Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-54

ECSMGE 24
XVIII EUROPEAN CONFERENCE
ON SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

Hydric and mechanical properties assessment of basalts from Madeira island, Portugal

Évaluation des propriétés hydriques et mécaniques des basaltes de l'île de Madère, Portugal

N. Cueto*
University of Alicante, Alicante, Spain
Laboratório Regional de Engenharia Civil, Madeira Island, Portugal

J.F. Vieira de Sousa, J.P.S. Perneta
Laboratório Regional de Engenharia Civil, Madeira Island, Portugal

R. Meza
GIS4tech, Spin-Off of University of Granada, Granada, Spain

M.L. Pereira
Instituto de Investigação em Vulcanologia e Avaliação de Riscos, Universidade dos Açores, Ponta Delgada, Portugal

**nora.cueto@ua.es*

ABSTRACT: This investigation explores the influence of physical properties on capillarity and uniaxial compressive strength from 56 specimens of basalts from Madeira Island, Portugal. Three well differentiated basalt types belonging to the Upper (massive and vesicular basalt) and the Middle (altered massive basalt) Volcanics Complexes were studied. Water absorption coefficient by capillarity and uniaxial compressive strength were assessed as a function of real and apparent densities, total and open porosities, water absorption at atmospheric pressure and unit weight applying simple and multiple linear regressions to obtain reliable prediction models. Water absorption coefficient by capillarity equations show high correlation coefficients ($R > 0.98$). The proposed best equation is expressed as a function of water absorption at atmospheric pressure and apparent density. Meanwhile, the best fit for uniaxial compressive strength, given by apparent density, open porosity, and unit weight has a moderate correlation. While apparent density has a predominant statistical weight in the prediction of uniaxial compressive strength, open porosity has a minor contribution. Unsupervised clustering processes using principal component analysis identifies three well differentiated groups whose inner cohesion is intimately related to open porosity (very low to high porosity), pore size and type (fine intercrystalline and large vesicular pore type, respectively) and the natural weathering degree of basalts. Some results obtained in this research could be used as indicator parameters in geotechnical classifications to assist with fast decisions when using basalts as building materials or as a foundation in civil engineering construction.

RÉSUMÉ: Cette étude explore l'influence des propriétés physiques sur la capillarité et la résistance à la compression uniaxiale de 56 éprouvettes de basaltes de l'île de Madère. Trois faciès bien différenciés appartenant au Complexes Volcaniques Supérieur et Moyen ont été étudiés. Le coefficient d'absorption d'eau par capillarité et la résistance en compression uniaxiale ont été comparés et liés aux masses volumiques réelles et apparentes, aux porosités totales et ouvertes, à l'absorption d'eau à la pression atmosphérique et au poids unitaire en appliquant une analyse statistique avancée. Le coefficient d'absorption d'eau par capillarité obtenu par des modèles de régression linéaire simple et multiple montrent des coefficients de corrélation élevés ($R > 0,98$; respectivement). La meilleure équation proposée est exprimée en fonction de la masse volumique apparente et de la porosité ouverte. Le meilleur ajustement pour la résistance à la compression uniaxiale, donné par la masse volumique apparente et la porosité ouverte, présente une corrélation modérée, où la masse volumique apparente avait un poids statistique prédominant dans la prédiction de cette variable, avec une contribution mineure de la porosité ouverte. L'analyse non supervisée de groupes identifie trois groupes bien différenciés dont la cohésion interne est intimement liée à la porosité ouverte à la taille, au type de pores et au degré d'altération naturelle des basaltes. Certains résultats obtenus pourraient être utilisés comme paramètres indicateurs dans les classifications géotechniques pour permettre une prise de décision rapide dans l'utilisation des basaltes comme matériaux de construction ou comme fondations pour les constructions de génie civil.

Keywords: Volcanic rocks; multivariate analysis; spontaneous imbibition; petrophysical properties; building rock.

1 INTRODUCTION

Research on the physico-mechanical properties of basalts is currently booming due to their potential use as reservoirs for hydrogen (Yaseri et al., 2023) and CO_2 (Iglauer and Al-Yaseri, 2021) storage in the accelerating race to find solutions for energy transition and climate change mitigation.

In Madeira Island, basalt studies are more focused on its use as a foundation material in civil engineering works, on its performance in slope stability for risk assessment, and on its use as an ornamental and building stone, both in new construction and in the conservation and restoration of the regional architectural heritage (Sempere-Valverde et al., 2023, Alves et al., 2019, Maia and Aslani, 2016, Lourenço et al., 2010). While physical (e.g. density, porosity, etc.) and mechanical (e.g. uniaxial compressive strength, elastic modulus, indirect tensile strength, point load index, etc.) properties of basalts are widely assessed worldwide (Pereira et al., 2021, and references therein), research on water transport mechanisms remains scarce.

Basalts used as building stones and with a pore size distribution ranging from 0.1 µm to 10 µm (within the medium range of capillary active pore size) are found to be more prone to deterioration due to the physicochemical processes induced by both water sorption and solutes' transport (Çelik and Kaçmaz, 2016). Moreover, basalts exhibit variations in their resistance due to material weathering, as showed by numerical evaluations on slope stability (Silva et al., 2023). Both erosion processes and changes in the hydraulic conditions of basaltic grounds due to water level variations are suggested as causes of such deterioration. From our own field experiences, we recognise that episodic slope collapses are either caused by torrential rains or stagnant water. In the latter, fluid movements are induced first by permeability and then by capillarity. Thus, the existence of a parameter that relates fluid transport integrated with other geoengineering properties is of foremost importance to better develop prevention plans and minimise geological hazards.

To address this problem, water transport in volcanic rocks has started to be considered in an internal database that has been developed by Laboratório Regional de Engenharia Civil (LREC) since 2012 (Vieira de Sousa et al., 2012) and is currently expanding to cover more territory of Madeira Island and incorporate parameters of critical importance in predicting both hydric and mechanical properties. In fact, capillarity and permeability have proved to be indicators of susceptibility to deterioration and possible collapse of volcanic rocks (Cueto et al., 2018, Perneta and Vieira de Sousa, 2023).

Therefore, the main objective of the present study is to determine the influence of physical properties on capillarity and uniaxial compressive strength. For this purpose, the results will be analysed by applying multivariate statistics and empirical equations will be provided to estimate these parameters. Final considerations will be addressed in the context of the application of these parameters as accurate indicators within geoengineering properties.

2 MATERIALS AND SAMPLING

2.1 Geographical and geological setting

The Madeira Island is the largest and most populated of the homologous Archipelago and is located in the eastern sector of the North Atlantic ocean, between latitudes 32º 38' N and 32º 52' N. It corresponds to a volcanic edifice (1861 m above sea level) that has been originated by a hot spot. Madeira Island comprises three main volcanostratigraphic terms: (a) Lower Volcanic Complex (CVI. > 5.57 My); (b) Middle Volcanic Complex (CVM. 5.57 - 1.8 My); and (c) Upper Volcanic Complex (CVS. 1.8 - 0.007 My) (Ramalho et al., 2015, Brum da Silveira et al., 2010), with alkali olivine basalts being an important rock material in this island (Hughes and Brown,1972).

2.2 Basalts

Three massive, one vesicular and one altered massive basalt samples were selected to carry out this study, from which 56 specimens in total were extracted. Massive basalts were quarried in São Vicente (Bc-SV) and São Martinho, Funchal (Bc-SA, Bc-SB), and the vesicular basalt sample (Bv-SV) was cored in São Vicente. Both belong to the Funchal Unit, CVS. The altered massive basalt (Bca-E) was obtained in Encumeada, Ribeira Brava, in the geological context of CVM, Penha d'Águia Unit.

At mesoscale, massive basalts are dark grey in colour and show almost no signs of weathering. In the Bc-SV sample, a very isolated vesicular porosity type can be seen (2.62 ± 1.80 mm). The Bc-SA and Bc-SB samples show a vesicular porosity type smaller than those observed in Bc-SV (0.88 ± 0.36 mm, 0.79 ± 0.24; respectively), but also isolated, and widely dispersed throughout the samples. In both samples, discontinuity surfaces are observed with increasing depth. These are fissures and, less frequently, stylotites-like discontinuities, with a very fine aperture (~1 mm), open or partially cemented by a whitish mineral. In sample Bc-SA the fissure density increases significantly compared to sample Bc-SB.

In vesicular basalts, macroporosity extends over 30-40% of the sample, has no preferential organisation and has a size variation in the range of 1.5 mm to 6 mm.

The altered compact basalt sample, Bca-E, is generally grey in colour, with some brownish areas. It has about 10% vesicular porosity and, in some specimens, this macroporosity is partially cemented by a whitish mineral. Isolated and narrow-opening fissures are present. The matrix of Bca-E is more porous than the rest of the studied basalts, probably and partly due to the natural weathering of the rock mass (W_2 in accordance with ISRM (1981)).

Bc-SV, Bv-SV and Bca-E samples were collected from outcrops, meanwhile Bc-SB and Bc-SA samples were obtained from a borehole drilled at depths of ~20 m to 35 m.

3 METHODS

The cylindrical specimens were cut according to the specifications of each test standard, i.e. h/d=1 (~70 mm). The number of specimens tested in each experiment, as well as the porous facies classification based on Anon. (1979), are stated in Table 1.

Petrophysical properties, namely real, ρ_r, and apparent, ρ_b, densities and total, p, and open, p_o, porosities were determined following the NP EN 1936 (2008) standard. Water absorption at atmospheric pressure, A_b, and water absorption coefficient by capillarity, C, were respectively carried out in accordance with NP EN 13755 (2008) and NP EN 1925 (2000) standards. The studies of spontaneous imbibition of water were completed with the analysis of capillary curves based on the SF model of Hall and Hoff (2021). To obtain the mechanical properties, tests have only been carried out to determine the uniaxial compressive strength, σ_c, according to NP EN 1926 (2008). The unit weight, γ_d, was obtained through the relation of total weight of oven-dried specimen and total volume of the specimen.

The descriptive and multivariate statistical analyses of the results were carried out using IBM SPSS Statistics 25.0.0 as in Cueto (2020), namely scatter diagram analysis, multiple linear regressions (LR), principal component analysis (PCA), and hierarchical cluster analysis (CA). Unsupervised cluster analysis using simplified PCA variables was performed employing the K-Nearest Neighbours algorithm from the scikit-learn Python 3 library (Jupyter Notebook 6.5.2).

4 RESULTS AND DISCUSSION

Table 1 shows the physical and mechanical properties results of the studied basalts, classified accordingly to Anon. (1979) as (i) very low - low porous, (ii) medium porous, and (iii) medium - high porous type. This grouping is exactly coincident with the massive, vesicular, and altered massive facies, respectively.

All multivariate analyses, whether dependent (LR) or interdependent (PCA and CA), prove that p_o is one of the main controlling factors in both hydric and mechanical properties. The higher the p_o, the higher the C and A_b, and the lower the σ_c. Empirical equations presented in Table 2 reveal that C can be predicted with high precision from Eq. 1. LR identified the variables A_b ($\beta = 0.999$) and ρ_b ($\beta = 0.019$) as significant predictors of C. This model is highly significant ($p < 0.001$; R = 0.98), however, among equations 1 to 4, Eq. 2 and Eq. 4 are the most efficient ones, because only one parameter is needed to estimate C and the models remain highly significant. This finding is reasonable since A_b and p_o are related through the saturation coefficient (Benavente, 2002). Equations 5 to 7 for estimating σ_c found, on the other hand, have moderate correlation coefficients (Table 2). The simplest (Eq. 7) predicts σ_c from ρ_b and maintains almost the same p (< 0.001) and R (~0.81) values.

The capillarity analysis shows two pore families controlling the water movement in Bv-SV. Large vesicular pores are well interconnected through the fine intercrystalline matrix porosity, extending and enhancing capillary suction. Despite this, the C results are lower than expected. This could be because the macropores size distribution is skewed towards values greater than 1.5 mm, which is the smallest size measured in this sample. Additionally, vesicles were detected overlapping each other, leading to an increase in the size of the macropores in their confluence zone. It has been verified experimentally that the mass of the water column is conditioned by the maximum pore size for capillary mobility. Jurin's Law for a wetting liquid supports this, as the capillary height for a pore radius of 1 mm is 1.5 mm. This suggests that gravity forces would be the primary mechanism in this situation and that fluid movement by capillarity would be insignificant (Hall and Hoff, 2021, Benavente, 2002).

Figure 1 displays the outcomes derived from unsupervised cluster analysis simplifying the PCA variables to assess the data quality from the categorization of rock facies. This process discriminated the three well-differentiated studied petrological varieties.

Table 1. Physico-mechanical properties of the studied basalts. Mean, standard deviation (SD), minimum (Min.) and maximum (Max.) values of real, ρ_r, and apparent, ρ_b, density; total, p, and open, p_o, porosity; water absorption at atmospheric pressure, A_b, water absorption coefficient by capillarity, C, unit weight, γ_d, and uniaxial compressive strength, σ_c. Upper, CVS, and Middle, CVM, Volcanic Complex; number of specimens tested, Nº.

Basalt	**Type**		ρ_r (kg/m^3)	ρ_b (kg/m^3)	p (%)	p_o (%)	A_b (%)	C ((g/m^2)/s$^{0.5}$)	γ_d (kN/m^3)	σ_c (MPa)
CVS	Massive *(Very low – low porous)*	Nº	39	39	39	39	33	21	39	39
		Mean	3065	2955	4.0	0.8	0.4	0.4	28.8	214.3
		SD	56	50	2.6	0.9	0.3	0.3	0.5	54.2
		Min.	2973	2805	0.9	0.0	0.0	0.1	27.2	103.0
		Max.	3167	3007	9.4	2.6	0.8	1.2	29.6	322.4
	Vesicular *(Medium porous)*	Nº	7	7	7	7	-	7	7	-
		Mean	3146	2383	24.2	5.0	-	2.1	22.3	-
		SD	27	121	4.2	1.1	-	0.5	1.4	-
		Min.	3100	2175	20.1	4.1	-	1.7	20.0	-
		Max.	3174	2491	31.4	7.1	-	3.1	23.5	-
CVM	Altered *(Medium – high porous)*	Nº	10	10	10	10	10	-	10	10
		Mean	2971	2580	12.6	10.0	4.2	-	25.3	109.9
		SD	77	248	7.2	6.9	3.0	-	2.4	52.5
		Min.	2893	2220	4.1	1.8	0.8	-	21.8	55.6
		Max.	3162	2893	23.4	20.4	9.0	-	28.4	212.5

Massive facies dominate the leftmost part in Figure 1, whereas vesicular facies is concentrated in the upper-right area. In the lower-right corner are grouped altered massive basalts.

Certain specimens of this last facies, however, are more related to massive facies due to their prominent physical properties as ρ_r and ρ_b. As a result, they are assigned to a zone closer to the massive facies group.

Nonetheless, the classification does not fall much short because it places these specimens outside of the massive facies' high point concentration and, in some cases, relatively near to the altered massive facies. Consequently, the specimens labelled in Figure 1 might be considered transitional since they fall between two facies.

These findings suggest that the inner cohesion of basalts facies is intimately related to open porosity (very low to high porosity), pore size and type (fine intercrystalline and large vesicular pore type, respectively), and the natural weathering degree of basalts (Table 1).

CA, performed with the shortest distance method (nearest neighbour) using the Euclidean distance as a measure of dissimilarity between specimens, aids unsupervised cluster analysis by identifying the three clearly distinguished facies.

These results underline the fact that if an unsupervised classification algorithm can perform a classification process with an extremely high level of accuracy, how much more could a supervised classification algorithm do with a large number of specimens? It may not only be able to categorise, but it may also be able to detect samples or specimens that lie between two facies and create additional sorts of inputs depending on the training data if properly labelled. This would shorten the time and cost of laboratory work, accelerate the generation of results, and help in making informed decisions.

Table 2. Logarithmic expressions of capillary absorption coefficient, C ((g/m^2)/s$^{0.5}$), and uniaxial compressive strength, σ_c (MPa), as a function of physical properties: water absorption at atmospheric pressure, A_b (%), apparent density, ρ_b (kg/m^3), open porosity, p_o (%), unit weight, γ_d (kN/m^3). R, multiple correlation coefficient.

Eq.	**Logarithmic expressions**	**R**
1	$LogC = -2.781 + 0.990 \cdot LogA_b + 0.867 \cdot Log\rho_b$	0.9828
2	$LogC = 0.213 + 0.974 \cdot LogA_b$	0.9827
3	$LogC = -2.179 + 0.611 \cdot Log\rho_b + 0.658 \cdot Logp_o$	0.9668
4	$LogC = -0.086 + 0.629 \cdot Logp_o$	0.9665
5	$Log\sigma_C = -27.767 + 12.240 \cdot Log\rho_b - 0.042 \cdot Logp_o - 8.510 \cdot \gamma_d$	0.8214
6	$Log\sigma_C = -12.736 + 4.333 \cdot Log\gamma_d - 0.026 \cdot Logp_o$	0.8147
7	$Log\sigma_C = -14.330 + 4.795 \cdot Log\rho_b$	0.8107

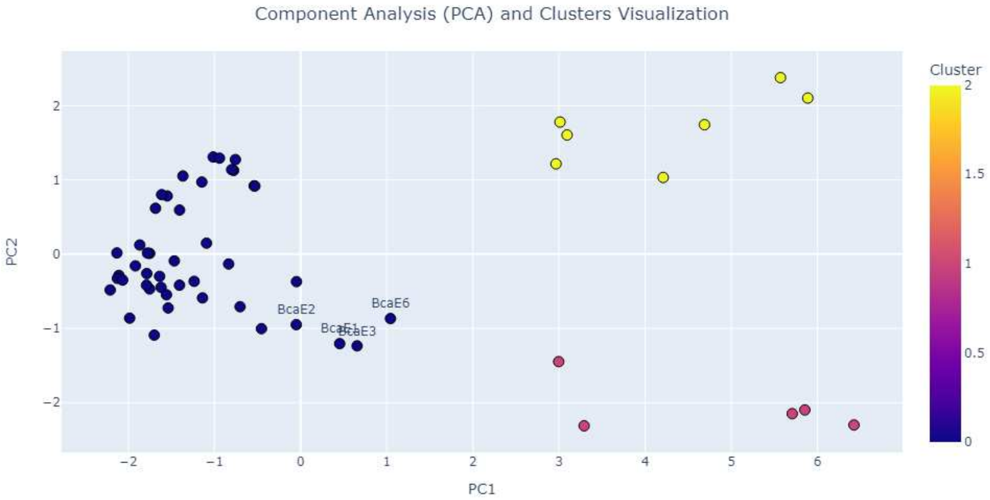

Figure 1. PCA and clusters visualization obtained from unsupervised cluster analysis. Massive (blue), vesicular (yellow) and altered massive (pink) basalt specimens. The labelled specimens belong to the altered massive facies, yet they exhibit prominent physical properties (i.e. ρ_r, ρ_b) similar to massive facies.

5 CONCLUSIONS

This investigation contributes to a better understanding of the physical properties influence on hydric and mechanical properties of basalts from Madeira Island, applying multivariate statistical analyses, and provides valuable insights for their application in geoengineering projects.

The equations developed in this study for water absorption coefficient by capillarity and uniaxial compressive strength can be used as reliable prediction models and can assist in assessing their suitability as construction and building materials, and for improving known classifications in civil engineering projects.

Unsupervised clustering processes using principal component analysis classified the basalts into three well-differentiated groups based on open porosity, pore size and type, and the natural weathering degree of basalts. This finding suggests that this approach can be used to guide the selection of specific types of basalts for different applications, considering their intrinsic controlling factors. In addition, this process can be further enhanced with the use of supervised classification algorithms for categorising samples accurately and identifying transitional specimens between facies into larger petrophysical databases, leading to more efficient and cost-effective laboratory work, faster generation of results, and better-informed decision-making.

Future works for gaining deeper understanding of water movement in vesicular basalts will be conducted, expanding the number of samples to be tested and conducting further microscopic analysis or employing advanced imaging techniques to identify and quantify the actual pore structure. This will provide a more comprehensive interpretation of the pore size distribution and its impact on sorption mechanisms.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by the European Union - Next Generation EU, by the Spanish Ministry of Universities, the University of Alicante (project reference: MARSALAS22-09), and the fellowship from “la Caixa” Foundation (ID 100010434) with the code LCF/BQ/DR22/11950029. The authors would also like to thank Dr. Christophe Ortiz and Prof. Carla Gonçalves, and Engs. Darren and Helen Gruett, for their valuable help in revising and editing respectively the French and the English texts.

REFERENCES

Alves, R., Faria, P., Brás, A. (2019). Brita Lavada - An eco-efficient decorative mortar from Madeira Island, *Journal of Building Engineering*, 24, 100756. https://doi.org/10.1016/j.jobe.2019.100756.

Anon. (1979). Classification of rocks and soils for engineering geological mapping part I: Rock and soil materials, *Bulletin of the International Association of Engineering Geology*, 19, 364-371. https://doi.org/10.1007/BF02600503.

Benavente, D. (2002). *Modelización y estimación de la durabilidad de materiales pétreos porosos frente a la* *cristalización de sales*, Ph.D. Thesis, University of Alicante, Spain.

Brum da Silveira, A., Madeira, J., Ramalho, R., Fonseca, P., Prada, S. (2010). *Carta Geológica (folhas A e B) e Notícia Explicativa da Carta Geológica da Ilha da Madeira na Escala de 1:50000*, Secretaria Regional do Ambiente e Recursos Naturais, Governo da Região Autónoma da Madeira e Universidade da Madeira, Funchal, Portugal.

Çelik, M. Y., Kaçmaz, A. U. (2016). The investigation of static and dynamic capillary by water absorption in porous building stones under normal and salty water conditions, *Environmental Earth Sciences*, 75, 307. https://doi.org/10.1007/s12665-015-5132-x.

Cueto, N. (2020). *Major controlling factors on fluid transport properties in complex marine and freshwater carbonate rocks: An integrated experimental and theoretical study on the relation between permeability and capillarity*, Ph.D. Thesis, University of Alicante, Spain.

Cueto, N., Vieira de Sousa, J. F., Fernandes, C., Benavente, D., Urbani, F., Meza, R., Fernandes, É., García-del-Cura, M. A. (2018). Water transport in lapilli tuff from Madeira Island, Portugal: implications on degradation mechanisms and durability, In: *16CNG - 16º Congresso Nacional de Geotecnia*, Açores, Portugal, 12 p.

Hall, C., Hoff, W. D. (2021). *Water Transport in Brick, Stone and Concrete*, 3rd ed., CRC Press, London. https://doi.org/10.1201/9780429352744.

Hughes, D. J., Brown, G. C. (1972). Basalts from Madeira: A Petrochemical contribution to the genesis of oceanic alkali rock series, *Contributions to Mineralogy and Petrology*, 37, 91-109. https://doi.org/10.1007/BF00371069.

Iglauer, S., Al-Yaseri, A. (2021). Improving basalt wettability to de-risk CO_2 geo-storage in basaltic formations, *Advances in Geo-Energy Research*, 5, 3, 347-350. doi: 10.46690/ager.2021.03.09.

ISRM (1981). Basic geotechnical description of rock masses, *International Journal of Rock Mechanics and Mining Sciences*, 18, 85-110.

Lourenço, J. C., Brito, J. M., Santos, J., Rosa, S. P. P., Rodrigues, V. C., Oliva, R. (2010). Geotechnical characterization of volcanic rocks and soils of Madeira Island, In: *ISRM International Workshop on Rock Mechanics and Geoengineering in Volcanic Environments*, Puerto de la Cruz, Spain.

Maia, L., Aslani, F. (2016). Modulus of elasticity of concretes produced with basaltic aggregate, *Computers and Concrete*, 17, 1, 129-140. http://dx.doi.org/10.12989/cac.2016.17.1.129.

NP EN 13755 (2008). Natural stone test methods. Determination of water absorption at atmospheric pressure, European Committee for Standardization, Brussels, Belgium.

NP EN 1925 (2000). Natural stone test method. Determination of water absorption coefficient by capillarity, European Committee for Standardization, Brussels, Belgium.

NP EN 1926 (2008). Natural stone test method. Determination of uniaxial compressive strength, European Committee for Standardization, Brussels, Belgium.

NP EN 1936 (2008). Natural stone test method. Determination of real density and apparent density and of total and open porosity, European Committee for Standardization, Brussels, Belgium.

Pereira, M. L., da Silva, P. F., Fernandes, I., Chastre, C. (2021). Characterization and correlation of engineering properties of basalts, *Bulletin of Engineering Geology and the Environment*, 80, 2889-2910. https://doi.org/10.1007/s10064-021-02107-7.

Perneta, J. P. S., Vieira de Sousa, J. F. (2023). Volcanic rocks from Madeira Island, Portugal. A contribution to its characterization, In: *18CNG - 18º Congresso Nacional de Geotecnia*, Évora, Portugal, 1387-1396.

Ramalho, R. S., Brum da Silveira, A., Fonseca, P. E., Madeira, J., Cosca, M., Cachão, M., Fonseca, M. M., Prada, S. N. (2015). The emergence of volcanic oceanic islands on a slow-moving plate: The example of Madeira Island, NE Atlantic, *Geochemistry, Geophysics, Geosystems*, 16, 2, 522-537. https://doi.org/10.1002/2014GC005657.

Sempere-Valverde, J., Ramalhosa, P., Chebaane, S., Espinosa, F., Gama Monteiro, J., Bernal-Ibáñez, A., Cacabelos, E., Gestoso, I., Guerra-García, J. M., Canning-Clode, J. (2023). Location and building material determine fouling assemblages within marinas: A case study in Madeira Island (NE Atlantic, Portugal), *Marine Pollution Bulletin*, 187, 114522. https://doi.org/10.1016/j.marpolbul.2022.114522.

Silva, E. C., Barros, M. J. S., Barros, J. G., Simões, D. H. A., Barros, L. A. M. (2023). Geological and geotechnical studies for slope stability analysis in the interior of Maranhão: Proposal for slope conformation in the city of Açailândia/MA - MA 125, In: *18CNG - 18º Congresso Nacional de Geotecnia*, Évora, Portugal, 1117-1126.

Vieira de Sousa, J. F., Sousa, D. M. F., Oropeza, C. R. (2012). Geotechnical characterization of volcanic rock materials of Madeira Island, In: *13CNG - 13º Congresso Nacional de Geotecnia*, Lisboa, Portugal.

Yaseri, A., Esteban, L., Giwelli, A., Sarout, J., Sarmadivaleh, M., Kanakiya, S., Adam, L. (2023). Potential of hydrogen underground storage in volcanic reservoirs of Australia: is it worth looking into? In: *AHRC2023 - Australian Hydrogen Research Conference*, Canberra, Australia. https://doi.org/10.2139/ssrn.4483701.