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ORIGINAL PAPER

Contribution of fractal dimension theory into the uniaxial compressive strength prediction of a volcanic welded bimrock

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Abstract

This study was carried out on Sille agglomerate which is a typical volcanic welded bimrock. Two precious historical monuments, Koimesis Tes Panagias Church and Sekili hill settlement carved in Sille agglomerate, have maintained their stability without any support for centuries although suffering from weathering and various stability problems. However, due to its heterogeneity and sampling difficulties, the overall strength of Sille agglomerate has not been investigated yet. This paper presents the relationships between fragmentation fractal dimension (D_F), fractal dimension of rough block surfaces (D_R), number of blocks (B_N), and volumetric block proportion (VBP) and the overall uniaxial compressive strength (UCS) of the Sille agglomerate. By using these properties as inputs, three statistically significant empirical models were developed for estimating the UCS of the Sille agglomerate. The results revealed that the D_F and D_R may be good predictors to estimate the UCS of welded volcanic bimrocks, and defining the properties of blocks by means of fractal theory provides significant contribution to the estimation of the UCS. It is observed that the failure planes in the core samples predominantly pass through the boundaries between matrix and blocks, and such behavior may indicate that the weakest component of the Sille agglomerate is boundaries. Accordingly, the UCS decreases due to the high D_R values which create more or further weakest zones in the bimrocks. Finally, it is concluded that the negative correlation between the UCS and the VBP was attributed to increase of the D_R due to the increase of the VBP.

Keywords Bimrock · Fractal dimension · Area to perimeter method · Strength · Agglomerate

Introduction

It is widely known that the determination of strength and deformation properties of heterogeneous and geologically complex rock masses such as pyroclastic rocks, melanges, fault breccias, lithified colluviums, and sheared serpentines has been highly challenging and their estimation have increasingly been studied for the last few decades. These rock masses were called as "bimrocks" (contraction of block-in-matrix rocks) for the first time by Medley (1994), and are traditionally composed of competent rock blocks and relatively weak fine-grained matrix. Sufficient strength and/or stiffness contrast (such as the ratio of uniaxial compressive strength (UCS) of blocks to those of matrix have to be greater than 1.5) is necessary for a block-in-matrix rock mass to be considered as a bimrock (Lindquist 1994; Medley 1994). Besides, Kahraman and Alber (2006) and Kahraman et al. (2008) studied fault breccias from Germany and Turkey having block strength values less and/or close to the matrix strength. Accordingly, these rock masses are not conventional bimrocks described by Medley (1994), but they are still block-in-matrix materials. Besides, some kinds of unwelded block in matrix materials consist of rock blocks and soils such as bimsoil (Zhang et al. 2016), soil-rock mixture (SRM) (Xu et al. 2007; Xu et al. 2011) and rock and soil aggregate (RSA) (Li et al. 2004). Recently, some researchers (Li et al. 2004; Xu et al. 2008; Xu et al. 2016) have applied various methods such as image processing analysis, X-ray computed tomography, numerical analysis, and large scale in situ tests in order to research unwelded block in matrix materials. Bimrocks and block-in-matrix materials exhibit variability in terms of their lithological and mechanical properties and cause problems in rock engineering applications. Therefore, overall mechanical and geo-engineering characterization of bimrocks becomes an important subject on the rock engineering studies to overcome

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and prevent problems in relation to the structures constructed on or in these materials.

According to some of the previous studies (e.g., Barbero et al. 2008; Sonmez et al. 2006a, 2016), the UCS and deformation modulus of both natural and fabricated bimrock samples increase with increasing volumetric block proportion (VBP). On the other hand, Kahraman and Alber (2006) stated that increasing VBP of the samples having weak blocks and strong matrix decreases the UCS values. In addition, Lindquist (1994), Afifipour and Moarefvand (2014), and Sonmez et al. (2006b) found similar results with the latter for the samples having VBP values greater than 70%, unwelded bimrocks, and artificial specimens, respectively. Although there is a general compatibility between the previous studies, some differences are remarkable in terms of the results of the studies due to the variable structures of bimrocks and block-in-matrix materials. In these studies, various predictive models have been proposed to estimate UCS values of such rock masses due to the difficulties of both extracting high-quality undisturbed samples and time-consuming and tedious in situ tests. S-wave velocity, average block diameter factor, matrix strength, block count, roughness line fractal, and fragmentation fractal dimension of the blocks together with or without VBP have been used as input parameters in the generating prediction models for the estimation of the UCS (Afifipour and Moarefvand 2014; Kahraman et al. 2008; Kalender et al. 2014; Mahdevari and Maarefvand 2016; Sonmez et al. 2016). Kalender et al. (2014) used the UCS of matrix and contact strength parameter (A) with the VBP as input parameters in bim strength criterion to predict the overall UCS of unwelded bimrocks. In addition, Sonmez et al. (2016) proposed empirical equations for estimating the UCS of a welded volcanic bimrock by using number of blocks and roughness line fractal dimension as input parameters specifying that these two input parameters have direct relationships with boundary strength between matrix and blocks. Kahraman et al. (2008) have found statistically significant relationships between average block diameter factor with VBP and UCS. Additionally, Mahdevari and Maarefvand (2016) investigated the effects of fractal dimension of the block size distribution, VBP, and maximum block size on the UCS of the large-scale synthetic samples of which VBP values varies between 50% and 75%. There are only two studies (Gokceoglu 2002; Sonmez et al. 2016) on welded bimrock that use soft computing techniques. Artificial neural network (ANN) and fuzzy logic methods have been used in these two studies for the prediction of the UCS of bimrocks. These researchers stated that these methods were quite useful techniques in prediction studies. Besides, in recent years, some new approaches to establish improved rock strength criterions have been suggested by some researchers. Fattahi and Moradi (2018) proposed a new model for estimation of the rock mass deformation modulus based on the basic concepts of a rock engineering systems (RES) approach. Cui (2019) put emphasis on the scientific challenge that lies in the understanding of how different types of joint are related to the failure criterion. Although Fattahi and Moradi (2018) and Cui (2019) have studied on rock masses different from those bimrock in this study, they have similarly focused on the strength behavior of rock mases by examining the various rock properties.

A semi-underground (hill) settlement called "Sekili Cave" and a semi-underground Church called "Koimesis Tes Panagias Church" were founded in rock by carving about 1500 years ago in Sille settlement, Turkey (Fig.1). These structures excavated in Sille agglomerates set important and typical examples for long-term behavior of man-made structures. There are rock tombs and paintings on the walls of the ancient rock-hewn semi-underground structures of archeological heritage dating back to the first Christian era. Since the Koimesis Tes Panagias Church and ancient Sekili Cave are suffering from stability problems, determining the physical properties and the UCS of "Sille agglomerate" is crucial. Thus, a kind of volcanic welded-bimrock Sille agglomerate was selected as the material of this study. Sampling studies were carried out in the vicinity of the church and the ancient settlement. Some large-sized agglomerate rock boulders (Fig. 2a) fell from the exterior surfaces and entrances of these structures because of the presence of discontinuities

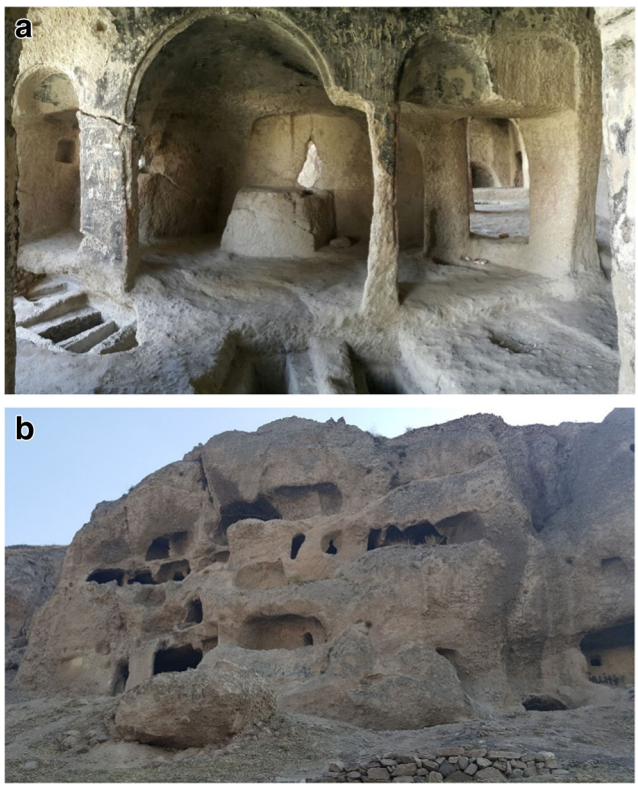

Fig. 1 Ancient monuments **a** Koimesis Tes Panagias Church and **b** Sekili Cave were founded in Sille agglomerate

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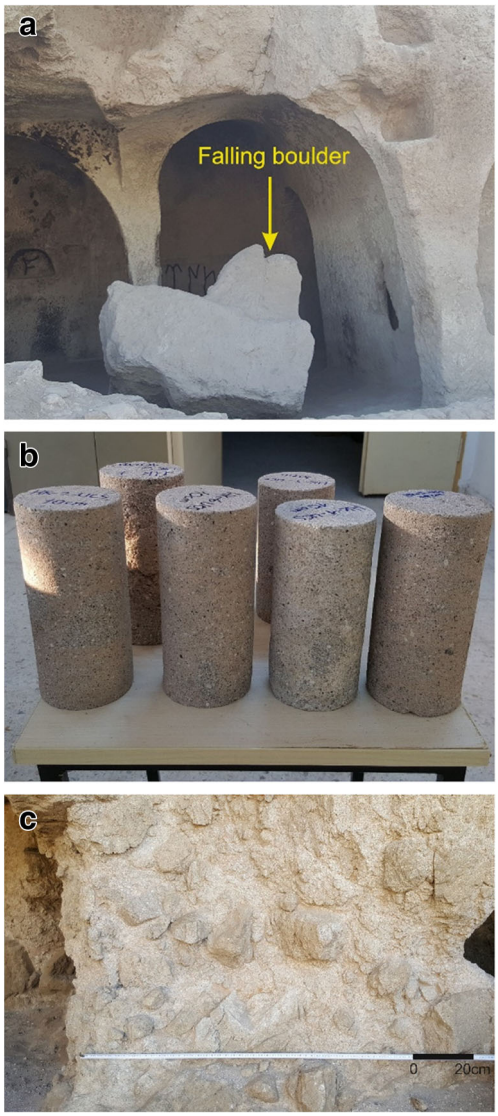

Fig. 2 **a** A falling boulder from the entrance of Koimesis Tes Panagias Church, **b** agglomerate core samples prepared in the laboratory, and **c** a typical view of an outcrop including tuff matrix and various size of andesite blocks

cutting the structures were gathered, and core specimens (Fig. 2b) were prepared in the laboratory.

Considering the previous studies, there is a lack of investigation concerning the effects of fractal dimension of the blocks on the UCS of natural welded bimrocks and relationships between fractal dimension and VBP. Therefore, the relationships between the UCS and fractal dimension of fragmentation in terms of block size distributions were evaluated. Since boundary strength is quite likely the weakest component of welded bimrocks and cannot be determined directly by experiments, number of blocks (B_N) and roughness of the outer surface of blocks were taken into consideration to define the effect of these components on the overall strength of welded bimrocks. In this study, roughness values of the block surfaces were defined by fractal dimension theory and its calculations and were expressed as roughness fractal dimension (D_R). The secondary goal of this study is (i) to provide statistically significant empirical models and (ii) to make available to practitioners for estimating the UCS of Sille agglomerate using properties determined from more practical and applicable methods.

Sampling studies and properties of Sille agglomerate

Pyroclastic deposits outcropped in the Sille region are composed of fall and flow deposits with lava domes. The unit formed in a terrestrial environment with eruptions of the Late Miocene-Early Pliocene volcanism (Ozkan 2017). The K-Ar ages of these rocks range from 11.95 to 3.35 Ma (Keller et al. 1977). In the field studies, it was clearly seen that the Sille agglomerate is made of blocks in various sizes in a relatively weak tuff matrix (Fig. 2c). Besides, in optical microscopy studies, it was determined that the blocks are andesite and the matrix material is tuff. It was also detected that these andesitic blocks have porphyritic texture and contain plagioclase, biotite, quartzite phenocrysts, and opaque minerals with a matrix of volcanic glass.

Medley (1994) measured the maximum observed dimension of about 1900 blocks of Franciscan melanges and revealed that bimrocks are scale-independent in terms of characteristic engineering dimension (L_c). Medley and Zekkos (2011) proposed a block/matrix threshold related to the scale of engineering interest by a characteristic engineering dimension such as a tunnel diameter, thickness of a failure zone beneath a landslide, footing width, height of a slope or excavation, laboratory specimen diameter, $\sqrt{A}$, and so on. When scaled by L_c, the block/matrix threshold is thus 0.05 L_c and the largest block d_{max} is 0.75 L_c. These researchers stated that blocks smaller than the block/matrix threshold (d_{min}) form the matrix material and have negligible geo-mechanical effect on overall strength. Considering the literature findings on scale independence, in this study, the block size distribution analysis and the uniaxial compressive strength tests were performed on agglomerate cores, and thereby, the findings can be accepted representing the overall agglomerate rock mass.

The historical and cultural structures within the Sille region are located in an archeological protection site area and sampling studies were carried out in accordance with the official permissions obtained from the Konya Cultural and Natural Heritage Protection Board. Therefore, limited number of matrix, andesite, and agglomerate (bimrock) boulders were collected and transported to the laboratory. Particular attention was paid to gathering of unweathered rock boulders from the field. In the present study, all core sampling studies were carried in accordance with the procedures of ASTM D4543 in the laboratory. A surface set diamond thin-walled core barrel

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suitable for soft rocks was used to extract core samples from the rock boulders. Core specimens were prepared to be length-to-diameter ratio of 2.0 to 2.5. Tuncay et al. (2019) revealed that the use of the lower bound of L/D is 2 suggested by ASTM that may result in UCS values 20% higher than the correct value, particularly for hard rocks. However, in this study, most of the bimrock specimens have L/D between 2.0 and 2.5 and this type of rock cannot be evaluated as hard rock considering the UCS values. According to ASTM, to disable the influence of the scale effect and to determine minimum strength without considering engineering dimension, it is recommended that the diameter of core specimens be at least ten times the diameter of the largest fragment. However, it is not reasonable to provide this requirement for bimrock and bimsoils. On the other hand, any suggested methods and/or standards have not yet been proposed for specimen preparation of such rock masses. In the previous studies, in order to estimate the strength and deformation properties of a block in matrix rocks, characteristic engineering dimension is taken into consideration and that concept is generally accepted in the literature. With the careful and exhaustive core drilling studies, a representative number of samples were prepared from tuff matrix and andesite constituents of agglomerate and directly from agglomerate. Since Sille agglomerate contains varying sizes (from pebbles to large blocks) of andesite blocks, to obtain agglomerate cores containing both blocks and matrix constituents, sampling was made from the agglomerate containing relatively small-sized andesite blocks (Fig. 2b). A total of 105 core samples were prepared, 30 of which were matrix, 28 of which were andesite blocks, and 47 of which were agglomerate (bimrock). Only 6 of these core samples (agglomerate) have 94-mm diameter and the rest of them have 54-mm diameters. Thus, d_{min} and d_{max} sizes range between 4.7 and 70.5 mm for 94 mm cores and range between 2.7 and 40.5 mm for 54 mm core samples.

Determination of volumetric block proportion

It is crucial to determine real-like VBP values of bimrocks because of the strong correlation between the geomechanical properties of the bimrocks and the VBP. Various methods have been employed for the determination of the VPB in the previous studies (Coli et al. 2011; Haneberg 2004; Kahraman et al. 2008; Xu et al. 2008). According to the literature, the VBP can be estimated by using measurements of borehole/block intersection length (chord) or scanlines on outcrops in 1-Dimension, and by image analysis on scanned images or on photographs, aerial photos, and geological maps in 2-Dimesion. Lastly, an equation including unit weights of matrix, blocks, and bimrock cores is used to calculate the VBP values (Lindquist 1994) in 3-Dimesion and 3-D sieving can be also carried out at the laboratory scale.

Uncertainty in estimating 3-D block size distribution from 1-D chord lengths of borehole and/or scanlines is quite likely influenced by the amount of available sampling data (Haneberg 2004; Medley 2002). Sieving analysis can only be carried out on unwelded bimrocks and bimsoils; otherwise, separation of blocks from matrix of welded bimrocks as well as for Sille agglomerate would be impracticable. Since the unit weights of matrix and block components of each core sample cannot be determined directly, the method for determination of the VBP in 3-D by using unit weights has not been preferred for the current study. On the other hand, in most of the previous studies (Coli et al. 2011; Kahraman and Alber 2006; Kahraman et al. 2008; Sonmez et al. 2005, 2006b), 2D digital image processing has been used for estimating the VBP values of bimrocks and this method is well-known in terms of providing satisfactory results. Besides, Haneberg (2004) stated that the error was in assuming that 2D measurements were equivalent to those of 3D values.

Sonmez et al. (2005) carried out 2-D image analysis on grayscale and RGB-colored photographs in order to estimate the VBP of Ankara agglomerate. The researchers stated that in case the blocks are approximately equi-dimensional in 3-D, the block proportions determined in 2-D can be considered equivalent to 3-D volumetric block proportions. In this study, therefore, image analyses were carried out on the photographs taken from outcrops of Sille agglomerate to examine the shape characteristics of the blocks (Fig. 3a). The ratio of Feret diameter to minimum Feret diameter of each block was calculated from image analyses. The results show that most of the blocks have a ratio less than 1.5. Therefore, the applicability of 2-D image analyses for Sille agglomerate was checked by the method of Sonmez et al. (2005). It is concluded that the blocks of Sille agglomerate have approximately same dimension in 2-D and 3-D measurements.

Since the blocks and matrix of Sille agglomerate have very low color contrast (see Fig. 2), it is not possible to perform image analysis with grayscale or RGB-colored photographs in which tonal discrimination is highlighted. For this reason, digital image processing analyses were carried out by using "ImageJ" computer program, to obtain digitizing images of photographs from outcrops and circumferential surfaces and top and bottom circular surfaces of core samples. Within this scope, tracing paper was wrapped on each core and block boundaries were manually traced one by one (Fig. 3b). The scales of the photographs from outcrops and the scales of the tracings have been recorded while conducting in situ and laboratory studies. The photographs from outcrops and tracings of the core samples were uploaded to ImageJ software. Set scale tool of ImageJ was used in order to digitize both tracings and photographs. Then, block boundaries were outlined again and block areas were filled semi-automatically in digitizing the images (Fig. 3a, b). The formats of images were converted to 8-bit and the blocks and matrix were adjusted by threshold

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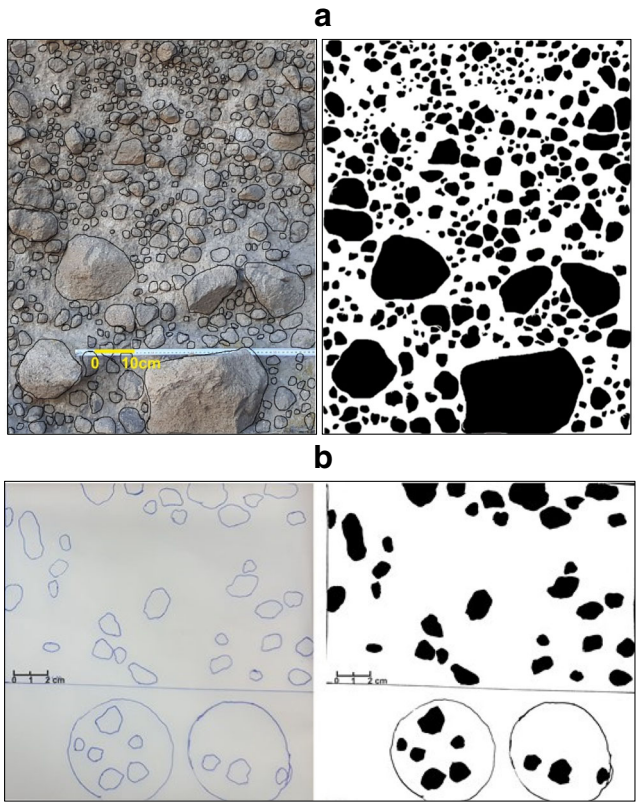

Fig. 3 Hand drawing of block boundaries and digitized images of **a** photograph taken from the study area and **b** outcropped blocks on circumferential, top and bottom circular surfaces of core sample

tool. Analyzed particle tool was used after defining all blocks. Therefore, some properties of blocks such as all of apparent Feret dimensions, roundness, perimeter, and area of blocks were determined through using digitized images. Number of blocks (B_N) was also counted automatically in digital image analyses. It should be also noted that the B_N of the core samples obtained from 2D images may be evaluated as apparent block numbers. And finally, areal block proportions of each core were calculated and these values were assumed equivalent to the VBP. The VBP values of core samples varied in a wide range (from 10 to 63%) because the sampling studies were conducted from outcropping rocks having different block proportions in the various locations in the study area.

Fractal dimension studies

The fundamental principle and estimations in the literature

Mandelbrot (1967) has developed the phenomenon of fractal geometry to identify the irregular and fragmented patterns and to quantify these patterns that appear to be chaotic and random. The fractal dimension is a real non-integer number and differs from Euclidean and topological dimensions. The fractal dimension always varies between 1 and 2 for irregular lines and between 2 and 3 for a surface. The fractal dimension of a fragmented pattern changes depending on the degree of "roughness" of the pattern. And the fractal dimension also has a different value for each pattern type (Bagde et al. 2002; Hyslip and Vallejo 1997; Kaye 1989). In recent years, the fractal geometry has been shown to be a robust and convenient approach for modeling and quantifying the multiscale structure of geologically complex and heterogeneous media such as rocks, soils, and fracture networks (Barton et al. 1995; Feder 1988; Ghanbarian et al. 2015; Ghanbarian and Hunt 2017; Ghanbarian et al. 2019; Gimknez et al. 1997; Mandelbrot 1982; Perfect 1997; Sahimi 2011).

If a fractal object is isotopically rescaled with the same scaling factor, a statistically similar object is reproduced and this feature is termed self-similarity. Theoretically, strict self-similar fractals have the property of scale invariance, i.e., the estimate of fractal dimension remains unique regardless of which scale level the assessment is made (Heping et al. 1997). For a self-similar fractal set, points $x = (x_l, x_2. \ldots, x_E)$ in E-dimensional space transform into newpoints $x' = (rx_1, rx_2. \ldots, rx_E)$, under the same value of scaling ratio r (Feder 1988; Sakellariou et al. 1991).

Actually, self-similarity does not represent for several fractal sets of interest. However, these sets are invariant to a more general form of transformation, the affine transformation, and they are called self-affine fractals (Sakellariou et al. 1991). A point of such a fractal set $x = (x_l, x_2, \ldots, x_E)$ in E-dimensional space is transformed by an affine transformation into a new point $x' = (r_1x_1, r_2x_2. . \ldots, r_E\ x_E)$, where the scaling ratios $r = (r_1, r_2\ldots, r_E)$ are not all equal (Feder 1988). The fractal dimension of a self-affine fractal is not uniquely defined (Feder 1988; Mandelbrot 1985). Its global value is $D = D_T$ (D_T means topological D), that is a self-affine fractal that is not fractal globally. But a local fractal dimension can be computed by means of standard procedures. This behavior of a self-affine fractal set involves a cross-over value of the sample interval, where the local value of the fractal dimension passes to the global one. Evidently, self-affinity is a generalization of self-similarity (Mandelbrot 1985; Sakellariou et al. 1991).

It should also be noted that the concept underlying fractals is self-similarity or self-affinity, that is, invariance against variations in scale or size (scale-invariance) (Mandelbrot 1967). It is known that there are many scale-invariant processes in nature and even in the universe. One of them is the distribution of the block sizes of bimrocks as Medley (1994) has demonstrated the scale-invariance of Franciscan melanges.

The Korcak's empirical law was presented in 1938 to describe the size-distribution of various geographical objects, including lakes and islands, and has developed the empirical relationship:

$$N(A > a) \sim a\text{-}b \quad (1)$$

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where $N(A > a)$ is the total number of islands having size A greater than a given comparative size a and b is a constant equal to *1/2* ($b = 1/2$) for all islands. Benoit Mandelbrot used Korcak (1938)'s law to show that fractals are applicable of describing many natural objects. Mandelbrot (1982) indicated that b actually ranged between island regions with b always being greater than 1/2 ($b = 1/2$). Accordingly, Mandelbrot (1982) discovered that the size distribution of a population of islands was intrinsically a consequence of fractal fragmentation and that the empirical constant b correlated with the fragmentation fractal dimension. Mandelbrot therefore proposed Eq.2 to quantify fractal fragmentation by developing the fractal dimension through this equation.

$$N(R > r) = cr^{-D_F} \quad (2)$$

where $N(R > r)$ is the cumulative frequency of blocks with a linear dimension R (radius, diameter, perimeter, etc.) greater than a given comparative size r and the exponent D_F is the fragmentation fractal dimension, and c is a constant coefficient related to the maximum block size. Unlike the roughness fractal dimension, the fractal dimension derived from Eq. 2 is not a measure of the irregularity of the pattern, but a measure of the size-number relationships of the fragmentation of the population (Hyslip and Vallejo 1997).

Taking the logarithm of both sides of Eq. 2 gives a linear relationship between $N(R > r)$ and r and the slope coefficient ($-m$) of this relationship is equal to D_F.

$$D_F = -m \quad (3)$$

Many size distributions in nature follow Korcak's empirical law, including the fragmentation of rock into smaller and smaller sizes (Hyslip and Vallejo 1997). Block size distributions in fragmented materials or blocky rock masses also quite likely show negative power law distribution which is presented in Eq. 2 (Coli et al. 2012; Bagde et al. 2002; Goodman and Ahlgren 2000; Medley 1994; Turcotte 1986; Xie and Pariseau 1993). In 3-Dimension, the fractal dimension is simply calculated by adding 1.0 to the 2-Dimension fractal dimension.

It is well documented in the literature that the surfaces of natural rock fragments and fractures are rough and follow self-affine scaling from fractal geometry (Brown 1987; Brown and Scholz 1985; Ghanbarian et al. 2019; Lee et al. 1990; Madadi and Sahimi 2003; Schmittbuhl et al. 1993). In the recent study, it is assumed that the rough boundary of blocks is fractal. And, in the fractal calculation methods that are presented, self-affinity is assumed. The particle profile roughness by means of "ratio of linear extents" was proposed by Mandelbrot (1982) with an equation given below (Eq. 4).

$$c = (\text{perimeter})^{1/DR/}(\text{area})^{1/2} \quad (4)$$

where c is a constant value for similar fractal shapes, and D_R is the roughness fractal dimension. Taking the logarithm of Eq. 4, a linear relationship (least-squares linear regression) is yielded between area (A) and perimeter (P) with D_R related to the slope coefficient (m).

$$D_R = 2/m \quad (5)$$

Evaluating the roughness fractal dimension using Eq. (4) and Eq. (5) is referred as the "area-perimeter" method (Hyslip and Vallejo 1997; Mandelbrot 1982). This method quantifies the roughness of fragments and determines D_R by evaluating an entire population of related shapes as opposed to individual particles (Hyslip and Vallejo 1997; Mandelbrot 1982). The A-P relation tells about complexity, "wiggliness," or degree of contortion of the perimeter, since a fixed length of rounded, smooth perimeter can enclose a larger area than a complicated one can (Lovejoy 1982). This degree of complexity can be characterized by the dimension D_R of the perimeter, which appears in the formula $P \sim \sqrt{A^{D_R}}$. For smooth shapes such as circles and squares $P \sim \sqrt{A^{D_R}}$, and $D_R = 1$, the dimension of a line. As the perimeter becomes more and more contorted and tends to double back on itself, filling the plane, $P \sim A$ and D_R approaches the value 2 (Lovejoy 1982). In the literature, there are successful applications which the area-perimeter method is used for roughness fractal dimension estimates.

Hyslip and Vallejo (1997) applied area-perimeter fractal dimensioning technique to quantify roughness of planar profiles of individual sand grains. Sakellariou et al. (1991) estimated unique local fractal dimension D_L values, as a roughness measure, by the area-perimeter method to suggest a more objective criterion for roughness classification for rock joint surface of ISRM (2007) profiles. Sakellariou et al. (1991) used digital terrain model for each respective rock joint surface. Araujo et al. (2017) concluded that combining image analysis with area-perimeter method of fractal dimensioning techniques is an accurate and efficient method to quantify the differences in particle morphology and surface texture of quartz sands. As Ghanbarian et al. (2019) summarized, the area-perimeter method has also been successfully applied to relate perimeter to area in clouds (Lovejoy 1982), metallic rough fractures (Mandelbrot et al. 1984), and soil and rock pores (Pachepsky et al. 1996; Schlueter et al. 1997). Furthermore, it has been also used in combination with the model of Patzek and Silin (2001) to describe fluid flow in tubular pores with rough surfaces, and to accurately estimate water relative permeability (Ghanbarian et al. 2016). It would seem that the fractal dimensioning has a universal applicability for quantification of particle roughness, and eventually, has the potential to predominate the other methods in acceptance and use.

Fractal dimension estimates of Sille agglomerate

Bimrocks, bimsoils, and soil and rock mixtures include various size and shape of rock blocks. Shape and size distribution characteristics of these blocks substantially affect the overall strength of such rock masses. Instead of describing the shape

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and size distribution characteristics of the blocks qualitatively, it is scientifically more convenient and practical to define them numerically. Thus, it is more appropriate to use these numerical values in the fields of engineering geology and particularly in the prediction studies. In the recent study, the surface roughness of the blocks was defined numerically using fractal dimension theory. In addition, the fragmentation fractal dimension theory was used for defining the size-number relationships of the block population in the agglomerate rock mass. These determinations were made on core specimens of Sille agglomerate and their results were used in regression analysis.

Franciscan Mélange has a range of fragmentation fractal dimensions between 1.1 and 1.7, with an overall value of about 1.3 in 2-D (Medley 1994). In addition, Coli et al. (2011) defined 2-Dimension the D_F values on log-log histograms of block size distribution of the Shale-Limestone Chaotic Complex bimrock (Italy) and indicated that the D_F values varied from 1.2 to 1.8. On the other hand, Mahdevari and Maarefvand (2018) selected 2, 2.5, and 3.5 as the D_F values in 3-Dimension for fabricating the artificial samples. Mahdevari and Maarefvand (2018) stated that the fractal dimension is less than 3 when the volumetric proportion of coarse aggregate is larger than fine one in the bimrocks and vice versa. And, in case that the fractal dimension is equal to 3, the block size distribution is uniform. Hyslip and Vallejo (1997) also found high D_F values for the high relative percentage of fine-grained material. Xu et al. (2007) also addressed the importance of determining the particle size distribution of soil–rock mixtures in evaluating its strength.

Although the concept of fractal theory is very helpful and is a practical tool to providing quantitative and unique numerical values, there is very limited study on determining the relationships between fractal dimension of block characteristics and overall strength parameters of bimrocks (Mahdevari and Maarefvand 2018; Sonmez et al. 2016). Sonmez et al. (2016) studied the effects of roughness properties of the blocks on the boundary strength by means of fractal theory. Additionally, Mahdevari and Moarefvand (2018) used the D_F of synthetic specimens obtained from block size distribution function to investigate the influence of the D_F on the UCS and deformation modulus of bimrocks. Based on the methods employed in the previous studies, the block size distribution function (Eq. 2) obtained from the curve of "cumulative frequency versus diameter of blocks" graph was used to estimate the D_F of each core sample individually. A graph cumulative frequency vs. diameter of block of a core sample to determine the block size distribution function and D_F is given in Fig. 4 as an example. According to that graph, the block size distribution function of the core sample is given in Eq. (6) and the D_F is the exponent of this equation (see Eq. (7)). The Sille agglomerate has D_F values varying between 1.239 and 1.948 in 2-D as shown in Table 1.

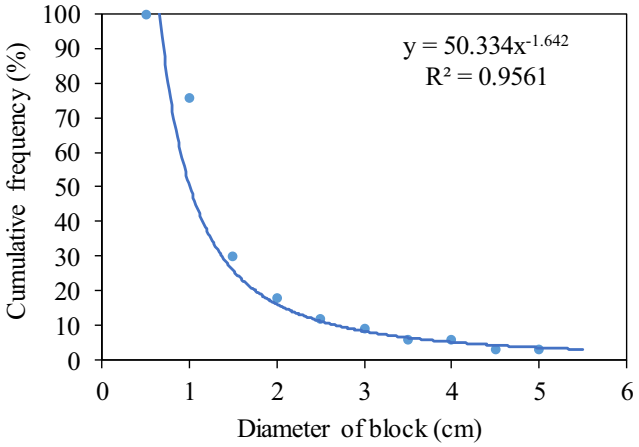

Fig. 4 Cumulative frequency versus diameter of block graphic of a core sample

$$y = 50.33x^{-1.642} \quad (6)$$

$$D_F = 1.642 \quad (7)$$

Another novelty of this study is applying area-perimeter method to the blocks in bimrocks for the first time. After all, the area and perimeter values of blocks in the Sille agglomerate core samples obtained from digital image analyses were calculated and then plotted on log-log graphs. The data pairs of six representative core samples were presented in the same log-log graph in Fig. 5a. Taken separately, as seen in Fig. 5a, data of each core sample fall on parallel straight lines which are very close to each other. A log-log graph of A-P relation of blocks within a core sample is given in Fig. 5b as a representative example. As seen from that figure, the exponent of the equation was defined as m parameter with a value of 1.9266. Finally, D_R of this core sample was calculated from Eq. 5 ($D_R = 2/m$) as $D_R = 1.0381$.

The author was inspired by the study investigating the fractal geometry of clouds' perimeter which was carried by Lovejoy (1982). To briefly mention, Lovejoy (1982) concluded that the rain and cloud perimeters are fractals and the relation between area and perimeters of clouds yielded least squares with an empirical value of $D_R = 1.35$ and a correlation coefficient 0.994 for a wide range of scales of digitized satellite and radar images. And, according to Lovejoy's approach to the scale issue of fractal theory in terms of area-perimeter method, if A-P relation is well-described throughout by a relation of the form $P \sim \sqrt{A^{D_R}}$, this shows the absence of characteristic length scales in the cloud perimeters. In the recent study, the digitized images of blocks were investigated in fractal studies similar to the planar shapes of clouds with rough boundaries. More importantly, the A-P relations of blocks of each core are well-described by the abovementioned equation and all the A-P relations have linear relationships with high

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Table 1 Descriptive statistics of UCS and the other properties of Sille agglomerate

Property	Number of samples	Min.	Max.	Mean	Std. deviation
UCS (MPa) (train data)	32	2.60	8.14	4.98	1.50
UCS (MPa) (test data)	15	2.25	7.6	4.59	1.58
VBP (%) (train data)	32	10	63	27	14
VBP (%) (test data)	15	18	62	35	11
B_N (train data)	32	13	60	32	12
B_N (test data)	15	14	49	30	12
D_F (train data)	32	1.283	1.854	1.590	0.1581
D_F (test data)	15	1.239	1.948	1.536	0.2140
D_R (train data)	32	1.0100	1.1399	1.0587	0.03464
D_R (test data)	15	1.0133	1.1205	1.0595	0.02837
γ_{dry} (train data)	32	15.7	17.1	16.3	0.31
γ_{dry} (test data)	15	15.2	17.6	15.9	0.28

UCS, uniaxial compressive strength (MPa); *VBP*, volumetric block proportion (%); D_F, fragmentation fractal dimension; D_R, roughness fractal dimension; B_N, number of blocks; γ_{dry}, dry unit weight (kN/m^3)

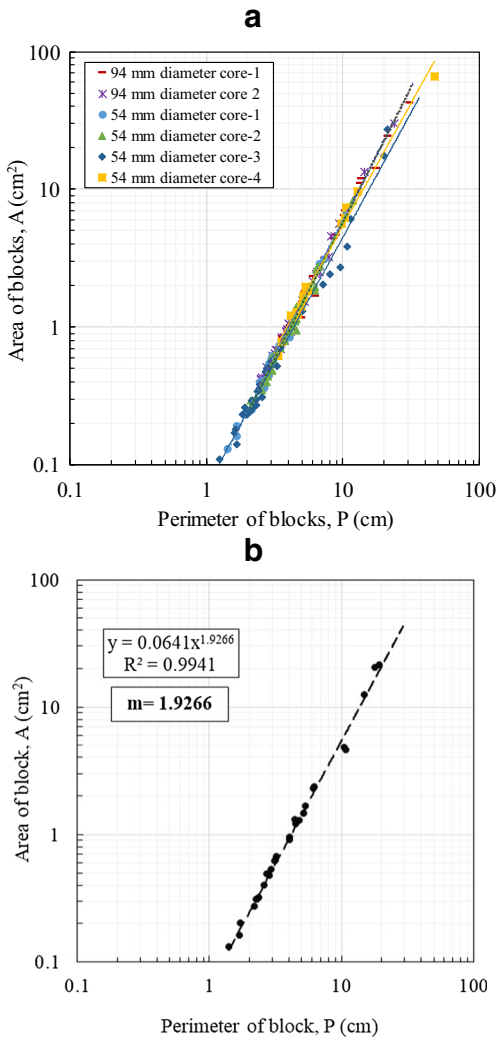

Fig. 5 **a** "Area-Perimeter" data pairs of each andesite block of six agglomerate 54 mm and 94 mm diameter core samples and **b** a log-log graph of A-P relation and "*m*" parameter of a representative core sample

correlation coefficients (between $r = 0.9791$ and $r = 9968$). It was concluded from Lovejoy (1982) that the A-P relations of cloud and rain areas show scale-invariance within the size range studied (1 km^2 to 1.2×10^6 km^2). In this study, a relatively narrow range of block's perimeters could be investigated and there is some evidence for scale invariance for the range of 54 and 94 mm diameters core samples (Fig. 5a). On the other hand, the scrutiny level is crucial in determining the fractal dimension, and self-affine fractals may probably have different fractal values for each different scrutiny level. Despite the indication of scale invariance realized in this study, considering the previous studies about self-affinity of rock surfaces mentioned above, the self-affinity condition is also considered. In case of estimating fractal dimensions for different scrutiny levels, the same scales and resolutions were used for each core sample and the digital image processing analyses were made according to these scales. According to the characteristic engineering dimension and block/matrix threshold that were proposed by Medley and Zekkos (2011) as detailed in the "Sampling studies and properties of Sille agglomerate" section of the recent paper, the scale range of this study is varied between 2.7 mm and 70 mm in terms of Feret diameters of blocks in core samples. Thus, the range of the scale for core samples will globally change in diameters that can be subjected to conventional laboratory experiments.

Laboratory test results

The laboratory testing program consisted mainly of the UCS tests and saturated and dry unit weight determinations. The tests have performed for both agglomerate and components of agglomerate (tuff matrix and andesite blocks) rock mass. Preparation of core specimens, UCS tests, and unit weight

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determinations were performed in accordance with the methods suggested by ISRM (2007). Grain crushing influences the strength properties of crystallized rocks and granular materials (Cole et al. 2010; Kazerani and Zhao 2014; Sandeep et al. 2018a, b). In the recent study, it is assumed that the failure occurs only at the boundary of grains and so no grain crushing is assumed in determining the UCS values. The UCS tests were carried out using the uniaxial rock compression test device with a maximum load capacity of 500 kN. The UCS of 47 core samples ranges from 2.25 to 8.14 MPa. Fifteen of 47 samples having the VBP values varying between 18% and 62% were randomly selected as test data (Table 1). Some statistical indices of various properties of agglomerate samples were summarized in Table 1. The results indicated that the UCS of matrix varies between 2 and 7.6 MPa and the UCS of the andesite blocks varies between 5 and 22.5 MPa. The UCS of matrix and agglomerate vary in close ranges and the majority of blocks have higher UCS values than those of matrix and agglomerate. The results indicated that there is a sufficient strength contrast between the blocks and the matrix. It is clear that the Sille agglomerate well coincides with the conventional bimrock definition.

Since the Sille agglomerate is a welded bimrock, it is quite difficult or almost impossible to separate the blocks from the matrix, for the fact that it is very hard to observe the exact pattern that the failure surface developed inside the core sample. However, the linear trace of the failure surface on the outer surface of the core sample has easily been observed. In other words, linear elements are the parts where the failure planes can clearly be observed. Thus, the shape of the failure surfaces and the path that they follow on the surface of the core specimen (boundaries, blocks, or matrix) were examined by visual inspection at the end of the UCS tests and their photographs were taken for illustration (Fig. 6). Xu et al. (2008) revealed that the stress concentration also occurs at the interface regions between "rock" blocks and "soils" of a kind of soil-rock mixture (SRM) in shear box tests through a digital image processing-based finite element method (DIP-FEM). Furthermore, Xu et al. (2008) stated that the interfaces between stiff block and soil constitute the internal weak regions of the SRM, alongside which the failure will occur. The welding degree of a bimrock is substantially important in terms of assigning the weakest component (strength of matrix or boundaries) of a bimrock. It was also observed that the tortuosity of failure planes increased with the increasing roughness of block surfaces.

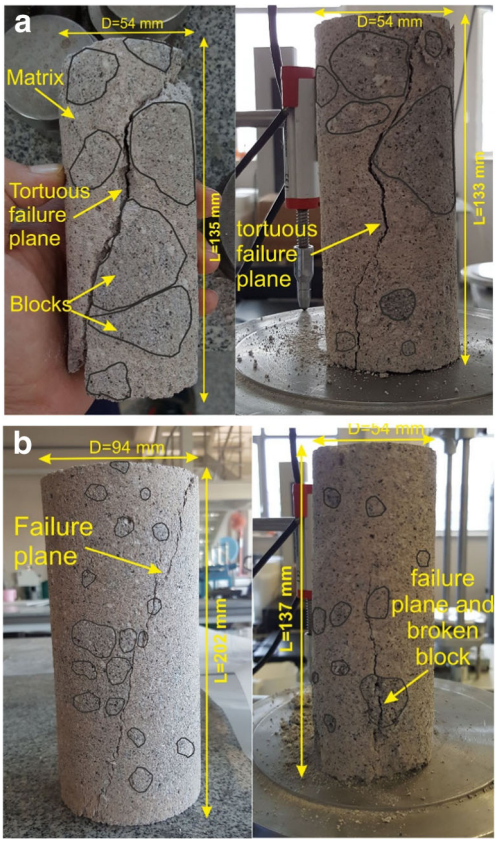

Fig. 6 Failure planes after UCS tests **a** the core samples containing coarse blocks with high D_R showed tortuous patterns along block boundaries and **b** failure planes passing through matrix and blocks in the samples mainly having fine blocks

Establishing predictive models for UCS of the Sille agglomerate

In addition to VBP, fractal dimension, roughness fractal dimension, and number of blocks were used for indirect determination of the UCS of agglomerate rock mass. For the purpose, simple and multiple regression analyses have been performed for the establishment of empirical relationships. First of all, tests of normality were performed to obtain normality distribution of data sets, and based on these analyses, it was concluded that all data sets show normal distribution. Validation tests of predictive models were done thanks to the UCS test data and significance levels of all regressions were investigated by t and F tests.

The core specimens of tuff matrix were extracted from matrix of the agglomerate rock mass where the matrix material is abundant. In parallel with that, the core specimens of andesite blocks were directly extracted from the large boulders of andesite block. Agglomerate core specimens were extracted from the boulders which include both blocks and matrix. Thereby, the UCS of the matrix and blocks was determined for the same rock mass but on different core specimens. Since the strength of the matrix and blocks directly within the agglomerate core specimen is unknown and the UCS values of these components were determined on different specimens, the UCS values of matrix and blocks were not used in estimating the UCS of the Sille agglomerate. It might be reasonable to use the UCS of matrix and blocks if indirect tests (e.g.,

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needle penetration test) could have been performed on matrix and blocks before conducting the UCS tests on the agglomerate specimens. Since the UCS of tuff matrix and/or andesite blocks of the agglomerate rock mass has not been used in prediction equations as an input, the proposed equations are only valid for the Sille agglomerate.

Simple regression analyses

It was thought that the estimation of the strength parameters of heterogeneous, mixed, and rock masses such as bimrocks by using a single parameter will probably decrease the prediction performance of the empirical equations. Simple regression analyses were performed, rather than creating predictive models, to find out the relationships between the abovementioned properties and the overall UCS and to make some assessments for the properties influencing the UCS. Simple regression analyses were conducted between VBP, D_F, D_R, and B_N as independent variables and UCS as dependent variable.

Unlike the other welded bimrocks having moderately VBP values, a negative linear relationship between the UCS and the VBP with a considerable value of coefficient of determination ($R^2 = 0.471$) was found (Fig. 7). More importantly, there is a statistically significant positive relation between the D_F and the UCS with correlation coefficient of 0.776 (Fig. 7). As it can be seen in Fig. 7, B_N has a positive linear relationship with UCS, on the contrary, the D_R has a negative linear correlation.

Multiple regression analyses

To generate empirical equations with high estimation capacity, variables such as VBP, B_N, D_F, and D_R obtained from simple regression analyses having statistically significant relationships with the UCS were used as input parameters. A variety of input combinations were tried to develop empirical equations with high coefficients of determination. Therefore, many equations were generated, but some of them were statistically non-significant, although the coefficients of determination were remarkably high. As a result, three significant empirical equations were developed for predicting the UCS, and these are given below with coefficients of determination:

$$UCS = 26.584 - 0.054\ VBP - 19.07\ D_R \quad R^2 = 0.638 \tag{8}$$

$$UCS = 21.43 - 0.037\ VBP - 15.747\ D_R + 0.039\ B_N \quad R^2 = 0.698 \tag{9}$$

$$UCS = 6.04 - 0.012\ VBP + 6.302\ D_F - 10.14\ D_R \quad R^2 = 0.822 \tag{10}$$

While the coefficient of determination of Eq. (8) is 0.638, by adding the B_N as an input into the equation, Eq. (9) having a higher coefficient of determination was yielded. More importantly, Eq. (10) has considerably high coefficient of determination ($R^2 = 0.822$) which is composed of independent variables VBP, D_F, and D_R. It should also be noted that the D_F and D_R represent both size distribution and shape characteristics of blocks. It would be more reasonable to use Eq. (10) for

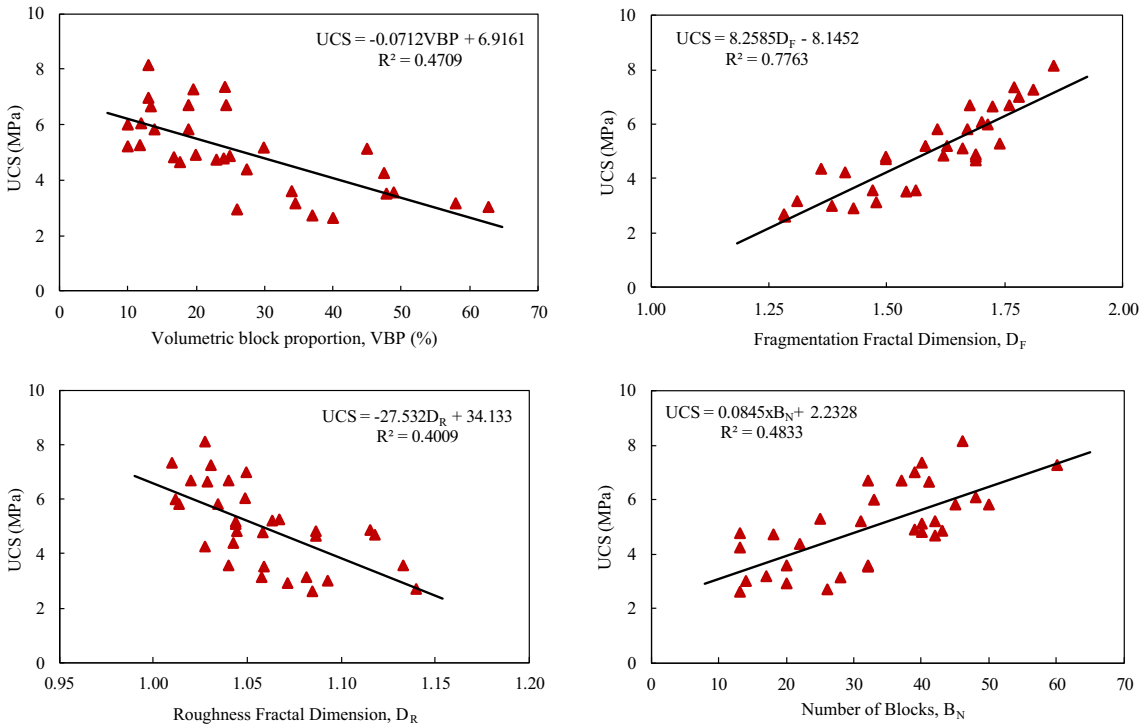

Fig. 7 Cross correlations between UCS and independent variables (VBP, D_F, D_R, and B_N) with coefficients of determination (R^2) of the relations

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practical estimation of the UCS, since Eq. (10) includes VBP in particular and D_F and D_R as efficient and complementary inputs.

Validation of the derived models

Within statistical analyses, t and F tests were also performed to investigate the significance levels of Eqs. (8), (9), and (10). Based on the analyses, it was detected that the F values are 25.578, 21.54, and 43.13 for Eqs. (8), (9), and (10), respectively, and the significance levels corresponding to these F values are less than $\alpha = 0.05$ significance level. In addition, the significance levels corresponding to the t values of the equations are also smaller than the $\alpha = 0.05$ significance level. The regression coefficients are different from zero and there are linear relationships between the UCS and the input parameters. The measured UCS values and those predicted from Eqs. (8), (9), and (10) were compared and given in Fig. 8, respectively. As can be seen from this figure, the measured versus predicted data were plotted for both "train data" and "test data," and the coefficients of determination of train data versus predicted data plots have higher values than those of test data cross-correlations. It should also be noted that cross-correlations of test data, which is a separate dataset of which properties were not used in regression analyses, were used to compare the estimation performance of the generated equations. While prediction performance of Eq. (8) and Eq. (9) determined by both train and test data is moderately high, Eq. (10) shows much better prediction performance. Since Eq. (10) has the highest value of coefficient of determination in terms of multiple regression and cross-correlations, UCS of the Sille agglomerate can be reasonably estimated from that equation with correlation coefficient of 0.7803, and thereby especially D_F and D_R in addition to the VBP can be good predictors for the UCS.

Discussion

Although some studies are available in the literature about the use of fractal geometry concept for prediction of mechanical properties of bimrock, the relation between the UCS and D_F of particularly natural specimens of welded bimrocks has not been investigated in the previous studies as yet. The relationships between the VBP and the UCS determined in previous studies and this study were presented in the same graphics (Fig. 9) and were compared. Because the UCS values of Sonmez et al. (2006a) and Zhang et al. (2019) were normalized and relatively very low, the UCS values of these two studies were multiplied by ten before being added to the graphics (Fig. 9). While the relationship between the VBP and the UCS is negative and linear in this study, it is positive and linear for Ankara agglomerate studied by Sonmez et al.

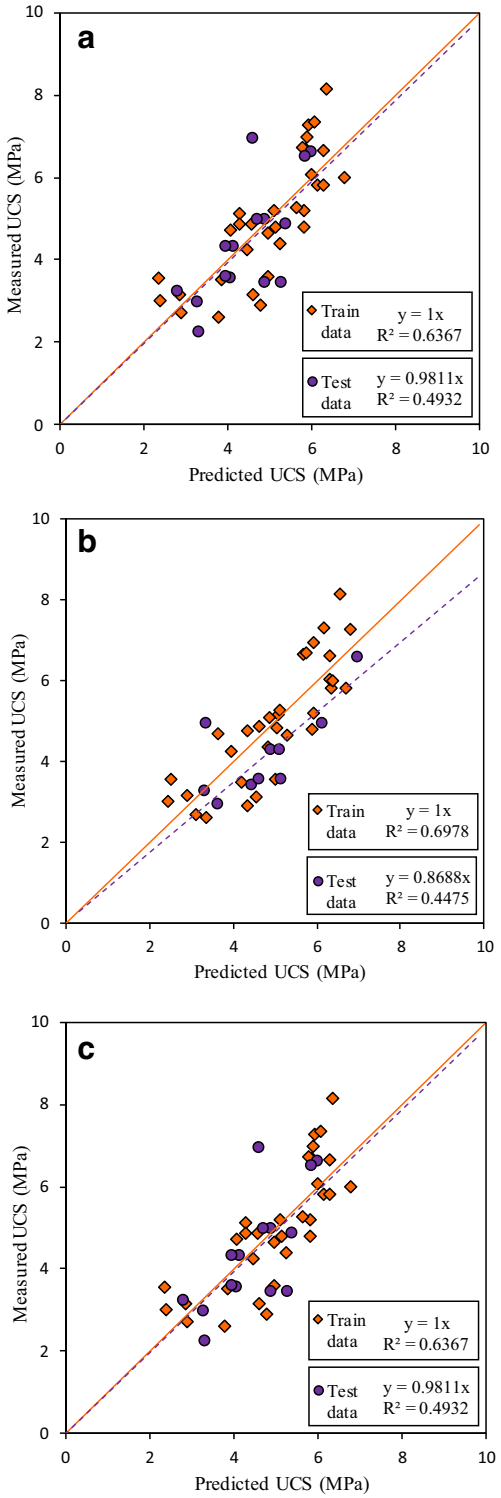

Fig. 8 Comparisons between the measured UCS (train and test data) and those predicted from **a** Eq. (8), **b** Eq. (9), and **c** Eq. (10)

(2016). As seen from the graphics in Fig. 9, the bimrock having high rock block proportion investigated by Afifipour and Moarefvand (2014) has negative exponential correlation between the UCS and the VBP, and Sonmez et al. (2006a) have also determined a similar correlation for artificial bimrock

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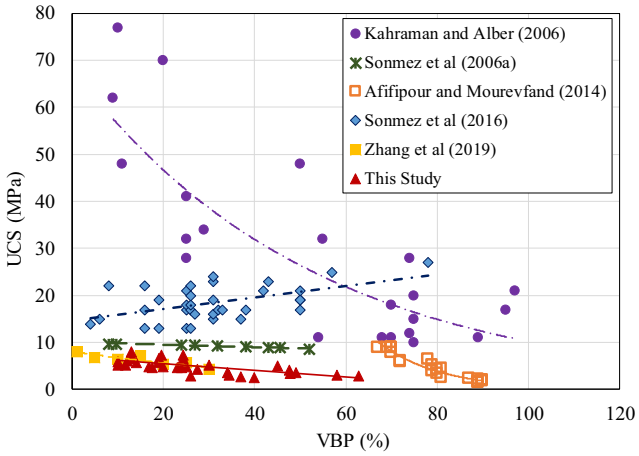

Fig. 9 Comparison of VBP-UCS relationships determined in the previous studies and in this study

samples having VBP values in normal levels. Kahraman and Alber (2006) have determined a negative exponential relationship between the UCS and the VBP having weak blocks and strong matrix. In addition to these, Kahraman et al. (2008) stated that they found no correlation between the UCS and the VBP of fault breccias having block strength values less and/or close to the matrix. Furthermore, the relation between these two parameters showed positive non-linear trend for the synthetic samples of Mahdevari and Maarefvand (2016). It is noteworthy that some of the correlations of simple relations presented in the literature, especially relationships between the VBP and the UCS, are incompatible with each other, and thereby investigating and ascertaining the reasons for these differences are inevitable.

Particular attention was paid to compare the results of the studies on similar bimrocks. Within this scope, results of Sonmez et al. (2016) and Kahraman et al. (2008) have been taken into consideration since the two materials of these studies are both natural and coincide with the definition of bimrock of Medley (1994). When comparing the results of these two studies with those obtained in the recent study, both the UCS of the Sille agglomerate and the strength ratio between the components have significantly lower values. For instance, the UCS values of Ankara agglomerate and the matrix which was investigated by Sonmez et al. (2006b, 2016) are 25 MPa and 10.55 MPa respectively and these values are much higher than those of the samples in this study. While the strength of the boundaries between the matrix and blocks is accepted as approximately equal to the strength of the matrix for welded bimrocks, the boundary strength between the matrix and blocks is expected to be less than the strength of the matrix for unwelded bimrocks according to the preliminary geo-mechanical classification for bimrocks introduced by Riedmüller et al. (2001) and Altinsoy (2006). However, if we accept the two conditions (welded and unwelded) as ends of welding, the degree of welding in between the two ends also should play a key role. Both considering the strength differences and the relationships of the same parameters differing from each other in these two studies, it has been thought that the welding degree of the Sille agglomerate is quite likely less than the Ankara agglomerate. Welding degree was thought of as the main reason for the differences between both the previous studies and the results of this study. Therefore, assessing the effect of welding degree on predictive models is crucial.

The frequency distribution graph of block sizes of each core specimen was drawn and most of them showed that there are some skewness in normal distribution. A Feret diameter distribution histogram of a core specimen showing skewness is given in Fig. 10a as an example. The geometric mean of block sizes of each core sample was assumed as a representative size due to the skewness in normal distribution. In addition, the block size frequency distribution of all blocks within 32 core specimens was presented in a generalized histogram in Fig. 10b. As can be seen from the histogram, the distribution has similar skewness. The geometric mean of all block sizes

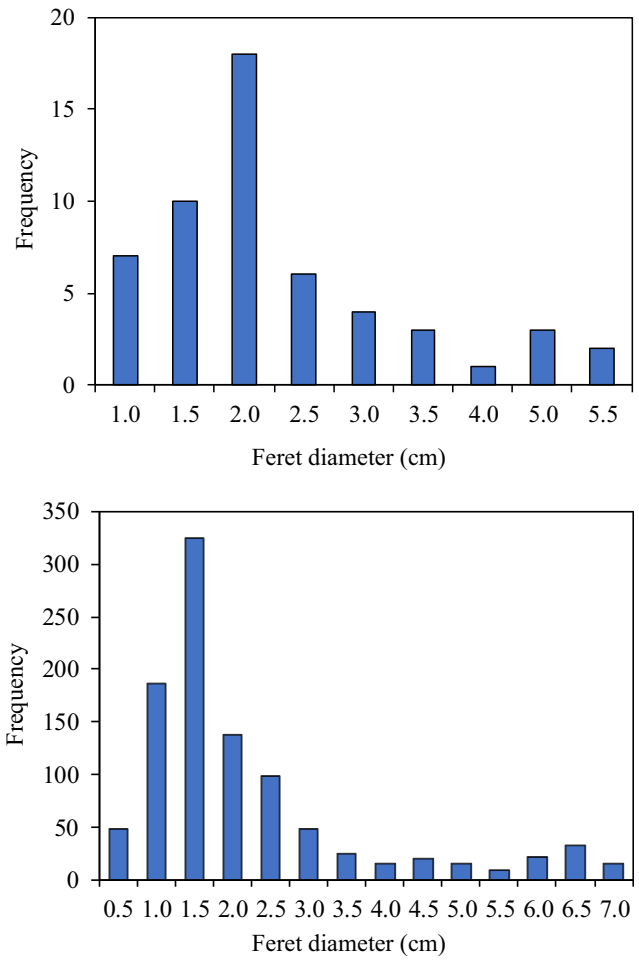

Fig. 10 **a** Frequency distribution of Feret diameters of blocks within a core specimen and **b** frequency distribution of all blocks within 32 core specimens

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was calculated to be 1.58 cm. Blocks with diameters smaller than 1.58 cm were classified as fine and those larger than this value were classified as coarse blocks. Based on that assumption, the core samples were divided into three groups as samples containing mainly coarse blocks, fine blocks, and coarse and fine together. The representative sizes of core samples both containing fine and coarse blocks range from 1.22 to 2.24 cm. The core samples with coarse and fine blocks have representative sizes varying between 1.88 and 3.44 cm and 1.16 and 1.58 cm, respectively. On the basis of self-classification of core samples, the D_F values of core samples were reviewed for fine, coarse, and both. As seen in Fig. 11, the D_F values of the core samples including fine blocks are generally higher than those containing coarse blocks. And the UCS of the samples with coarse blocks has also lower values than those having finer blocks. While B_N of core samples containing coarser blocks are quite likely low, and the core samples with fine blocks may have low or high B_N values. There is a positive relation between the B_N and the UCS in the core samples having mainly coarse blocks with low values of B_N, and thereby higher values of D_F decrease the UCS.

An increase in D_R of blocks also means an increase in surface area of blocks. Considering the bimrocks, the rougher block surface means greater contact surface (or boundaries) between matrix and blocks. On the other hand, the contact surfaces can be considered as surfaces of weakness depending on the welding degree of bimrocks. Thus, the increment in D_R directly signifies increased weakness surfaces. As mentioned in the "Laboratory test results" section, the welding degree of a bimrock is critical in terms of defining the weakest component (strength of matrix or boundaries) of a bimrock. In fact, the roughness is thought to increase the UCS due to the increment of the friction for most of the rock materials. However, if the roughness causes an increase of another structure such as weakness planes, it may cause a decrease in the UCS.

Based on the results, the patterns of the failure planes passing predominantly through the boundaries reveal that the weakest component of the Sille agglomerate is boundaries. The increase of D_R yielded an increase in the sum of the weakest zones and therefore the UCS of the bimrock was decreased. Likewise, the negative correlation between the UCS and the VBP was attributed to the increase of the D_R due to the increase of the VBP. Since the effect of the VBP on the UCS depends on D_F and D_R, it is concluded that using only VBP as a predictor will probably be insufficient to estimate the UCS.

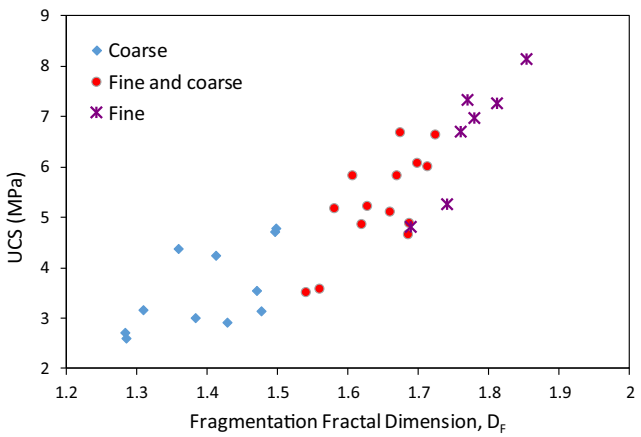

Fig. 11 The relationship between the D_F and the UCS considering size of blocks

Fourier analysis has been widely performed to quantify the planar image of granular materials. Visual comparison of the fragment to the standard charts figuring fragment roundness, sphericity, roughness, etc., is another popular method to characterize particle roughness. Due to some limitations in applicability, exact quantification of fragment roughness using these methods has not been globally successful. Therefore, the quantification of block roughness by area-perimeter method can make a significant contribution to the researches on the overall strength of bimrocks in terms of providing accurate quantification of roughness with a quite simple method. A fractal model of bimrock in terms of block boundaries may be appropriate at various scales of searchable areas of such rock masses. Further studies are needed to estimate and/or calculate fractal dimension values of components of bimrocks locally and/or globally.

Conclusion

Recently, some empirical approaches have been developed to estimate the strength and deformation properties of various types of bimrocks in the literature due to the challenges related to the specimen preparation. In this paper, studies have been carried out on establishing practical estimates of the uniaxial compressive strength of the Sille agglomerate which is a typical volcanic bimrock and as mentioned before two historical rock-hewn settlements carved in. It is evident from the results that there is an inversely proportional linear relationship between the VBP and the UCS. Moreover, there is a statistically significant positive relation between the UCS and the D_F with a considerably high coefficient of correlation. Besides, the D_R and the B_N have negative and positive linear relationships with UCS, respectively.

By considering the difficulties of representative sampling from Sille agglomerate according to the testing standards, three statistically significant empirical models were developed in order to estimate the UCS from VBP, B_N, D_R, and D_F. In addition to the VBP, the parameters D_R and D_F which represent roughness and size distribution characteristics of the blocks, respectively, will provide significant contribution to the prediction of the UCS of bimrocks. The results revealed that the fractal dimension theory provides significant contribution to the estimation of the UCS.

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The results revealed that the failure planes passing mostly through the boundaries between the blocks and matrix indicate that the weakest component of the Sille agglomerate is boundaries. Another remarkable result is the increase of D_R caused an increase in the sum of the weakest zones and therefore, the UCS of the bimrock decreased.

Lastly, various instability problems in/on ancient Sekili Cave and Koimesis Tes Panagias Church have been observed due to long-term loading, weathering, and structural discontinuities in the agglomerate. These ancient structures have maintained their stability without any support for centuries. It is crucial to determine the physical properties and the overall UCS of Sille agglomerates in terms of rock improvement and restoration projects which should be urgently applied in order to protect Sekili Cave and Koimesis Tes Panagias Church. Thus, the practitioners will be able to predict the UCS of the Sille agglomerate by using the empirical equations proposed in the recent study of which inputs can be determined from more practical and applicable methods.

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