Relationships between Volumetric Block Proportions and Overall UCS of a Volcanic Bimrock

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Block-in-matrix rocks (bimrocks) are mixtures of stronger blocks or rock enclosed by weaker matrix rocks (1). The overall strength of bimrocks tends to be greater than the strength of the matrix alone because the presence of blocks influences the mechanical properties above a threshold volumetric proportion of blocks (2). Therefore, the determination of the volumetric block proportion of bimrocks is of crucial importance for the estimation of their overall mechanical properties.

Three measurement methods are commonly used to determine the volumetric block proportion of bimrocks:

- One-dimensional (scanline and borehole);
- Two-dimensional (image analyses on photographs and window mapping); and
- Three-dimensional (sieve analyses).

Although the sieve analysis method is the most exact method for laboratory-scale studies, separation of blocks from the weaker matrix is often impossible, depending on the number and size of blocks, and the degree of contact strength between blocks and matrix. Accordingly, extensive studies have been performed on means of determining volumetric block proportions using one-dimensional (boreholes) and two-dimensional (image analyses and physical model) methods. These studies have revealed that the accurate determination of 3D volumetric block proportion using 1D and 2D methods is widely influenced by the amount of sampling and actual block proportion, as well as the shapes, block size distribution and orientation of the blocks (1, 3, 4).

In this study, node-counting and image classifications on grayscale and Red-Green-Blue (RGB)

Beziehung zwischen Gesteinsblockvolumen und Druckfestigkeit von vulkanischem Block-in-Matrix Gestein (Bimrock)

Der Beitrag befasst sich mit dem Zusammenhang zwischen Gesteinsblockvolumen und Druckfestigkeit von Ankara Agglomerat. Dieser Fels besteht aus überwiegend vulkanischem Gestein gemischt mit Tuffmatrix; rosafarbene und schwarze Andesitbblöcke mit harter bis sehr harter Konsistenz werden von einer Tuffmatrix mit relativ geringer Festigkeit umgeben. Das Blockvolumen wurde mithilfe eines Bildanalyseverfahrens näherungsweise ermittelt. Die rosafarbenen und schwarzen Andesitblöcke des sogenannten Bimrock (Block-in-Matrix Gestein) wiesen erhebliche Farbunterschiede zur Tuffmatrix auf, was die Bildanalyse von schwarz-weiß und RGB Farbfotoaufnahmen von Aufschlüssen wesentlich erleichterte. Die mithilfe des Bildanalyseverfahrens ermittelten Gesteinsblockabmessungen wurde mit den Schätzungen verglichen, die durch Anwendung der nulldimensionalen „Knotenzählmethode“ ermittelt wurden. Aufgrund der annähernden Gleichförmigkeit der Vulkangesteinsblöcke kann angenommen werden, dass die zweidimensionalen Abmessungen des Gesteinsblocks, ermittelt durch die Messung anhand von Fotoaufnahmen, dem Blockvolumen entsprechen. Das gemessene Gesteinsblockvolumen wurde zur annäherungsweisen Bestimmung der einachsigen Druckfestigkeit von Ankara Agglomerat als Funktion des Volumengehalts eines Gesteinsblock verwendet. Hierzu wurden auf Regression basierende Gleichungen entwickelt. Das Verhältnis zwischen dem Blockvolumen und der Druckfestigkeit von Ankara Agglomerat hat einen nicht linearen Verlauf, was darauf schließen lässt, dass die Gesamtfestigkeit des Bimrock von der Festigkeit der einzelnen Gesteinblocktypen abhängt. Diese Abhängigkeit mag bedingt sein durch die underschiedlichen Festigkeitseigenschaften zwischen Gesteinsblöcken und Felsmatrix und erfordert weiterreichende Untersuchungen.

This paper describes a study into the relationship between volumetric block proportions and unconfined compressive strength (UCS) of Ankara Agglomerate, a volcaniclastic block and tuff matrix mixture containing relatively weak tuff matrix surrounding stronger pink andesite blocks and very strong black andesite blocks. Volumetric block proportions were estimated using image analysis methods. The pink and black andesite blocks in the bimrock exhibited significant color contrasts with the tuff matrix, which facilitated image analysis of grayscale and RGB colored photographs of outcrops. Estimates of block proportions from image analysis were checked against estimates generated using the zero-dimensional “node-counting method”. 2D block proportions estimated from measurements of photographs were considered to be equivalent to the volumetric block proportions because the volcanic blocks were approximately equi-dimensional. The measured volumetric block proportions were incorporated into a further stage of the study by developing regression-based equations to estimate the overall uniaxial compressive strength of Ankara Agglomerate as a function of volumetric block proportions. The non-linear relationship between volumetric block proportions and overall UCS of Ankara Agglomerate, suggests a dependence between overall UCS of the bimrock and the strengths of the different types of blocks. This dependence may be due to variations in block/matrix strength contrasts and requires further study.

Table 1 Statistical evaluations of uniaxial compressive strength (UCS) and unit weight (γ) for the constituents of Ankara Agglomerate (5, 13).

Tabelle 1 *Statistische Auswertungen von einachsiger Druckfestigkeit (UCS) und Wichte (γ) für Bestandteile des Ankara Agglomerats (5, 13).*

Statistical parameter	γ [kN/m³]	UCS [MPa]
Black Andesite Blocks		
Number of samples	35	33
Average	24.30	91.09
Standard deviation	0.231	11.62
Minimum	23.84	72.15
Maximum	24.70	119.89
Pink Andesite Blocks		
Number of samples	16	16
Average	22.66	49.85
Standard deviation	0.936	11.44
Minimum	21.03	33.99
Maximum	23.35	78.03
Tuff Matrix		
Number of samples	23	21
Average	16.88	10.55
Standard deviation	0.883	1.89
Minimum	15.17	6.41
Maximum	18.23	14.42

Fig. 1 Outcrop of volcanic block and tuff mixture (PA: pink andesite blocks, BA: black andesite blocks; T: tuff).

Bild 1 *Aufschluss einer Vulkangesteinsblock- und Tuffmischung (PA: rosafarbene Andesitblöcke, BA: schwarze Andesitblöcke; T: Tuff).*

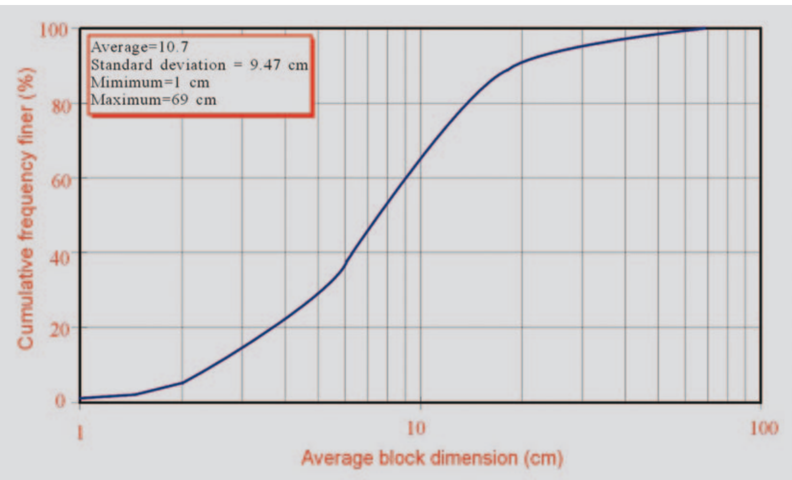

Fig. 2 Block-size distribution of andesite blocks in volcanic block and tuff mixture.

Bild 2 *Blockgrößenverteilung von Andesitblöcken in Vulkangesteinsblock- und Tuffmischung.*

colored photographs were performed to determine the volumetric block proportion of Ankara Agglomerate, a volcanic block and tuff mixture, which according to the criteria of Medley (1, 3), is a bimrock at laboratory and outcrop scales. The longest and shortest observable dimensions of the blocks were measured from photographs taken from different locations and orientations, in order to evaluate the shape of the blocks as well as identify the relationships between 2D block proportion obtained from photographs, and an estimate of the 3D volumetric block proportions.

The general procedure outlined in this paper was used to generate estimates of volumetric block proportions, which were then incorporated into a conceptual approach for the determination of the overall UCS of Ankara Agglomerate (5, 13), the preliminary results of which are reported in this paper.

Properties of the volcanic block and tuff mixture

Ankara Agglomerate is a volcaniclastic block and tuff mixture composed of pink (lighter) and black (darker) andesite blocks ranging in size from a few centimeters to about one meter (Figure 1). The blocks are cemented by weak tuff matrix. To determine the engineering properties of the constituents of the volcanic block and tuff mixture, a series of laboratory tests were performed on specimens of the pink and black andesite blocks and tuff matrix, collected from a site in Ankara, Turkey (5). The uniaxial compressive strength (UCS) and unit weight tests on the blocks and tuff were performed in accordance with the suggested method of ISRM (6). The results of the tests are summarized in Table 1. The average values of UCS for pink and black andesite blocks are 49.9 and 91.1 MPa, respectively, and that of the tuff matrix is 10.6 MPa. The minimum and maximum ratio of UCS of blocks to the UCS of tuff matrix is 2.4 and 18.7, respectively. Furthermore, a total of 270 NX-size core samples of Ankara Agglomerate were tested in accordance with the ISRM procedure (6) to obtain the overall UCS values of Ankara Agglomerate. The maximum and minimum UCS values of Ankara Agglomerate were 5.7 and 55 MPa, respectively, and the average UCS value was 24.9 MPa.

Medley (1) has suggested a threshold value of at least 2 for the ratio of UCS of block to UCS of matrix for a geological rock mixture to be considered as a bimrock. The UCS data of the constituents of the volcanic block and tuff mixture (see Table 1) clearly indicates that there was significant mechanical contrast between blocks and matrix, and that the volcanic block and tuff mixture investigated could be evaluated as a bimrock.

In addition, Medley (1) has also suggested that in a bimrock at the scale of engineering interest, the size and volume of blocks be sufficient to affect the overall properties of the mixture. Medley

(1) also suggested that at any scale of interest being considered ("characteristic engineering dimension"), blocks would range between 5 and 70 % of that scale. The 2D measurements of blocks in the Ankara Agglomerate revealed that the block sizes ranged between 1 and 69 cm (mean value, 10.7 cm), as indicated in the block-size distribution graph shown as Figure 2. Blocks ranged to about 1 m in size in observed outcrops. Hence, at the characteristic engineering dimensions of the laboratory test specimens (cm scale), the Ankara Agglomerate is a bimrock, because block sizes occupied the full 5 to 70 % range in laboratory scale. However, at the scale of an outcrop (for example, 10 m height) Ankara Agglomerate has "small blocks" limited to between 0.5 and 1 m in size.

The results of this study, based on laboratory scale specimens and photographs of outcrops are applicable to larger volumes of the Ankara Agglomerate if it can be demonstrated that the Ankara Agglomerate has some scale-independence in block size distributions (1, 7).

Determination of volumetric block proportions by image analysis

Previous research (2) revealed that the overall strength of a bimrock mass having between about 25 and 70 % volumetric block proportion is directly related to the volumetric block proportion, with no dependence on the strength of the blocks. Below 25 % the strength can be taken as that of the matrix (2). Accordingly, for the purposes of study into the geomechanical behavior of Ankara Agglomerate (5, 13), the overall strength of the volcanic block and tuff mixture was assumed to be primarily dependent on the volumetric proportion of andesite blocks. It was thus vital that the volumetric block proportions be determined.

In some bimrock materials at laboratory scale, careful sieve analysis can be used to separate hard blocks from weak matrix to obtain representative block size distributions and volumetric block proportions (8). However in this study, separation of the andesite blocks from weak tuff matrix was impossible because of the weak welding ("cementation") between the volcanic blocks and matrix. Instead of physically separating block and matrix constituents, image analysis methods were used to estimate the volumetric block proportions. Advantage was taken of previous research where 1D scan-line surveys, and node-counting (zero dimensions) and 2D image analyses have also been used to estimate volumetric block proportions (1, 3, 4, 9). Based on correlations between 1D, 2D and 3D evaluations these earlier studies indicate that the quantity of sampling, the actual volumetric block proportion, and the shape and orientation of blocks control uncertainties in estimation of volumetric block proportion (1, 9).

To define the block dimensions and shapes of the volcanic block and tuff mixture, the longest and shortest dimensions of individual block were measured from scanlines oriented at different directions across photographs taken of different outcrops of the Ankara Agglomerate. As shown in Figure 3, 75 % of the measured blocks have 2D major:minor dimension ratios less than 1.2, which indicated that the blocks are approximately equi-dimensional in 2D and 3D. The rationale for this assumption was that the fragmented, volcaniclastic genesis of the bimrock resulted in probable random block orientations within the rock mass, and that the many measurements in 2D sufficiently captured 3D block dimensions. In that case, the uncertainties in the estimation of 3D block proportions, based on 2D measurements, would be less than those for bimrocks with ellipsoidal blocks such as melanges studied by Medley (1, 9) or the idealized mixtures analyzed by Haneberg (12).

To estimate the volumetric block proportions of the volcanic block and tuff mixture at field scale, image classifications and node-counting methods were performed on grayscale and RGB colored photographs of the bimrock. For this purpose, scaled photographs were taken perpendicular to nearly planar exposures of Ankara Agglomerate (see Figure 1). The overall objec-

Fig. 3 Cumulative frequency distribution of the ratio of the lengths of longest axes to lengths of shortest axes of andesite blocks.

Bild 3 *Summenhäufigkeitsverteilung des Längenverhältnisses von längster zu kürzester Hauptachse von Andesitblöcken.*

tive of image classification procedures is to automatically categorize pixels into classes or themes (10) using "unsupervised classifications" or "supervised classifications". In the unsupervised approach, the image data are first classified by aggregating them into the natural spectral (tonal) grouping or clusters present in the image (10), whereas supervised classification involves a training step followed by a classification step. In this study, the supervised image classification method of training, classification and output stages were performed for the determination of the pink block, black block and tuff matrix constituents of the Ankara Agglomerate, using both grayscale and colored photographs of outcrops exposures.

The colored photographs of agglomerate exposures (outcrops and drill core) were scanned in RGB and grayscale with high resolution. Some known constituents on parts of the colored images were first defined in the training stage of image classification (Figure 4a). In the training stage of the grayscale photographs, the pixel value ranges of each constituent were determined within the overall grayscale tonal spectrum of 0 to 255 grayscale shades. The black andesite has a range of grayscale pixel values of 0 to 61 in. Except for some small deviations in the unweathered core samples, the range of grayscale pixel values for the tuff and pink andesite is generally between 62 to 115 and 116 to 255, respectively, according to the image analyses performed by Gokceoglu and others (11). In the second stage, whole images were classified on the

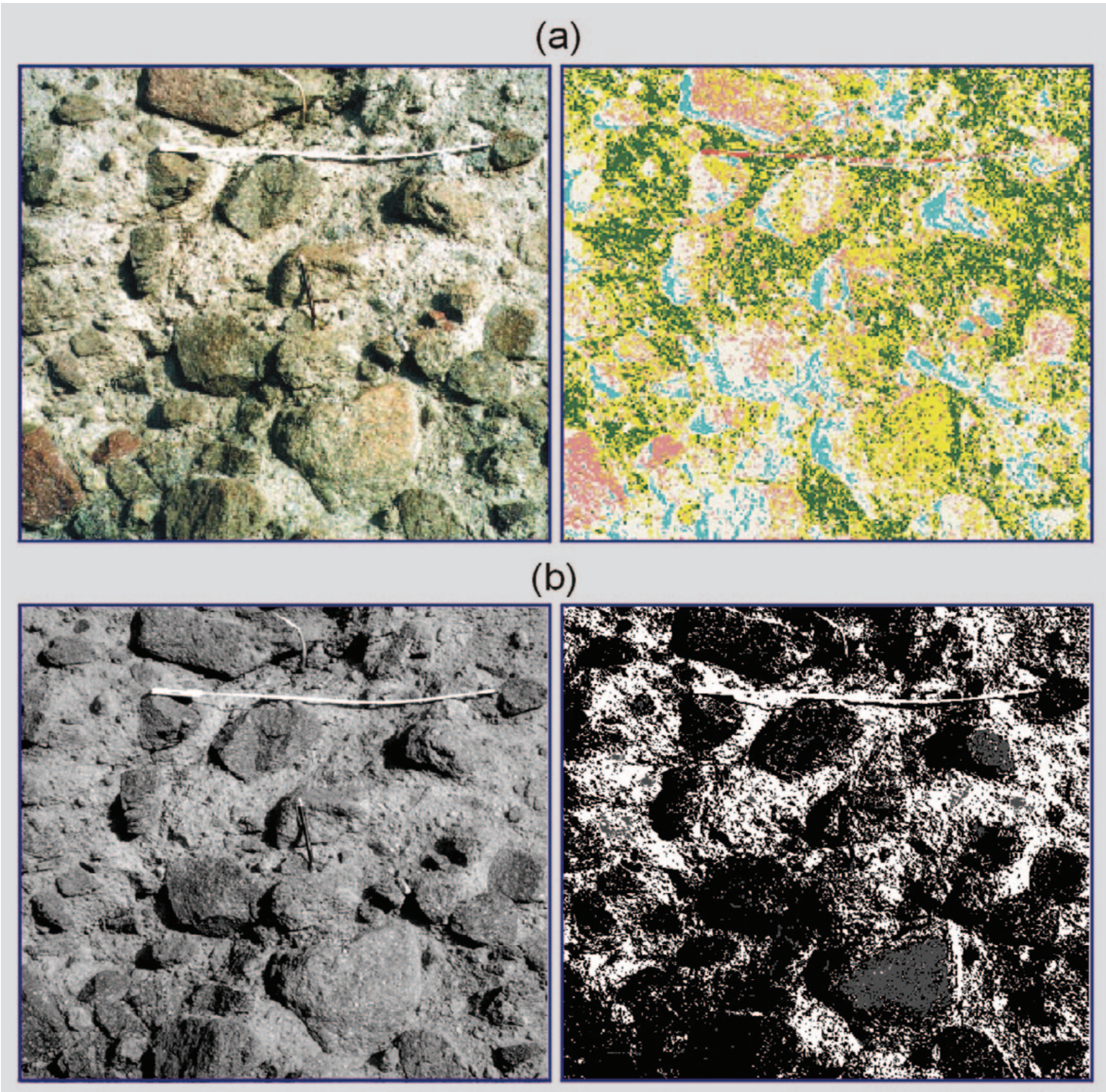

Fig. 4 Original and classified views of Ankara Agglomerate exposures (a) RGB colored image and (b) grayscale image (white scale bar is 1 m long).

Bild 4 *Original und klassifizierte Ansichten von Ankara Agglomerat Aufschlüssen: a) RGB Farbfotoaufnahmen und b) Schwarz-weiß Aufnahmen (weiße Messskala entspricht 1 m).*

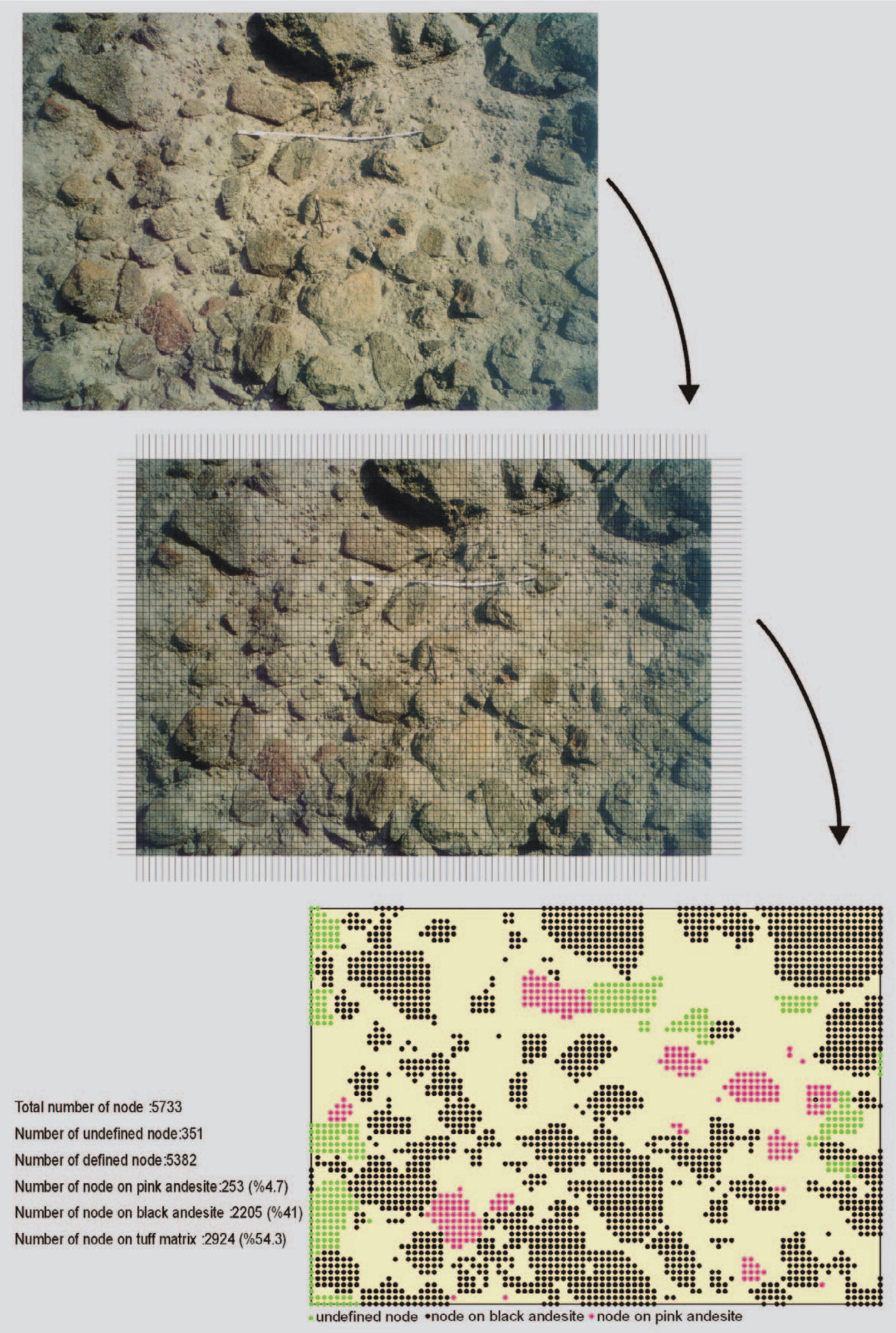

Fig. 5 Stages of the node-counting classification.

Bild 5 *Phasen der Knotenzählzuordnung.*

basis of the results of the training stage. Each pixel in the image data set was categorized into the constituents (Figure 4b) using a minimum-distance-to-means classifier, since the minimum-distance-to-means strategy is mathematically simple and computationally efficient (10).

In the node-point-counting method, a mesh having squares of 1 cm^2 was overlaid on the photographs (Figure 5). At each intersection (node) of the mesh, the underlying material was visually classified as being tuff, black andesite or pink andesite. (This method is similar to point-counting performed by mineralogists and petrologists using rock thin sections viewed through microscopes in order to determine mineralogical proportions necessary to petrographically classify

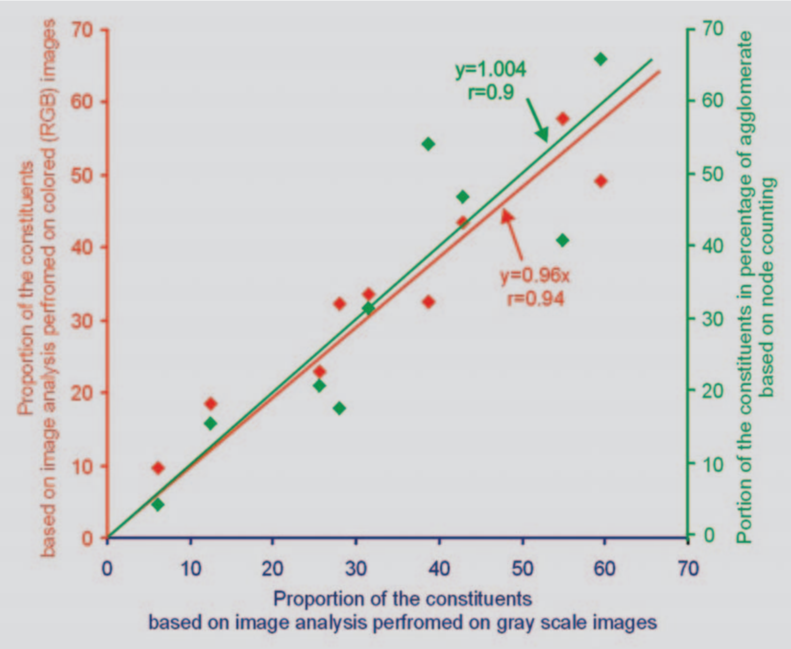

Fig. 6 Cross-check between proportions of the constituents of agglomerate estimated from the image analysis method performed on grayscale images, compared to estimates based on image analyses performed RGB colored images (red plot), and the node-counting method (green plot).

Bild 6 *Überprüfung der Größenverhältnisse von Agglomeratbestandteilen, geschätzt anhand Bildanalyse von Schwarz-weiß Aufnahmen, im Vergleich zu Schätzungen mithilfe der Bildanalyse von RGB Farbbildern (rote Linie), und Knotenzählmethode (grüne Linie).*

the rock sampled by the thin section.) The percentages of each constituent of the agglomerate exposures were determined by dividing the number of node intersections for each constituent by the total number of intersections of the mesh (see Figure 5).

A cross-check between the proportions of the constituents obtained from image classification employed on grayscale and colored photographs showed that similar estimations of the proportion of the constituents was obtained (Figure 6). As can be seen from Figure 6, there is no significant difference between the two methods, hence the more practical image classification method was used to obtain further estimates of volumetric block proportions of the volcanic block and tuff mixture.

Preliminary evaluation of the UCS of Ankara Agglomerate

The volumetric block proportion data described in this paper are being used to develop relationships between volumetric block proportions and overall UCS for Ankara Agglomerate (13). The proportion of the constituents of Ankara Agglomerate core samples were determined by using grayscale image analysis performed on both halves of split core samples.

In a further stage of the study, the relation between block proportions and the UCS values of the Ankara Agglomerate core samples was evaluated. It was also of interest to determine if there was any dependence between overall UCS and strengths of the two block types. In other words, since black andesite is stronger than pink andesite, it was assumed that the mechanical influence of stronger black andesite blocks on the overall UCS could be higher than the influence of the weaker pink blocks.

The sum of the proportions of black and pink andesite blocks was equal to the total volumetric block proportion in the specimens. However, a composite block proportion was used to study the differences in overall UCS due to differences in the proportions of the two different block types. A weighted "equivalent block proportion", or EBP, accommodates two or more types of blocks differing in individual mechanical properties:

$$EBP = \sum_{i}^{n} VP_i \frac{UCS_i}{UCS_{max\_block}} \qquad [1]$$

where VP is the volumetric block proportion of i^{th} block, UCS is the uniaxial compressive strength, n is the number of different types of blocks, and UCS_{max_block} is the uniaxial compressive strength of the stronger block type.

The uniaxial compressive strengths of the Ankara Agglomerate specimens were then normalized by dividing them by the average uniaxial compressive strength of the matrix: this parameter is denoted as UCS_N. The distributions of the data between EBP and UCS_N are illustrated in Figure 7.

Two exponential type equations were obtained by regression analyses of the data of shown in Figure 7:

$$UCS_N = 1.3361 \exp(1.12 x EBP) \quad [2]$$

$$UCS_N = \exp(1.6874 x EBP) \quad [3]$$

As shown in Figure 7, the regression line forced to intersect to value of "1" on the y axis (data pair of EBP=0, UCS_N=1) yields a trend that is more slightly more representative of the data than the unforced trend. The relationship of Figure 7 is non-linear, particulary above about 70 % equivalent block proportion, suggesting that the dependence of overall bimrock strength on block proportion is more complex than previously understood. The plot also indicates that at high equivalent block porportions the overall bimrock becomes uniformally stronger, with less data scatter. This behavior supports the recommendation of Medley (1), based on the work of Lindquist and Goodman (2), that at high volumetric block proportions (greater than about 70 to 75 %), block/matrix rock mixtures should be considered as a blocky rock masses with wide infilled joints, for which fabric conventional rock engineering methods should be applied.

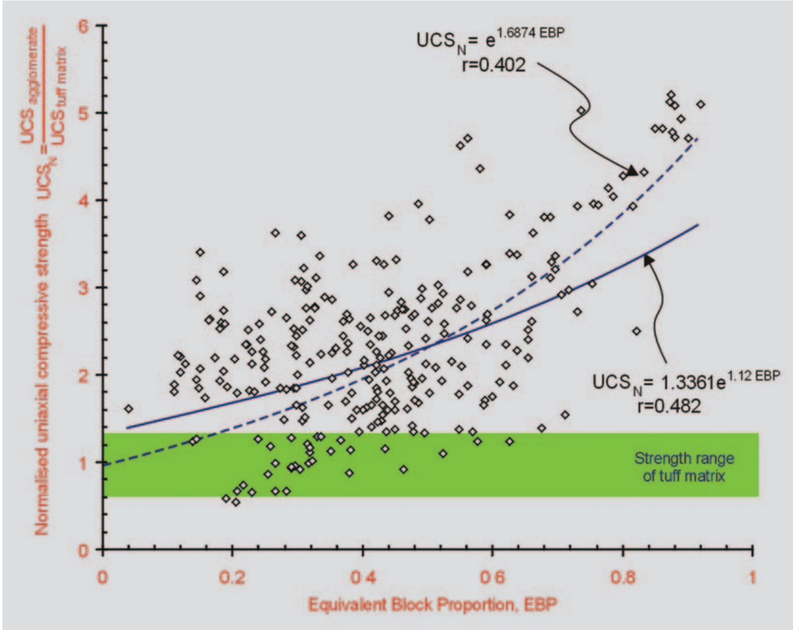

Fig. 7 Relationships between equivalent block portion (EBP) and UCS of Ankara agglomerate. Trend forced through intercept (0, 1) is slightly more representative of data.

Bild 7 *Beziehungen zwischen äquivalentem Blockanteil (EPB) und Druckfestigkeit von Ankara Agglomerat. Verlauf durch Schnittpunkt (0,1) repräsentiert Daten etwas besser.*

The preliminary work also revealed an apparent but unexpected relationship between the strength of the blocks and the overall UCS for the two different types of blocks. Until now it has been assumed that overall bimrock strength is not influenced by block strength, as long as there is sufficient block/matrix strength contrast to force failure surfaces around blocks (1, 2). However, this study shows that the interaction between blocks and matrix is more complex than previously assumed, and that block/matrix strength contrasts for two or more mechanically diverse blocks may also influence the overall mechanical behavior of the bimrock. Further work is underway to examine the problem.

Conclusions

Based on the work performed for this study, the following conclusions are presented:

- If there is sufficient color contrast between constituent blocks and matrix, image analysis methods are practical for the determination of the block proportions of outcrops, laboratory specimens and similar exposures of bimrocks.
- If the shapes of blocks of a bimrock are approximately equi-dimensional in 3D, the block proportions obtained from 2D measurements can be considered equivalent to the 3D volumetric block proportions.
- When using image classification on grayscale images, the surfaces must be slightly weathered or unweathered. If the surfaces are weathered, image classifications using coloured photographs should be employed.
- The relationship between equivalent block proportion (EBP) and UCS values of Ankara agglomerate indicates that the effect of EBP on UCS is small for lower EBP values , but exponentially increases with higher values of EBP.
- There is an apparent dependence between UCS and individual block strengths, which requires further study.

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