Physico-mechanical properties of components of fault breccia (mean values with standard deviation)

Material type	Compressive strength (MPa)	Elastic modulus (GPa)	Density (g/cm^3)	Porosity (%)
Greyish shale	52.9±10.1	16.6±3.7	2.57±0.05	6.3±0.2
Greyish shale with red veins	63.6±1.1	21.3±0.9	2.65±0.02	6.6±1.7
Greyish-brownish shale	32.6±6.2	12.8±2.1	2.56±0.02	10.7±1.1
Brownish shale	89.3±6.9	15.7±1.9	2.66±0.04	5.9±1.3
Matrix	70.1±17.1	11.5±2.0	2.63±0.03	4.8±1.0

Fig. 7. Tested samples.

this case the breccia is not a conventional bimrock, which requires some strength contrast between block and matrix, with blocks stronger than the matrix.

5.2. Compressive strength tests on the fault breccia

Twenty-four core samples having different diameters (Fig. 7), ranging from 7.6 to 101.3 mm, were used for the compressive strength tests. The two samples were original 101.3 mm cores. 22 smaller samples were cored from original 101.3 mm cores. Most of the cores had a height to diameter ratio of 2–2.5. Some 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 [16]:

$$\mathrm{UCS} = \frac{8\mathrm{UCS}_1}{7 + 2(d/h)}, \tag{1}$$

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 generally passed around block boundaries (Fig. 8). Failures through blocks were commonly observed in the samples having VBP higher than 68.3% (Fig. 9) or having large blocks (Fig. 10). Dominant matrix failures were seen in the samples having VBP lower

Fig. 8. Failure plane passing around block boundaries (VBP = 70.7%).

Fig. 9. Failures through blocks in the sample having a VBP of 88.2%.

Fig. 10. Failures through blocks in the sample having large blocks and block size >75% of characteristic engineering dimension (VBP = 74.6%, diameter = 30.1 mm).

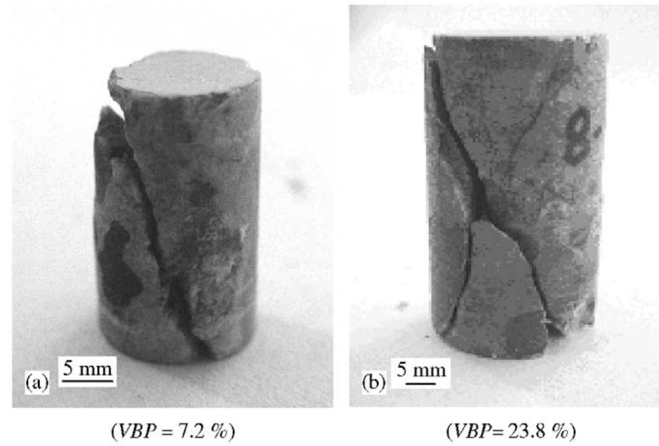

Fig. 11. Failure dominantly through matrix in the samples having low VBP.

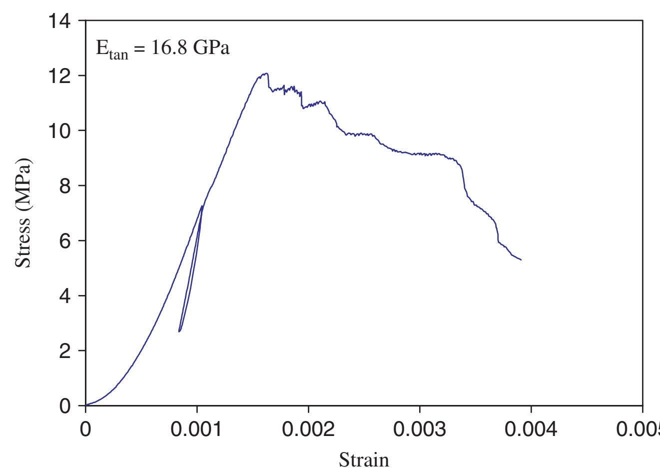

Fig. 12. Stress–strain diagram for sample no. 1 (101.3 mm-diameter).

than 28.5% (Fig. 11). Failures rarely passed through pre-existing joints in a few samples.

5.3. Elastic modulus tests on the fault breccia

During the uniaxial compressive strength tests, deformation measurements were carried out using high-resolution LVDTs. Stress–strain curves were plotted, as shown by the two examples in Figs. 12 and 13. Tangent Young's modulus values were obtained from stress–strain curves at a stress level equal to 50% of the ultimate uniaxial compressive strength.

6. Results and discussion

VBP, UCS and *E* values are given in Table 2. The VBP of the samples ranges from 7.2% to 94.6%. UCS values show a wide range, from 9.8 to 86.6 MPa. Elastic modulus values range from 3.0 to 16.8 GPa. The range in modulus values is not as great as the UCS values.

The scale effect on the UCS of the fault breccia was investigated graphically. The plot of UCS versus core diameter is shown in Fig. 14, where the data points are scattered below the approximately 40 mm-core-diameter. 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 bimrock 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 a range of VBPs. 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, reflecting that the large cores have approximately the same VBP. As shown in Fig. 15, the samples having diameters higher than 40 mm have nearly the same VBP. The VBP dependence of UCS can be seen in Fig. 16. As indicated in the figure, there is a strong relation between UCS and VBP. The relation follows a logarithmic function. The equation of the curve is

$$UCS = -22.43 \ln VBP + 115.44 \quad R^2 = 0.73, \tag{2}$$

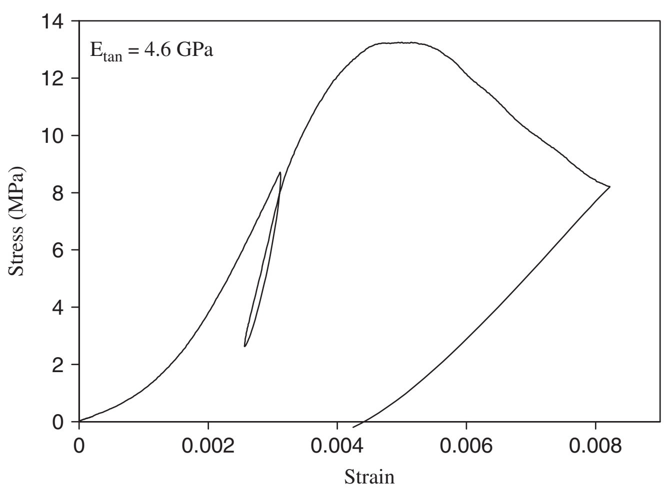

Fig. 13. Stress–strain diagram for sample no. 3 (62.6 mm-diameter).

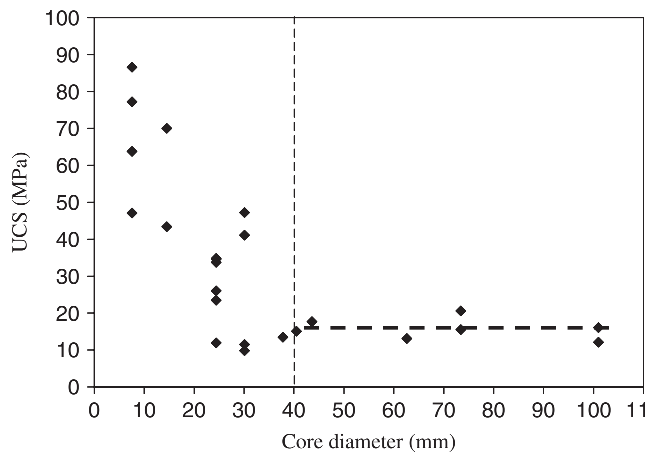

Fig. 14. UCS versus core diameter (high UCS for small diameter cores reflects bias to successfully sampling component because bimrock would full apart).

Table 2
Volumetric block proportion, compressive strength and elastic modulus values

Sample no.	Sample diameter (mm)	Number of counted block	Volumetric block proportion (%)	Compressive strength (MPa)	Elastic modulus (GPa)
1	101.3	131	70.0	12.1	16.8
2	101.3	170	75.0	16.1	10.8
3	73.0	289	76.7	20.6	10.6
4	73.0	116	77.0	15.5	5.2
5	62.6	93	54.5	13.1	4.6
6	43.6	122	70.7	17.7	9.4
7	40.5	20	94.4	15.1	7.1
8	37.8	25	68.3	13.5	6.4
9	30.1	60	74.6	11.5	5.9
10	30.1	72	50.4	47.2	9.1
11	30.1	27	77.6	41.1	12.3
12	30.1	64	76.3	9.8	3.0
13	24.4	32	56.0	33.8	8.5
14	24.4	58	23.1	26.0	5.1
15	24.4	35	88.2	11.9	5.9
16	24.4	17	96.6	23.5	14.2
17	24.4	7	22.8	34.8	10.3
18	24.4	37	28.5	34.6	12.3
19	14.5	20	23.8	43.4	10.1
20	14.5	14	18.2	70.1	15.8
21	7.6	6	7.8	77.2	10.4
22	7.6	12	7.2	63.8	14.2
23	7.6	5	10.6	47.1	9.7
24	7.6	12	8.5	86.6	11.6

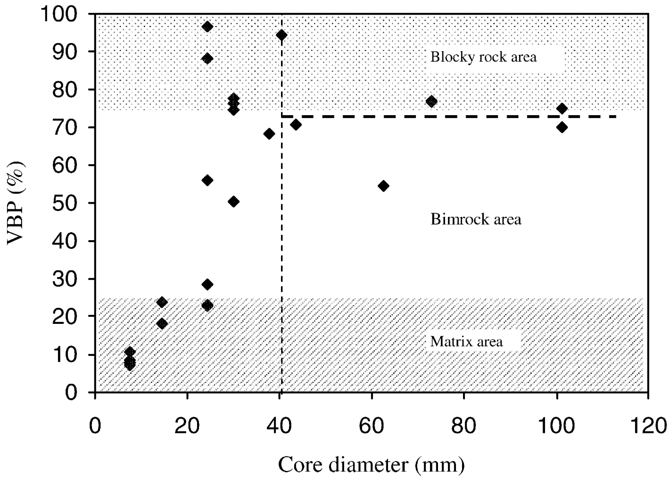

Fig. 15. Volumetric block proportion (VBP) versus core diameter (Matrix, bimrock and blocky rock areas are shown according to Medley [2].

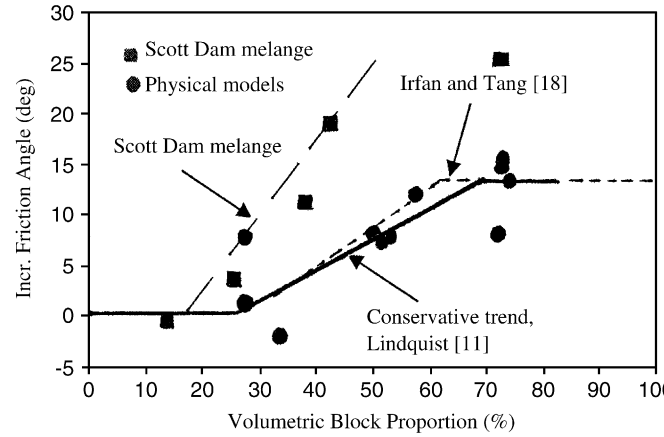

Fig. 17. Relation between friction angle and volumetric block proportion (after Medley [17]) [11,18].

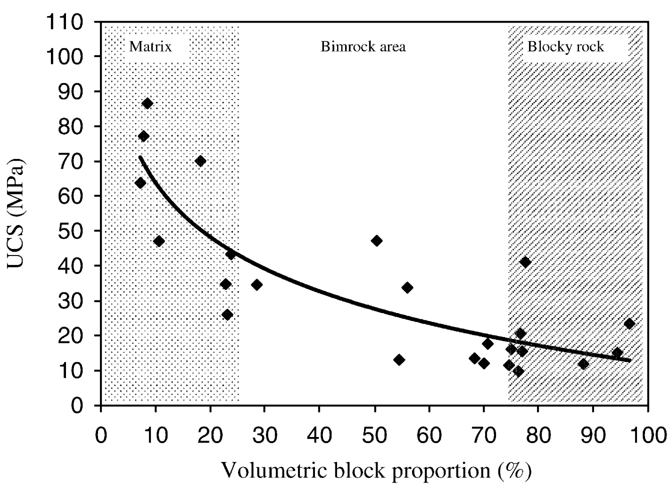

Fig. 16. VBP versus UCS (Matrix, bimrock and blocky rock areas are shown according to Medley [2].

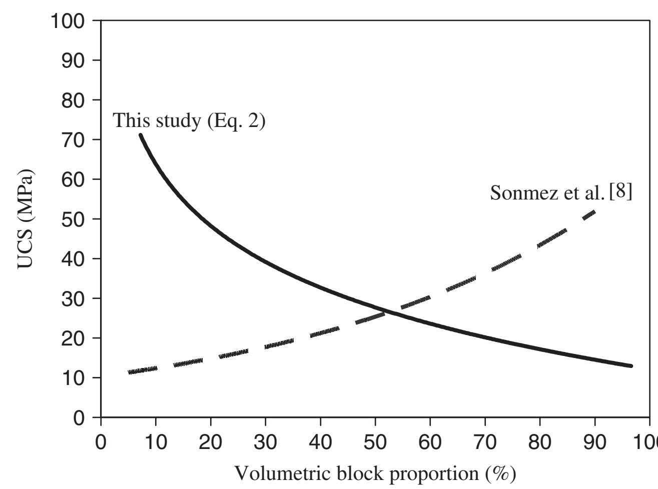

Fig. 18. Schematic comparison between Eq. (2) and the equation derived by Sonmez et al. [8].

where UCS is the uniaxial compressive strength (MPa) and VBP is the volumetric block proportion (%).

Lindquist and Goodman [6] and Lindquist [11] identified a conservative relation between strength and VBP for melange bimrocks (Fig. 17). 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. In this study, since the breccia has blocks weaker than the matrix, which is different from the study of Lindquist and Goodman [6] and Lindquist [11], the strength of the breccia decreases with increasing VBP. However, the result shows some similarity to the conservative relation between strength and VBP for melange bimrocks. That is to say the data points below about 20% VBP generally reflect the matrix. Above approximately 70% VBP, the UCS of the breccia is approximately uniform.

As shown in Fig. 16, decreasing VBP increases UCS. This result is different from the findings of Sonmez et al. [8]. They found that UCS for Ankara Agglomerate increases with increasing equivalent block proportion. The schematic comparison of the two study is indicated in Fig. 18. The difference between the two studies is due to the matrix type. The matrix of Ankara Agglomerate is weaker than the andesite blocks. However, the breccia tested in this study has a strong matrix as explained in Section 4.

There is no clear relation between E and core diameter as shown in Fig. 19. There seems to be two different trends for below and above 40 mm-diameter cores, which must be further investigated. Similarly, no clear relation could be found between E and VBP (Fig. 20). Although there is a good correlation between E and VBP for about 20% and 70% VBP (Fig. 21), there are few data points, the relation requires further investigation.

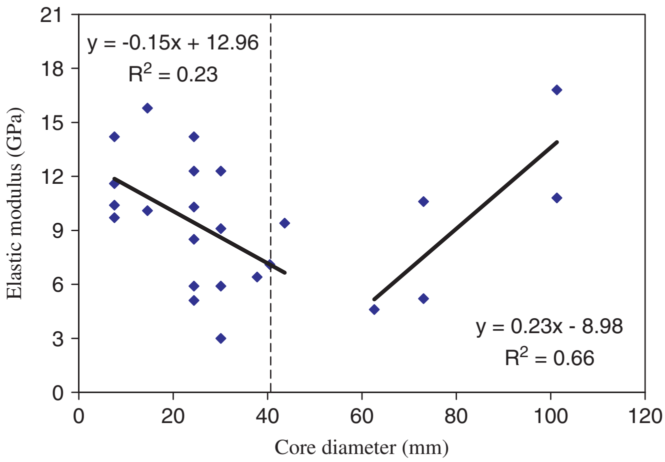

Fig. 19. Elastic modulus versus core diameter.

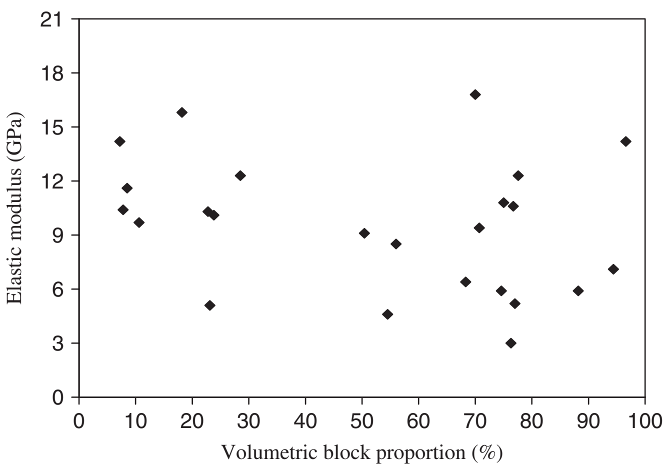

Fig. 20. Elastic modulus versus VBP.

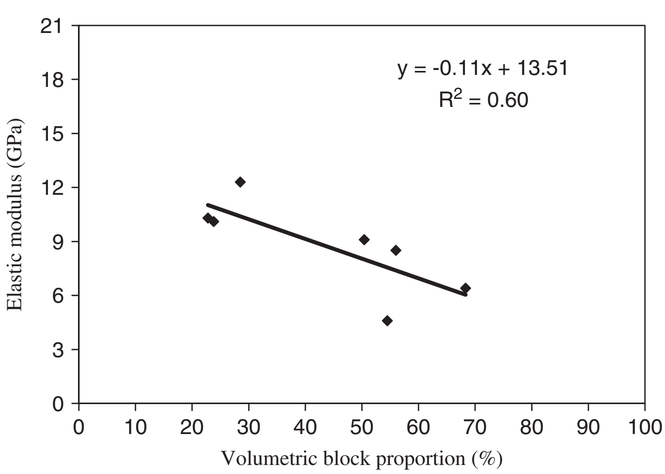

Fig. 21. Elastic modulus versus VBP for about 20% and 70% VBP.

7. Conclusions

Determination of strength and elastic properties of fault breccias is very difficult, because obtaining standard test samples is not easy. Indirect methods to estimate the properties of fault breccias will be useful for practitioners. Volumetric block proportion obtained from image analysis is an easy method for the estimation subject to accommodation of uncertainty. From effort to develop predictive models for the UCS and E of a fault breccia from VBP, the following conclusions were obtained:

(a) The scale effect is an important factor for the strength of breccia. The smaller the breccia block the larger the scale effect.
(b) The scale effect is related to VBP, in that the smaller breccia block may have different VBP values.
(c) The UCS of this breccia can be estimated from VBP.
(d) The scale effect on the E on this breccia is not clear.
(e) There is a dependence between E and VBP for about 20% and 70% VBP.

Further research is necessary to check the validity of these results and the derived equation for other breccia types where matrix is stronger than blocks. In addition, the dependence between E and VBP needs further research.

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