CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2025; 35 (2): 0015-0023
DOI: 10.59440/ceer/201332
Original Research Article

EXPERIMENTAL ASSESSMENT OF STRUCTURAL COLLAPSE IN PYROCLASTS

Fausto MOLINA-GÓMEZ[1*], Miguel Ángel MILLÁN[1], Rubén GALINDO-AIRES[1]
[1] Structures and Building Physics, Universidad Politécnica de Madrid, Spain
[2] Geotechnical Engineering, Universidad Politécnica de Madrid, Spain

Abstract

During intense volcanic eruptions, the magma forcefully expelled gives rise to pyroclastic materials, such as volcanic ashes and macro-porous rocks. This magma has the potential to shatter into small particles with a notably expansive surface area. Meanwhile, the solidification of larger magma fragments in scoriae and pumices produces a high gas content. Consequently, abundant voids and bubbles within the pyroclasts lead to high porosity and low density. The geomechanical behaviour of these pyroclasts is complex due to their internal structure and the bounding between their particles, which may break under relatively low confinements, producing a structural collapse that calls for a distinctive approach to tackling geotechnical challenges within these volcanic rock formations. This paper describes novel procedures to assess the structural collapse of various pyroclasts collected in the Canarias Islands (Spain). The outlined procedures cover sampling, laboratory handling and isotropic compression triaxial tests. Following these recommendations ensures reliable characterisation of the structural collapse of pyroclasts, which can be utilised to calibrate constitutive models and construct or design geotechnical structures.

Keywords: rock mechanics, isotropic compression strength, laboratory testing, pyroclasts

1. INTRODUCTION

Pyroclastic deposits are typically found in volcanic regions such as the Canary Islands, Central and Southern Italy, and Cappadocia. These deposits are composed of materials with low densities controlled by porosities greater than 0.40 and can be classified as volcanic ashes and volcanic rocks. Their mechanical behaviour falls between hard soils and weak rocks. This unique behaviour is influenced by their high porosity and special structural composition, which significantly affect their deformability and shear strength characteristics. These materials are susceptible to fabric changes induced by chemical alterations that can reduce their durability. Under high pressures, their structure breaks down, leading to significantly increased deformability and causing them to behave more like soils. The strength and

[1*] Corresponding author: Fausto Molina-Gómez, ETSAM, Universidad Politécnica de Madrid, Avenida Juan de Herrera n.4, 28040, Madrid, Spain, e-mail: fausto.molina@upm.es

deformability of these geomaterials depend on their internal structure, particularly the degree of bonding between the particles.

Over the last few decades, various studies have been conducted to characterise a variety of macro-porous rocks [1–5]. These results showed that pyroclastic materials have low density and weak bonds between particles. Therefore, they are prone to sudden and dangerous failures without significant warning signs due to their high deformability, which causes collapse when increasing the confining pressure. This phenomenon is called structural collapse. Structural collapse is produced when a highly porous material loses the bond between the particles after reaching a critical pressure, causing a significant decrease in volume and the formation of new material [6].

Assessing isotropic collapse is crucial for understanding the mechanical behaviour of low-density pyroclastic rocks, as their highly porous nature makes them particularly susceptible to volumetric instability. Serrano et al. [7] developed a yield criterion that emphasises the significance of macroporosity in determining their collapse behaviour, providing a framework for predicting failure under different stress path conditions. Evaluating isotropic collapse is particularly relevant for the safe design of foundations and geotechnical structures in pyroclastic deposits, where sudden volumetric reductions can significantly impact stability [6,8].

In laboratory settings, isotropic collapse is typically investigated by gradually increasing confining pressure in a controlled environment while measuring volumetric strain responses until failure occurs. This approach differs from the conventional consolidation stage in triaxial testing, focusing on capturing the critical pressure at which collapse initiates. However, despite its engineering significance, the literature lacks extensive studies explicitly addressing the structural collapse of geomaterials. Most experimental research on pyroclasts primarily examines shear strength using unconfined compression and triaxial tests, which, while valuable, do not fully characterise the material's response to isotropic stress conditions. Expanding research in this area would enhance predictive models and improve geotechnical applications involving pyroclastic formations.

This study presents new experimental procedures to assess the structural collapse of pyroclasts collected in the Canarias Islands (Spain). The results of an extensive experimental testing program carried out at the Geotechnical Laboratories of UPM and CEDEX in Madrid, Spain, are outlined. The procedures include details of sample handling and the description of isotropic compression tests. The paper provides initial results from an ongoing project aimed at characterising the mechanical behaviour of these materials, building on previous findings reported by Conde [8]. These results demonstrate the effectiveness of the proposed method for assessing the structural collapse of various pyroclasts using a triaxial testing apparatus specifically adapted to apply controlled isotropic pressures.

2. MATERIALS

2.1. Description of pyroclastic materials

The samples used in this study were collected from various blocks of pyroclasts originating in Tenerife, El Hierro and La Palma (Canarias Islands, Spain). These blocks were carved in situ and then covered with paraffin for transportation using custom-made boxes explicitly designed to hold four blocks of approximately 30x30x30 cm^3 each. These procedures were implemented to minimise any potential disturbances during transport. Afterwards, in Madrid, the blocks were categorised according to their lithotype using the classification proposed by Hernández-Gutiérrez and Rodríguez-Lozada [9]. Table 1 presents the classification of lithotypes.

Table 1. Lithotypes identified in the classification by Hernández-Gutiérrez and Rodríguez-Lozada [9]

Basaltic pyroclasts	Lapilli (LP)	Loose (S)	LPS
		Welded (T)	LPT
	Scoria (Es)	Loose (S)	ESS
		Welded (T)	ESW
	Basaltic ashes (CB)	Loose (S)	CBS
		Welded (T)	CBT
Sialic pyroclasts	Pumice (PZ)	Loose (S)	PZS
		Welded (T)	PZT
	Sialic ashes (CS)	Loose (S)	CSS
		Welded (T)	CST

The samples examined here cover the five lithotypes defined in Table 1, that is, lapilli, scoria, pumice, basaltic ashes, and salic ashes. All these lithotypes are welded. Figure 1 displays some samples obtained from various blocks with different lithotypes for testing, highlighting the transport box and samples aspect.

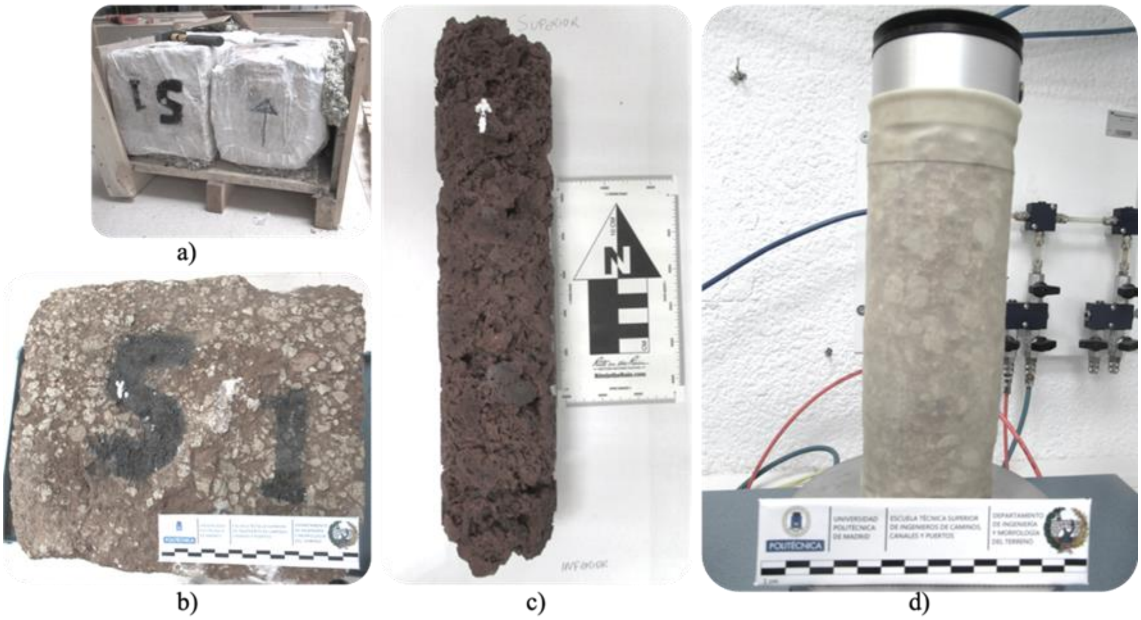


Fig. 1. Pyroclastic samples: a) box transport, b) block, c) macroporous pyroclastic material; d) ready to test

2.2. Preparation of pyroclastic specimens

In the laboratory, the blocks made of stiffer materials were drilled. The blocks were drilled using a diamond drill bit and trimmed with a sharp knife. The diameter of samples ranged from 64 to 70 mm, while their height ranged from 120 to 150 mm. Even though the specimens were prepared with extreme care, the high porosity of the pyroclasts makes these materials sensitive, leading to various irregularities along the specimens. As a result, some specimens were unsuitable for mechanical tests but were used for physical classification. To address these issues, some blocks of soft materials (such as Pumice samples) were trimmed to prevent the samples from developing cracks before collapse testing were trimmed. Figure 2 depicts the procedures for the preparation of samples in the laboratory.

a) b)

Fig. 2. Procedures for sample preparation: a) drilling; b) trimming

3. ISOTROPIC TESTING AND RESULTS

In the laboratory, structural collapse is assessed by increasing the isotropic pressure until the specimen reaches the isotropic compressive strength (P_c). In this study, upgraded triaxial equipment was used. Such triaxial equipment can increase uniformly and automatically the confining pressure using a series of digital pressure/volume controllers with a capacity of 250 cm^3. Besides, it can test pyroclastic specimens at confining pressures of up to 3500 kPa. An automatic system controls the step-by-step motor, which moves a worm screw, and a piston connected to it in a straight line through a gearbox. This action is achieved through a nut attached to a pressure cylinder. The piston moves inside the cylinder, pressuring the water (usually deaerated). The pressure/volume controllers communicate with the computer through binary signals and can execute various control algorithms, such as maintaining a constant pressure, a steady volume, or a ramp-up pressure increase. Figure 3 schematises the novel configuration.

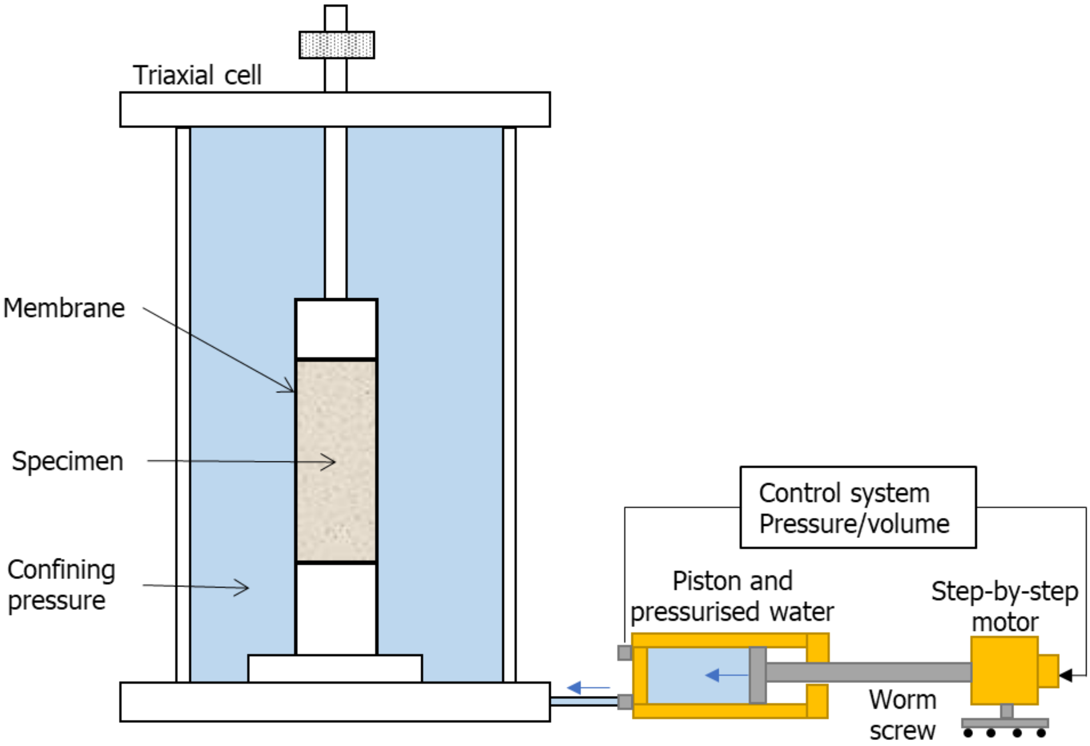
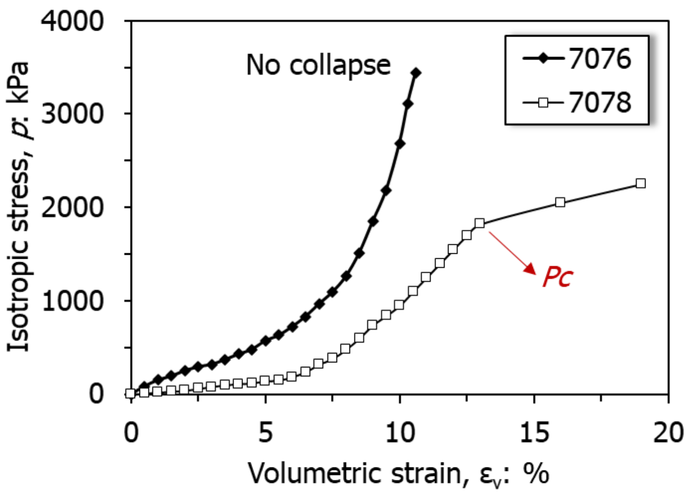


Fig. 3. Configuration for isotropic compression tests

The pressure is measured by a transducer connected to the base of the cylinder, while the volume change is calculated by counting the motor steps. Therefore, the isotropic compression tests can be represented by plotting the isotropic pressure (*p*) and the volumetric strains (ε_v). P_c was determined by monitoring the volume change during the pressure increment. Therefore, when the specimen exhibited a sharp change in volume, it was a clear indication of the onset of structural collapse caused by breaking particle bonds. The procedure involved the use of oilcloth membranes to prevent punctures during testing caused by potential specimen irregularities. This allows for preventing potential compliance during isotropic compression tests. All tests were carried out in dry samples. Figure 4 presents the typical results of isotropic compression tests and the final aspect of the specimen after testing.



a)

b)

Fig. 4. Typical results of isotropic triaxial compression testing: a) stress-strain curves; b) final aspect of the specimen

In Figure 4, the results from two samples are presented. The first sample, represented by bold dots, did not collapse; the triaxial apparatus reached a maximum isotropic pressure of 3500 kPa. In contrast, the second sample, represented by white squares, experienced structural collapse in 1835 kPa. The collapse was identified by a sudden increase in volumetric strain, which changed from 12.3% to 16.2%, indicating the P_c value. This behaviour confirms that structural collapse induces significant deformations within the soil deposit or rock mass, which can severely compromise the stability of foundations, slopes, embankments, and other geotechnical structures. The sudden volumetric change highlights the need for careful assessment of the collapse potential in pyroclastic materials, particularly in areas where high confining pressures might be encountered, to prevent unexpected failures and ensure long-term structural stability.

Table 2 presents the results obtained from diverse samples with different lithotypes. Besides, this table includes the results of the dry unit weight (γ_d) of each specimen. Samples that do not exhibit collapse correspond to denser materials, indicating that their internal bonds are stronger and less prone to failure due to their reduced porosity. As a result, these samples experience more constant volumetric strain variations. Hence, the data reveal a clear trend: specimens with lower γ_d collapsed at lower P_c values. This behaviour can be attributed to the higher porosity–lower density–and causes weaker internal structure or bounding [7]. Figure 5 shows a strong correlation between P_c as a function of γ_d by a high determination coefficient (R^2 = 0.85). This high correlation highlights the significant influence of γd on the mechanical behaviour of pyroclastic materials, emphasising the importance of characterising the dry unit weight to predict the collapse potential. This reinforces the need to understand the mechanical response of pyroclastic soils under different confining pressures to anticipate the Pc structural collapse values more effectively.

Table 2. The results of experimental research and computer calculations

Sample ID	**Lithotype**	γ_d (kN/m^3)	$\boldsymbol{P_c}$ (kPa)
4386-B2	PM-L-M	10.82	3280
4386	PM-L-M	10.13	No collapse*
6633	PM-L-M	9.24	No collapse*
7066	LP-L-M	11.7	No collapse*
7076 +	LP-L-M	12.07	No collapse*
7077	LP-L-M	12.78	No collapse*
7080	LP-L-M	10.5	No collapse*
3857	LP-W	9.64	1640
5143	LP-W	9.7	1140
7068	LP-W	9.68	1600
7069	LP-W	8.64	1400
7071	LP-W	9.6	1300
7074	LP-W	8.71	1100
3876	LP-W	11.5	1400
7067	LP-W	9.79	1220
7078 +	LP-W	10.86	1835
7073	LP-SW	5.7	200
7075	LP-SW	8.95	400
7072	LP-SW	11.1	1400
6634	PM-W	5.2	180
6638	PM-W	5.36	204
3573	PM-W	5.4	400
3762	PM-W	5.1	230
4385	PM-W	3.6	160
4385	PM-W	3.5	160
3825	SC-SW	8.75	1400

* No collapse below 3500 kPa

+ Results in Fig. 3

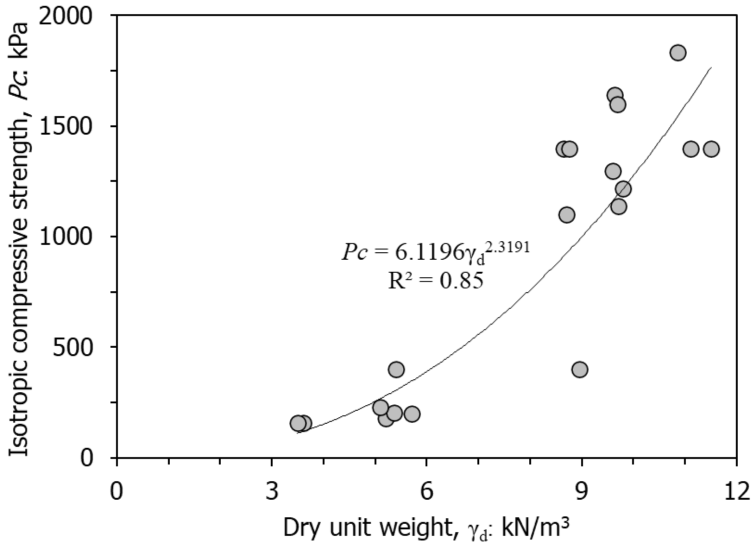


Fig. 5. Correlation between isotropic compressive strength and dry unit weight for various pyroclastic materials

4. CONCLUSIONS

This study described a series of novel experimental procedures to assess the structural collapse behaviour of pyroclastic materials under varying confining pressures using a novel experimental procedure. The results provide critical information on the mechanical response of these materials, particularly the relationship between dry unit weight (γ_d) and the collapse pressure (P_c). The upgraded equipment, capable of applying confining pressures up to 3500 kPa, allowed for precise control of pressure conditions, facilitating the accurate measurement of isotropic compressive strength in pyroclastic specimens. The combination of automatic pressure/volume controllers and a worm-screw piston mechanism enabled smooth, uniform pressure increases, contributing to the reliability of the experimental data. The results showed that specimens with lower γ_d values were more prone to collapse at lower P_c, attributable to their higher porosity and weaker internal structure. This relationship was confirmed by a strong correlation (represented by a determination coefficient $R^2 = 0.85$) between P_c and γ_d, highlighting the influence of density on the mechanical stability of pyroclastic soils. The findings emphasise the importance of accurately characterising pyroclastic materials when predicting collapse behaviour under high-pressure conditions. This research provides a foundation for future studies on pyroclastic soils and has practical implications for engineering projects in regions where these materials are prevalent, offering a reliable method for assessing collapse potential through laboratory testing.

ACKNOWLEDGEMENTS

This publication is part of the project PID2022-139202OB-I00, Neural networks and optimization techniques for the safe design and maintenance of transport infrastructure: volcanic rock geotechnics and Slope Stability (IA-Pyroslope), funded by the State Research Agency of the Ministry of Science, Innovation and Universities and the European Regional Development Fund, MCIN/AEI/10.13039/501100011033/ERDF, EU. The authors thank Professor Alcibiades Serrano, Dr. Áurea Perrucho, Dr. Margarita Conde, and the CEDEX technical staff for their support.

REFERENCES

1. Serrano, A and Olalla, C 1994. Ultimate bearing capacity of rock masses. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* **31**, 93–106.
2. Vallejo, LIG, Hijazo, T and Ferrer, M 2008. Engineering Geological Properties of the Volcanic Rocks and Soils of the Canary Islands. *Soils and Rocks* **31**, 3–13.
3. Cecconi, M, Scarapazzi, M and Viggiani, GMB 2010. On the geology and the geotechnical properties of pyroclastic flow deposits of the Colli Albani. *Bulletin of Engineering Geology and the Environment* **69**, 185–206.
4. Tommasi, P, Verrucci, L and Rotonda, T 2015. Mechanical properties of a weak pyroclastic rock and their relationship with microstructure. *Canadian Geotechnical Journal* **52**, 211–223.
5. Topal, T and Doyuran, V 1997. Engineering geological properties and durability assessment of the Cappadocian tuff. *Eng Geol* **47**, 175–187.
6. Serrano, A, Galindo, R and Perucho, Á 2021. Ultimate Bearing Capacity of Low-Density Volcanic Pyroclasts: Application to Shallow Foundations. *Rock Mech Rock Eng* **54**, 1647–1670.
7. Serrano, A, Perucho, A and Conde, M 2016. Yield criterion for low-density volcanic pyroclasts. *International Journal of Rock Mechanics and Mining Sciences* **86**, 194–203.
8. Galindo, R, Serrano, A and Olalla, C 2017. Ultimate bearing capacity of rock masses based on modified Mohr-Coulomb strength criterion. *International Journal of Rock Mechanics and Mining Sciences* **93**, 215–225.
9. Conde, M 2013. *Caracterización geotécnica de materiales volcánicos de baja densidad* [Geotechnical Characterisation of low-density volcanic materials]. PhD Thesis. Universidad Complutense de Madrid.
10. Canarias, G de 2011. *Guía Para La Planificación y Realización de Estudios Geotécnicos Para La Edificación En La Comunidad Autónoma de Canarias* [Guide for the planning and execution of geotechnical studies for buildings in the Autonomous Community of Canary Islands].