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Numerical Modelling of Uniaxial Compressive Tests on Sille Bimrock

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Abstract

This study numerically investigates the mechanical behaviour of a welded blocky pyroclastic rock mass located in Sille (Turkey), that can be assigned as agglomerate-bimrock (block-in-matrix rock). Two cultural-archaeological heritage sites, very attractive tourist destinations, were carved in the Sille bimrock mass about 1500 years ago: a hill settlement called "Sekili Cave" and a semi-underground Church called "Koimesis Tes Panagias Church". These antique rock-hewn structures suffer from serious stability problems such as shear fractures of the pillars, structurally controlled rock falls, overbreak and matrix erosion, but still a significant part of them has nevertheless maintained instability for years. To preserve these historical structures, the knowledge of the mechanical behaviour of the Sille agglomerate is crucial. This paper focuses on numerical simulations of uniaxial compressive tests performed on the Sille bimrock, with the aim to calibrate the mechanical parameters to be used for future stability analyses of the rock-hewn structures. Suitable heterogeneous models have been considered for 2D Finite Element (FEM) analyses, by introducing the interfaces between the matrix and blocks, for a reliable simulation of the behaviour of this challenging rock mass.

Keywords

Bimrock, Finite Element Analysis, Rock-hewn structures, Heritage site, Uniaxial compressive tests

1 Introduction

Two historical structures within a hill settlement, known as "Sekili Cave" and "Koimesis Tes Panagias Church", dating back to approximately A.D. 500, were carved into an agglomerate rock mass medium in Sille (Konya, Türkiye) (Fig 1). This ancient hill settlement preserves archaeological heritage from the early Christian era, such as rock tombs and valuable wall paintings. Most of these structures are exposed to atmospheric conditions and, as a result, are particularly susceptible to physical weathering due to climatic factors. Some instability problems such as discontinuity-controlled failures, wedge failures

from the ceiling, shear failures at the pillars, and roof collapses caused by excessive weathering and long-term loading have been observed in the hill settlement (Fig 2).



Fig. 1 Some views from (a) Sekili Cave and (b) Koimesis Tes Panagias Church and rock-cut tombs.

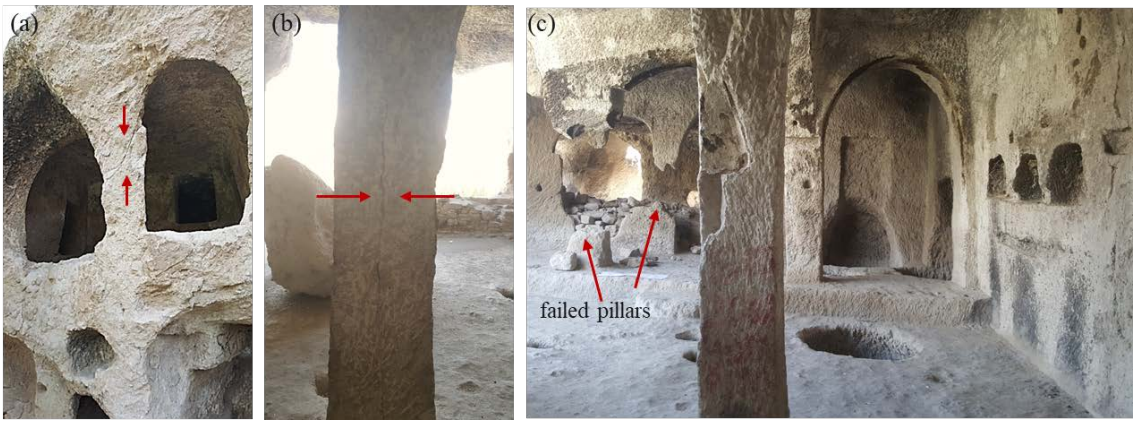


Fig. 2 Instabilities caused by unconfined compressive stress.

The base rock of the hill settlement, defined as agglomerate, is a type of welded pyroclastic deposit comprising competent rock blocks embedded in a low-strength fine-grained matrix. Given its inherent and geomechanical characteristics, the rock mass is a geotechnically complex formation, and specifically an agglomerate-bimrock (block-in-matrix rock). Determining the strength properties and modelling the failure mode of the bimrock is essential for preserving these historical structures and implementing necessary protective measures.

In various studies focusing on bimrocks, deformability and uniaxial compressive strength (UCS) assessments have been conducted, and the relationship between the UCS and parameters such as volumetric block proportion (VBP), block orientation, block shape, matrix type, and block size distribution has been examined (e.g. Avşar 2020; Barbero et al. 2008; Kalender et al. 2014; Afifipour and Moarefvand 2014; Kahraman et al. 2008; Mahdevari and Maarefvand 2016; Li et al. 2023; Sonmez et al. 2004). Besides, Barbero et al. (2008), Napoli et al. (2022), Hu et al. (2024), Sharafisafa et al. (2024) conducted numerical analyses to investigate the geomechanical parameters and/or strength of various bimrocks. Artificial laboratory specimens (Hu et al. 2024; Sharafisafa et al. 2024) and numerical model samples (Barbero et al. 2008; Napoli et al. 2018; Napoli 2021) have been used in these previous studies.

In this paper the geometry of two heterogeneous bimrock samples subjected to unconfined compression tests was reproduced, and the laboratory tests were simulated (i.e., back-analyzed) through 2D Finite Element Method (FEM) analyses. For the calibration of the mechanical properties of the models, reference was made to Avşar (2020) by utilizing laboratory test results of Sille bimrock and the failure modes of the samples. The numerical models were generated through the RS2 software from Rocscience.

2 The Sille agglomerate-bimrock formation

This study investigates a pyroclastic rock mass outcropping in the historical Sille settlement in Türkiye, which formed in a terrestrial environment during eruptions associated with Late Miocene-Early Pliocene volcanism (Özkan 2017). The K–Ar ages of the rocks range from 11.95 to 3.35 Ma (Keller et al. 1977). Based on in-situ surveying, Avşar (2020) stated that Sille agglomerate is comprised of rock blocks of various sizes in a relatively low strength tuff-like matrix with an evident welding (Fig. 3). The optical microscopy examinations indicated that the blocks are andesite with porphyritic texture and contain plagioclase, biotite, quartzite phenocrysts, and opaque minerals. Additionally, based on the observation of different outcrops, no preferential orientation in the distribution of the blocks was detected (Avşar 2020 and Avşar 2021). While some large blocks have clear angularity, smaller blocks are mostly rounded or semi rounded.

In this study, some of the laboratory results presented by Avşar (2020), including UCS values and stress-strain responses of these UCS tests, were used as database for the numerical analyses. The laboratory tests carried out by Avşar (2020) were conducted on both the agglomerate-bimrock and its individual components (tuff matrix and andesite blocks) to characterize their strength. Bimrock boulders were gathered around the rock-hewn structures, and bimrock specimens were extracted from them in the laboratory. Block-to-block contacts were infrequent in the laboratory specimens, as most blocks were dispersed within the fine-grained matrix, due to the rather low Volumetric Block Proportions (VBP). UCS tests were conducted on these agglomerate-bimrock cores. Therefore, according to the literature on the scale independence of block size distribution (Medley 1994; Medley and Zekkos 2011), it can be said that the UCS values obtained represent the overall agglomerate-bimrock mass. Core specimen preparation, UCS tests, and unit weight measurements followed ISRM (2007) guidelines. The UCS tests were performed using a uniaxial compression device with a maximum load capacity of 500 kN. The UCS values for the 32 core specimens ranged from 2.60 MP to 8.14 MPa, with an average value of 4.98 MPa (Avşar 2020).



Fig. 3 A view from side wall of Koimesis Tes Panagias Church presenting various size of andesite blocks welding in a fine-grained matrix.

3 Numerical Modelling

To evaluate the stability of the historical sites of Sekili Cave and Koimesis Tes Panagias Church and preserve them, an advanced numerical study should be performed. To this end, a proper calibration of the mechanical parameters of the Sille agglomerate's components (i.e. matrix, blocks and block-matrix contacts) is a crucial issue. Such a calibration is indeed necessary to accurately set up a rock-hewn structure model and carry out future stability analyses.

In this regard, this paper presents the results of 2D FEM numerical simulations conducted using the software RS2 from Rocscience, in order to reproduce the uniaxial compression tests performed by Avşar (2020) on two representative Sille bimrock samples. The UCS and Volumetric Block Proportion (VBP) determined in the lab for these specimens were 5.17 MPa, VBP = 30% for specimen 1, and 3.55 MPa, 49% VBP for specimen 2, respectively (Fig. 4). The geometry of the specimens (i.e. the shape, dimensions and position of the rock inclusions) was replicated by carefully inspecting the real bimrock

cores. To more reliably model the heterogeneous rock samples, the block-matrix contacts were considered and simulated by introducing interface elements (i.e. "joints") in the RS2 software. Six-node triangular elements were chosen to mesh the bimrock models. A non-uniform mesh size, with higher density around the blocks, was used, and local mesh refinements were adopted to guarantee a high-quality meshing. The bottom model boundary featured fully restrained boundary conditions, while free boundary conditions were applied to the other external boundaries (Fig. 4).

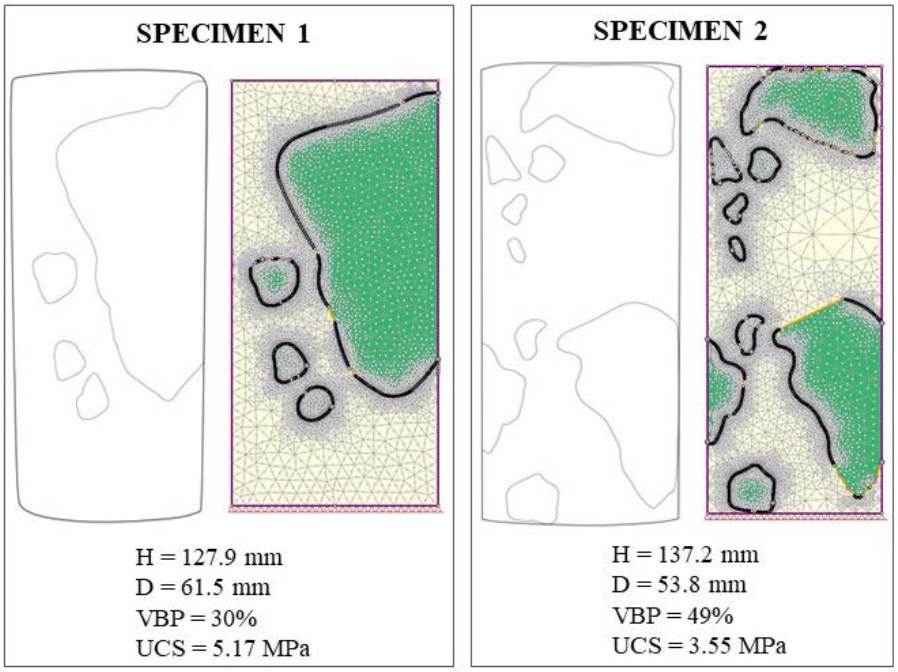


Fig. 4 - Front views of the two agglomerate specimens analyzed numerically, mesh characteristics and boundary conditions applied.

A constant null field stress and an elastic perfectly-plastic Mohr Coulomb failure criterion were applied to the matrix, blocks and interfaces. The application of the load was simulated by progressively increasing its magnitude, through several load stages. The properties obtained from the back-analyses are listed in Table 1.

Table 1 Mechanical parameters of the bimrock components obtained from the back-analysis

Material Type	**Unit Weight γ [kN/m^3]**	**Poissson's Ratio ν [-]**	**Young's Modulus E [MPa]**	**Tensile Strength σ_t [MPa]**	**Cohesion c [MPa]**	**Friction Angle φ [°]**
Matrix	16	0.25	2000	0.61	2	24
Block	24	0.25	8700	5	10	50
Joint	-	-	-	0.61	2	24

Although the limitation of the 2D analyses (i.e. plain-strain conditions), the concentration of the maximum shear strains obtained from the numerical analyses accurately reproduced the actual failure mode detected in the laboratory. A comparison between the actual specimen and the numerical analysis result is shown in Figure 5 for specimen 1 and in Figure 6 for specimen 2. From these figures, the fundamental role of the stronger rock blocks is evident. Specifically, it can be seen that the maximum shear strains are localized close to the stronger rock blocks, where stresses concentrate, and that a plasticization of the joint elements (i.e. block-matrix interfaces) occurs close to the failure surface. Moreover, the specimen with the highest VBP (i.e. specimen 2) experiences a shear band that connects the different rock blocks, while a more irregular distribution of the maximum shear strains is shown in the specimen with the lowest block content (i.e. specimen 1). With reference to this low-VBP specimen, it is worth noting that the actual failure surface (Fig. 5b) crosses one of the rock inclusions and that this behaviour was not reproduced in the numerical analysis. The reason for such a difference can be attributed to some defects (i.e. cracks) that the rock block may have experienced during the sample preparation, as well as to three-dimensional effects, that a 2D analysis cannot catch.

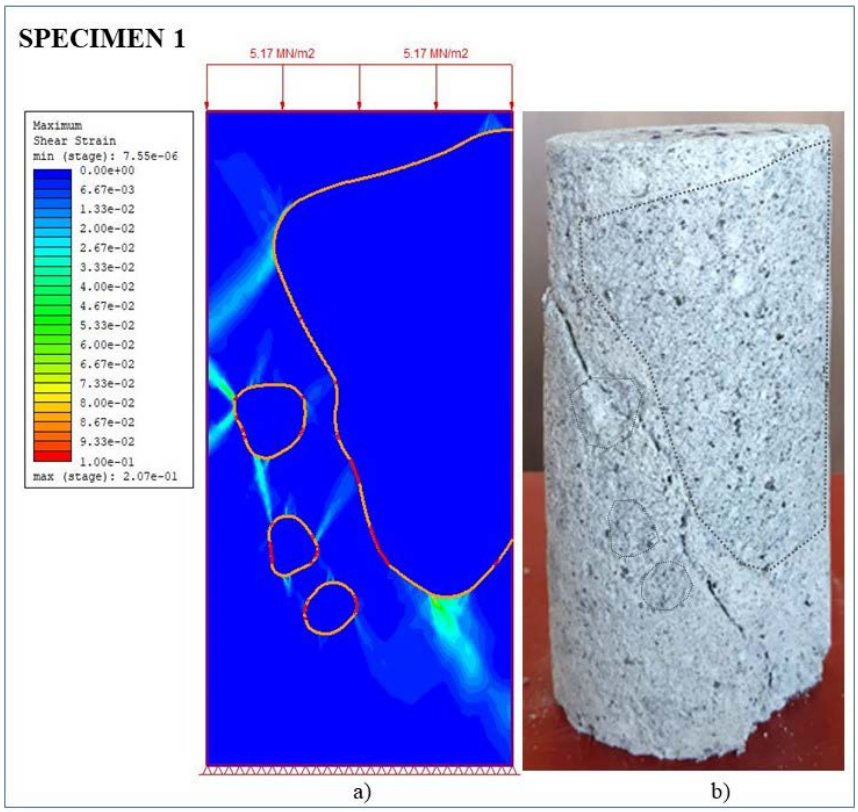


Fig. 5 Specimen 1: a) maximum shear strains of and plasticized interface joints (in red); (b) specimen after the UCS test, with block outlines drawn in the illustration and failure surface developing close to block boundaries.

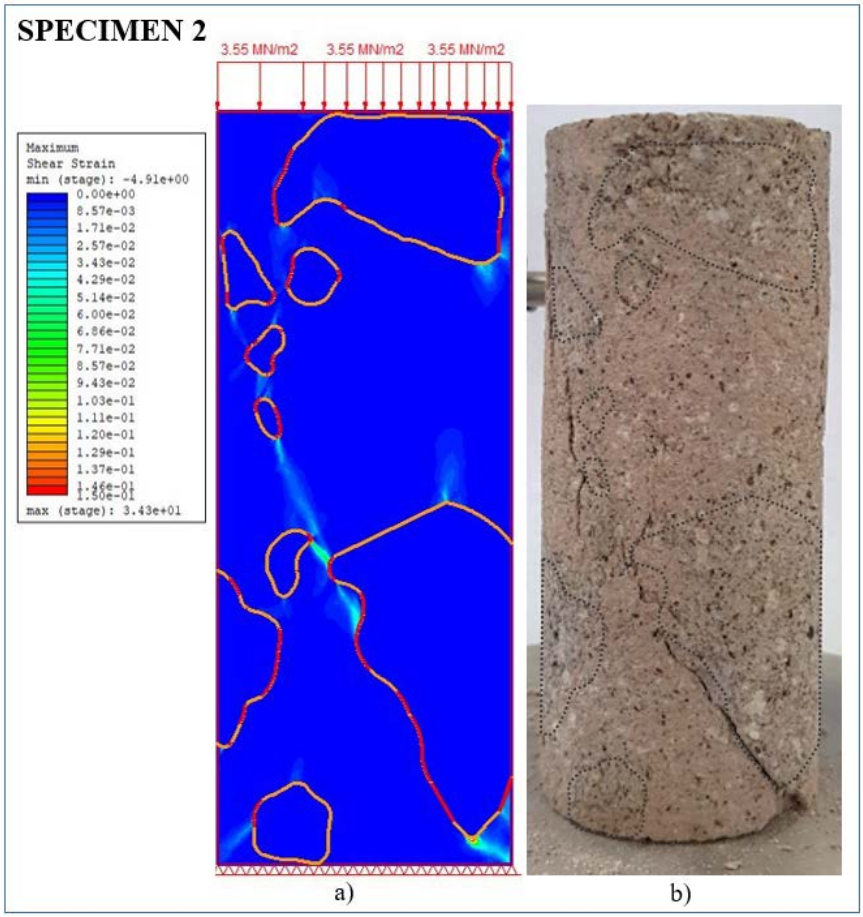


Fig. 6 Specimen 2: a) maximum shear strains of and plasticized interface joints (in red); (b) specimen after the UCS test, with block outlines drawn in the illustration and tortuous failure surfaces developing along block boundaries.

4 Results and Conclusions

The way rock inclusions affect the behavior of bimrocks has long been a question of great interest. In this regard, many laboratory tests as well as numerical analyses have been carried out since the 90s by many researchers on different block-in-matrix formations. These studies have clearly demonstrated that the strength and failure mode of block-in-matrix formations are strongly affected by the quantity, position, shape, orientation and dimension of the blocks, which must be explicitly taken into account when numerical analyses are carried out (Medley and Zekkos 2011; Barbero et al. 2007; Napoli 2021; Sonmez et al. 2004), to properly account for their effect on the development of irregular and tortuous failure surfaces.

In the framework of the experimental research on the Sille agglomerate carried out by Avşar (2020), the tortuosity of the failure surfaces of the specimens tested in uniaxial compression was readily observable on the outer surface of the core specimens. The path across the core specimen's surface (whether along boundaries, blocks, or matrix) was analyzed through visual inspection at the end of each UCS test. It was additionally noted that the tortuosity of failure surfaces augmented as the roughness of block surfaces (that quantified by fractal dimension analysis) increased. Another notable finding is that the failure planes predominantly traverse the boundaries between the blocks and the matrix, indicating that block-matrix contacts are the weakest component of the agglomerate-bimrock. Our numerical models have successfully captured the overall mechanical behaviour observed in the laboratory tests, particularly in terms of the distribution of maximum shear strains and the localization of plasticization zones, which largely validate the failure modes identified experimentally. However, certain discrepancies should be further examined: In laboratory tests, natural flaws within the rock blocks and stress accumulations due to sample preparation can influence the failure path. Since these pre-existing defects cannot explicitly incorporated into the numerical model, some deviations between the predicted and observed failure surfaces are inevitable. The 2D modelling approach may not fully capture critical three-dimensional mechanisms involved in the failure process. Specifically, in the laboratory specimens, the failure surface was observed to cut through one of the rock inclusions, a behaviour that was not reproduced in the numerical simulation, likely due to the inherent limitations of 2D modelling.

All these findings are correctly reproduced by the numerical models reported in this paper, providing the parameters and the simulation procedure for modelling the real case. Specifically, they constitute a tool for correctly interpreting the instability processes affecting the critical structural elements constituting the historical Church like, for example, the columns represented in Figure 2. Nevertheless, in the future 3D numerical analyses will be carried out to better reproduce the mechanical response of such complex heterogeneous geomaterials.

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