International Society for Rock Mechanics and Rock Engineering
Norwegian Group for Rock Mechanics

ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Mechanical characterization of an ornamental stone quarry under flexural buckling

M.T Carriero, M.R. Migliazza, F. Vagnon
Politecnico di Torino, Torino, Italy
federico.vagnon@polito.it

A.M. Ferrero
University of Torino, Torino, Italy

Abstract

Flexural buckling is a specific type of rock mass instability that occurs mainly in layered rocks with discontinuities approximately parallel to the slope face. It poses a significant threat in ornamental stone quarries, especially those operated as open-pit mines with quarry faces reaching heights this of several hundred meters. This instability can lead to the sudden collapse of large sections of the quarry face, endangering the safety of workers and infrastructures. Therefore, it is crucial to evaluate the stability of the rock faces during exploitation phases and closely monitor these instabilities to ensure the safety conditions over time.

The Lorgino quarry, located in the municipality of Crevoladossola in the northern part of Piedmont Region, Italy, is potentially susceptible to this instability due to its main foliation parallel to the exploitation faces, the quarry's height of up to 100 m and geological and structural variations within the environment.

To develop a numerical model for hazard assessment, a detailed and extensive material characterization campaign has been conducted. Non-destructive tests, including density estimation and ultrasonic pulse velocity measurements and destructive test, such as bending, uniaxial compressive strength and triaxial tests, were performed on rock samples in cubes, slabs and cylinders forms, directly retrieved form quarry faces with orientations different from the main foliation. This comprehensive investigation aimed to evaluate the physical and mechanical characteristic of the rock mass.

The results highlight a medium to high material anisotropy of the tested lithotypes, particularly in terms of seismic velocity and tensile strength. One lithotype exhibited significant differences in mechanical characteristics compared to the others, suggesting the need for further investigations and focused attention in the numerical modeling setup.

Keywords

Flexural buckling, dolomite-marble quarry, destructive tests, non-destructive tests, anisotropy.

ISRM

NBG

1 Introduction

Flexural buckling is a complex mechanical process in which an externally loaded rock or rock block undergoes sudden and unstable deformation due to excessive bending stress. It typically occurs when a material, initially stable under load, is subjected to compression, leading to lateral deformation. Under certain geometric conditions and critical loads, this can result in material failure.

In rocks, two primary conditions contribute to flexural buckling: i) minimal jointing in the rock mass, with continuous joints parallel to the walls as the dominant set, and ii) axial stresses parallel to the dominant joint set that exceed the material's strength. As a result, layered rocks are more prone to undergoing this instability process.

Although the potential for buckling failure can be predicted using geological structures and high-precision observation technologies, the mechanisms behind such failures remain unclear, making monitoring and management challenging. Numerous studies have explored buckling failure in layered rock slopes, using analytical methods based on Euler's theory, energy equilibrium theory, and elastic slab stability theory to calculate critical buckling lengths. Researchers have also advanced these methods with elastic-plastic plate theory and tangent-modulus theory, and have studied the influence of lateral forces, joint strength, and slope dip. Numerical methods, including the distinct element method (DEM), finite-element software, and UDEC, have been employed to model the stability and deformation of buckling landslides in various contexts (Feng et al., 2010; Garzon, 2016; Sun et al., 2022 and reference herein).

Despite the widespread use of analytical and numerical methods to evaluate buckling, most studies focus on qualitative assessments of critical buckling lengths and deformation characteristics, with fewer addressing the progressive deformation process, sliding displacement, and failure behavior of landslides. Moreover, the petrophysical characteristics and mechanical properties of rock masses, such as tensile and compressive strength, have been largely overlooked in previous research (Wang et al., 2023). These properties are crucial for assessing rock stability under bending stresses. Environmental factors, such as the presence of water, can also influence buckling by altering the rock's resistance to compression. Moisture and freezing can reduce the cohesion between mineral particles and promote crack propagation, increasing susceptibility to buckling under load. Additionally, topography and the geometry of rock formations are critical factors in predicting these phenomena.

Thus, accurate material characterization, including both physical and mechanical properties, is essential for reliable analytical or numerical analysis. Given the anisotropic nature of the rock, with primary bedding, schistosity, or foliation planes, a comprehensive estimation of elastic moduli in all relevant directions is necessary.

In ornamental stone mining, where large blocks of rock are extracted from significant depths, the risk of flexural buckling becomes a critical consideration for both safety and efficiency during excavation. The behavior of rock masses under stress, coupled with the geometric constraints of quarry walls and cutting techniques, presents unique challenges for engineers and geologists.

In this context, the Lorgino quarry serves as an ideal case study for evaluating the potential for buckling, especially as future extraction plans may require deepening the quarry floor and increasing the height of the quarry faces. This article analyzes four main types of rocks, representative of the natural variability of materials extracted from the quarry. The experimental campaign measured physical and mechanical properties along directions perpendicular and parallel to the main foliation. Non-destructive tests (ultrasonic wave velocity), partially destructive tests (strip load), and destructive tests (bending tensile, UCS, and triaxial tests) were conducted. The results reveal marked anisotropy in strength and wave velocity values between the analyzed directions. Finally, elastic constants were calculated to model the mechanical behavior of the lithotypes, highlighting significant differences among them.

2 Case study

The Lorgino quarry (Fig. 1), located in Crevoladossola (Verbano-Cusio-Ossola province, Italy) and managed by Tosco Marmi S.r.l., is situated within a dolomite limestone unit. This unit includes dolomites and saccharoid marbles of various colors embedded in folded gneiss (Fig. 1a).

The rock mass has three joint sets (Carriero et al., 2023): one parallel to the main foliation (160/70) and two orthogonal sets (240-275/80-85). Excavation benches are designed to be nearly parallel to the main foliation (Fig. 1b).

Future extraction plans for the quarry may involve deepening the current quarry floor and increasing the height of the quarry faces to up to 100 meters. Given the specific structural geology of the quarry, which is sandwiched between folded gneiss within a complex anticline fold, a thorough evaluation of the potential for buckling is necessary to ensure the safety of mining operations.

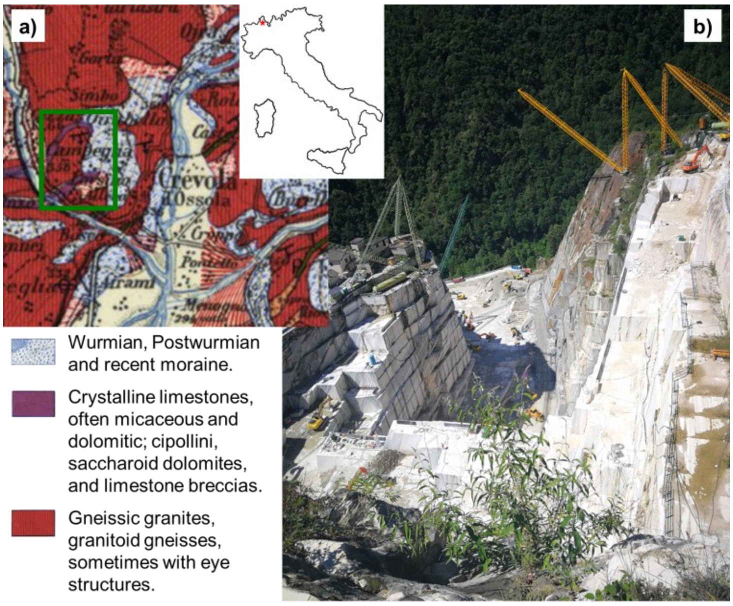

Fig. 1 a) Sketch of the 1:100000 geological map of Italy – Foglio 15 Domodossola and b) overview of the quarry showing the evolution of the quarry benches as a function of rock foliation.

3 Material and Methodology

3.1 Sample collection and preparation

Four main rock types were analyzed in this paper (Fig. 2a-d) as they are representative of the natural variability of the geomaterial exploited in the quarry. Petrographically, these rock types can be classified as follows:

- CLASSIC: impure dolomitic marble characterized by a medium saccharoid grain.
- BLUE: dolomitic marble characterized by a banded structure.
- BROWN: impure dolomitic marble characterized by a fine and weakly heterogeneous grain.
- BLACK: graphite phyllitic mica schist exhibiting a distinctly schistose structure.

178 samples of different shapes were tested: 64 cylinders with average dimensions of ϕ54*H120mm, 108 slabs with average dimensions of L220*B30*H60mm, and 6 cubes with 150mm edges. The samples were saw-cut or cored from a single large block for each rock type. In particular, for a comprehensive physical and mechanical characterization, the samples were tested along two different directions with respect to the main foliation plane: one axis perpendicular (named “verso”) and one parallel (named “contro”) to it. Table 1 lists the number of samples for each shape and direction with respect to the main foliation.

Table 1 Number of samples tested for each type of rock, shape, and direction with respect to the main foliation.

Rock Type	Cylinders "Verso"	"Contro"	Slabs "Verso"	"Contro"	Cubes
CLASSIC	13	3	15	8	1
BLUE	11	4	25	9	2
BROWN	12	4	18	6	2
BLACK	14	3	21	6	1
TOTAL	50	14	79	29	6

3.2 Methodology used

3.2.1 Non-destructive tests

All the specimens were measured following the recommendations of the ISRM, determining their volume and bulk density. Then, ultrasonic pulse velocity (UPV) measurements were performed to estimate the P-wave (on all the samples) and S-wave velocity (on cylinders and cubes), mesoscopic anisotropy, and dynamic elastic moduli. The measurements were performed using the Pundit Lab (©Proceq) ultrasonic pulse generator and acquisition system (Fig. 2e) with two cylindrical 250 kHz tx-rx transducers for both V_P and V_S determination (on cylinders and cubes) and exponential 54 kHz tx-rx transducers for V_P measurements only (on slabs due to the limited dimensions of B and H).

3.2.2 Partially destructive tests

The structural geological context of the quarry and the meso-structure of the material suggest the presence of transverse isotropy (further details are provided in the results section). Recently, Yim et al. (2022) proposed a method for determining the five elastic constants of this type of rock by performing strip load tests, which generate various stress–strain relations from a non-uniform stress field in a single specimen.

Following this procedure, UCS tests were conducted up to 35 kN, about the 10% of the peak load with a constant strain rate of 0.002 mm/s, using a 3D-printed Veroclear loading plate (Fig. 2i). This plate ensures a non-uniform stress distribution in the upper part of the cylindrical samples while maintaining a uniaxial compressive stress distribution at the bottom. Each specimen was equipped with 8 strain gauges, following the configuration shown in Fig. 2j.

The strip load test provides multiple stress-strain relations for a single specimen, but no simple analytical solution exists for the stress fields, which depend on the applied load and elastic constants. Numerical modeling was employed to calculate the elastic constants from strain measurements, using the COMSOL Multiphysics® finite element software. The Gauss–Newton method, combined with a substitution approach in cases of poor convergence, was applied to optimize the elastic parameters by minimizing the difference between the modeled and measured strains (using root mean square error (RMSE) theory).

3.2.3 Destructive tests

Three types of destructive tests were performed: four-point bending tensile tests, UCS tests, triaxial tests.

Four-point bending tests were conducted on 30 slab specimens for the evaluation of the tensile strength (Fig. 2f). The followed load scheme in the test consist of a distance between the lower supports of 180 mm, while the upper supports (where the load is applied) are placed centrally at 60 mm. The tests were carried out by applying an average loading rate of 0.016 kN/s. The tests were conducted on the two directions analyzed for a total of 30 specimens.

UCS tests were performed on 16 cylindrical samples, each equipped with two diametrically opposite pairs of strain gauges (Fig. 2g), one parallel to the axial axis (67 mm long) and one along the circumference (36 mm long). A pre-load of 0.1 kN was applied to the samples, and then a constant rate load of 0.8 kN/s was applied up to failure.

Triaxial tests were performed on 14 cylindrical samples using a Hoek cell (Fig. 2h) with four confinement target values of 2, 4, 8, and 12 MPa, a pre-load of 0.1 kN, and the application of the vertical load at a rate of 1 kN/s.

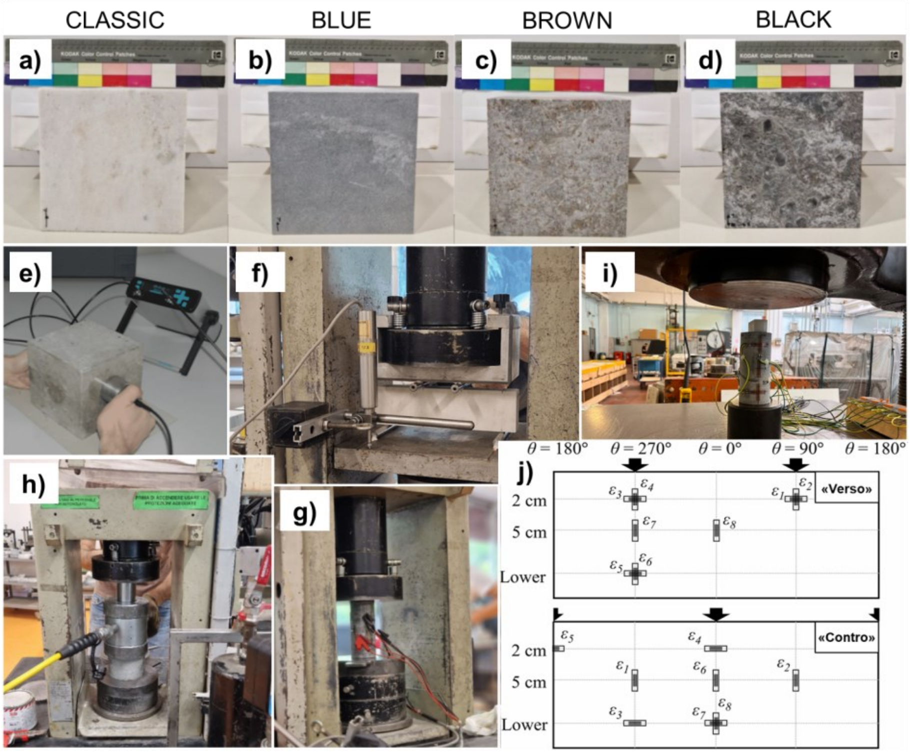

Fig. 2 a-d) Collected samples in the Lorgino quarry. e) Non-destructive (UPV) and f-i) destructive test (four-point bending tensile test (f), UCS (g), triaxial test (h) and single strip load method (j)). j) Unfolded circumferential view of the strain gauge setups.

4 Results

4.1.1 Non-destructive tests

Regardless of the type of marble, a noticeable anisotropy is observed between Verso and Contro (Fig. 3): in fact, both in terms of V_P and V_S, the propagation speed is always higher in the Contro direction. In the cube, the two "verso" direction exhibts analogous UPV values, confirming the transversally isotropic behaviour hypothesised to perform load strip tests.

In terms of ultrasonic wave speeds, the analyzed lithotypes show values comparable to the reference values for marbles (4000 – 6000 m/s for V_P and 2000 – 3000 m/s for V_S). BLUE and BROWN have the lowest and highest measured V_P values, respectively (the same consideration applies to the V_S values), but they are, with CLASSIC one, the most homogeneous. The opposite is true for the BLACK samples, which show porphyroblasts ranging from millimetric to centimetric sizes that affect the determination of wave propagation characteristics in the material, as also mirrored by the wider range of density values observed.

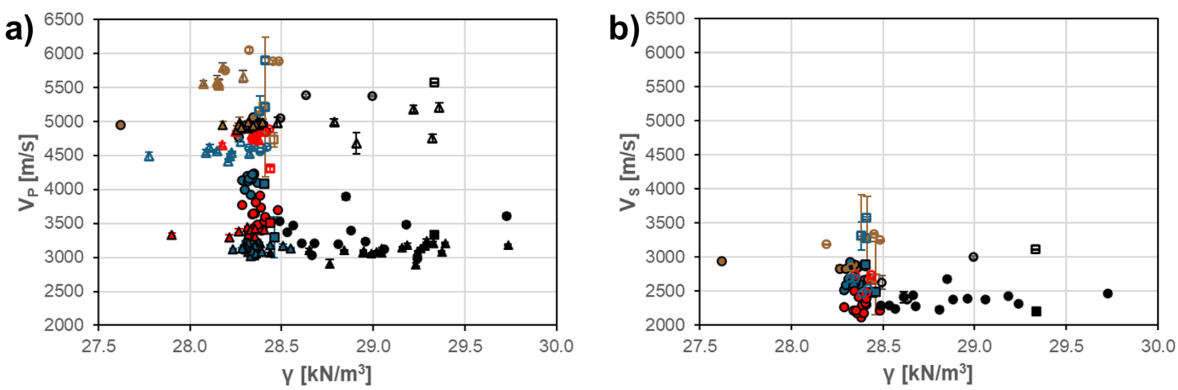

Fig. 3 V_P (a) and V_S (b) versus density for the 178 samples collected. The marker shape corresponds to the shape of the sample: square for cube, circle for cylinder, and triangle for slab. Empty markers represent the "contro" condition, and filled markers represent the "verso" condition. The color corresponds to the material type: red for CLASSIC, blue for BLUE, brown for BROWN, and black for BLACK. Where not visible, the error bar are smaller than marker size.

4.1.2 Partially destructive tests

Based on the results of the UCS tests, strip load tests were performed up to about 10% of the UCS peak to remain within the elastic domain and prevent any irreversible deformations of the Veroclear plate. Currently, strip load tests have been performed only on BLUE samples. The authors plan to replicate this procedure for the CLASSIC and BROWN samples as well. The BLACK samples, due to their high heterogeneity, as highlighted in the previous results, will not be tested using this procedure.

Table 2 lists the strains evaluated when the load was equal to 35 kN for Verso and Contro direction in the BLUE lithotype.

Table 2 Result of the strain at load equals to 35 kN for "Verso" and "Contro" samples following the strain gauge configuration reports in Fig. 2j.

	"Verso"	"Contro"
	BL.V.7.C	BL.C.4.C
ε1 [-]	1.43E-04	-3.65E-04
ε2 [-]	-7.38E-04	-5.49E-04
ε3 [-]	1.57E-04	2.88E-05
ε4 [-]	-7.54E-04	6.51E-04
ε5 [-]	4.56E-05	6.07E-04
ε6 [-]	-4.22E-04	-5.93E-04
ε7 [-]	-4.68E-04	1.12E-04
ε8 [-]	-4.83E-04	-5.43E-04
E [GPa]	43.74	39.65
ν [-]	0.16	0.25

Even though the 5 elastic variables are independent, G_2 was initially assumed to be the average of the values obtained from three different formulations: Saint-Venant (1863), Worotnicki and Talesnick (1993), and Ringel (1999). The obtained value for G_2 was 16.5 GPa.

Starting from the configuration of the 4 elastic constants listed in Table 2, plus the previously evaluated G_2 (E_1 = 39.65 MPa, E_2 = 39.65 MPa, ν_1 = 0.25, ν_2 = 0.16 and G_2 = 16.5 MPa), the deformation numerically evaluated from the COMSOL model were compared with the laboratory results. Fig. 4 shows the iterative process of refining the numerical model and the comparison between the laboratory strain measurements and the numerical strain values obtained through the COMSOL model, until the error between the measured and simulated values is minimized. This process was repeated until the RMSE error stabilized around $2*10^{-5}$. The obtained elastic constants for the BLUE lithotype were as follows: E_1 = 34.05 GPa, E_2= 32.34 GPa, ν_1 = 0.3, ν_2 = 0.13 and G_2= 20.14 GPa.

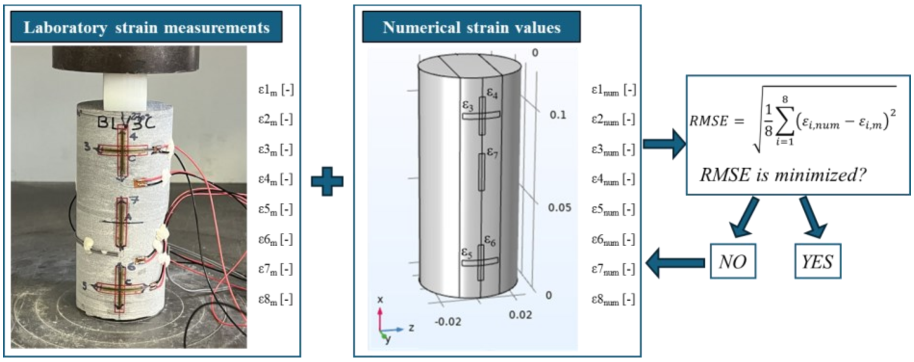

Fig. 4 Iterative process diagram for determining elastic constants.

4.1.3 Destructive tests

Regarding the four-point bending test, for all lithotypes, the tensile strength is higher along the "Contro" direction and lower along the "Verso" direction (Fig. 5a), with a ratio between the two varying from 2.1 to 3.7. The tensile strength along the "Verso" direction ranges from 3.7 MPa (BLACK samples) to 5.9 MPa (BROWN samples), while along the "Contro" direction it ranges from 9.9 MPa (BLACK samples) to 16.8 MPa (BROWN samples). In both directions, the BLACK lithotype exhibits the lowest strengths, while the BROWN lithotype shows the highest.

For UCS, the highest value, 175.7 MPa, was measured for the CLASSIC in the "Contro" direction, while the lowest value, 68.1 MPa, was measured for the BLACK in the "Contro" direction (Fig. 5b). In the case of CLASSIC (red dots in Fig. 5b), the compressive strength in the "Contro" direction is greater than that in the "Verso" direction, while in the other cases, the opposite is observed. This is also supported by the high VP-VS ratio, indicating a higher stiffness of this material compared to others. Poisson's ratios (Fig. 5c) show a higher variability in the results; however, BLACK samples confirm the heterogeneity and anisotropy of this lithotype.

Results from triaxial tests (Fig. 5d) confirm the relationship between the lithotype previously discussed for bending tests and UCSs.

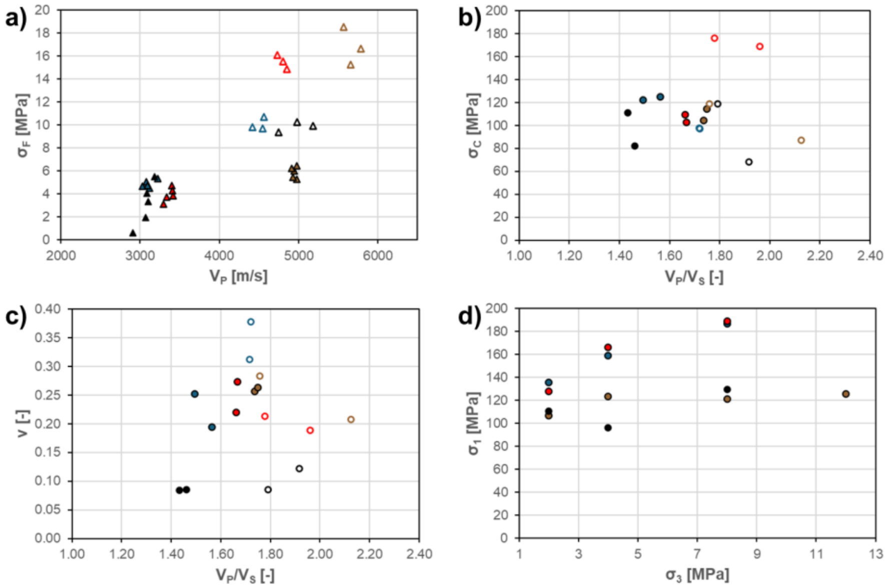

Fig. 5 a) Flexural resistance versus V_P values. b) Uniaxial compressive strength and c) Poisson's ratio vs the V_P/V_S ratio. d) Peak σ_1 and σ_3 obtained in triaxial tests. The marker shape corresponds to the shape of the sample: square for cube, circle for cylinder, and triangle for slab. Empty markers represent the "contro" condition, and filled markers represent the "verso" condition. The color corresponds to the material type: red for CLASSIC, blue for BLUE, brown for BROWN, and black for BLACK. Where not visible, the error bar are smaller than marker size.

The destructive tests' results of the were combined into the Hoek-Boen criterion, both for peak and residual conditions. Fig. 6 summarizes the results. For peak strength, two groups of fitting curves were identified: the first includes the CLASSIC and BLUE lithotypes, with a σ_{ci} value of approximately 112 MPa and m_i = 24.1; the second includes the BROWN and BLACK lithotypes, with σ_{ci} around 82 MPa and m_i = 15.5. Under residual conditions, the strength envelopes converge with average parameters of σ_{ci} around 19.4 MPa and m_i = 13.8.

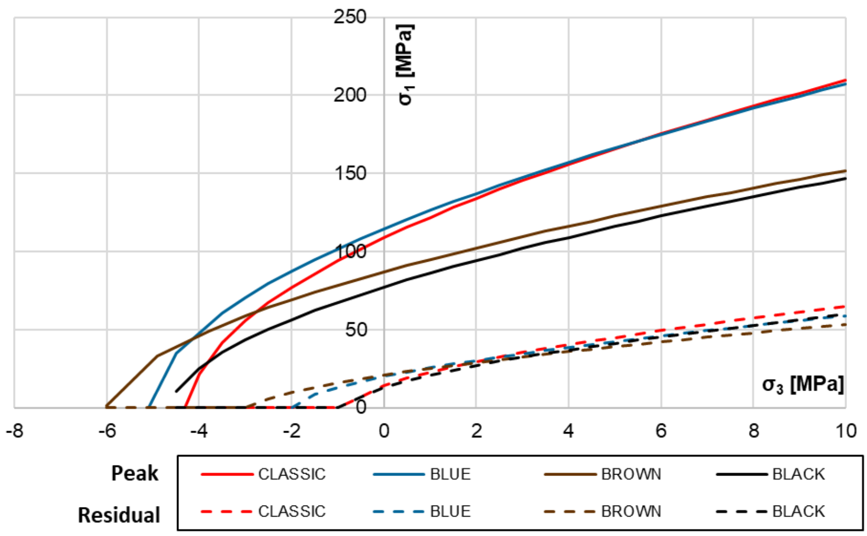

Fig. 6 Hoek-Brown criterion for the analyzed lithotypes.

5 Conclusions

The tests performed provided a comprehensive physical and mechanical characterization of the lithotypes from the Lorgino quarry.

Summarizing the main results of this study, we can say:

- the unit weight is 28.3 kN/m³ for CLASSIC, BLUE, and BROWN, and 29.0 kN/m³ for BLACK.
- regardless of the lithotype, the direction identified as "Contro" has higher V_P values than the "Verso" direction, indicating medium to high anisotropy of the material. For V_S, this difference is less pronounced.
- the range of V_P and V_S values for the four lithotypes is comparable to reference values for similar materials.
- the BLACK samples, in comparison with the other lithotypes analyzed, show a high dispersion of results. This is mainly due to the material's high heterogeneity, with the presence of millimetric to centimetric crystalloblasts.
- the Hoek and Brown criterion identified two classes of peak strength as a function of the considered lithotype: CLASSIC and BLUE exhibit the same trends, highlighting their quite similar high mechanical characteristics. Conversely, BROWN and BLACK converge to another trend, reflecting their lower mechanical characteristics.
- total agreement and convergence on a single trend for the residual strength.
- the procedure for the estimation of the five elastic constants provides results for the BLUE lithotype that are in agreement with the values obtained independently for the "Contro" and "Verso" directions.

This characterization will be fundamental for the next steps of the research: the development of a numerical model to forecast stability conditions, particularly with respect to flexural buckling, as the quarry exploitation plan progresses. The preliminary analysis, conducted using a simplified analytical model (Giani 1992), demonstrates that, in the current configuration, the potential for flexural buckling is remote.

References

Feng J, Zhou DP, Yang T (2010) Stability analysis of consequent rock slopes using elastic-plastic plate theory. Chin J Geotech Eng, 32(8): 1184-1188

Garzon SER (2016) Analytical solution for assessing continuum buckling in sedimentary rock slopes based on the tangent-modulus theory. Int J Rock Mech Min Sci, 90: 53-61. 10.1016/j.ijrmms.2016.10.002

Sun C, Chen C, Zheng Y et al. (2022) Assessing the stability of dip slopes based on analyzing the stress at a key point on the sliding surface. Int J GeoMech, 22(9): 04022152. 10.1061/(ASCE)GM.1943-5622.0002548

Wang Q, Zhang R, Zheng H, Zhou P (2023) An analytical solution of critical sliding displacement for the flexural buckling failure of layered rock slopes. International Journal of Rock Mechanics and Mining Sciences 169: 105450. https://doi.org/10.1016/j.ijrmms.2023.105450

Carriero MT, Migliazza MR, Comina C et al. (2023) Geotechnical and Geophysical Investigation of a Rock Mass for the Design Check of an Ornamental Stone Quarry. Paper presented at the 15th ISRM Congress, Salzburg, Austria.

Yim J, Hong S, Lee Y and Min KB. 2022. A novel method to determine five elastic constants of a transversely isotropic rock using a single-orientation core by strip load test and strain inversion. International Journal of Rock Mechanics and Mining Sciences. 146: 105115. 10.1016/j.ijrmms.2022.105115

Giani GP. 1992. Rock Slope Stability Analysis. CRC Press