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## Article

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# Geotechnical characterisation of volcanic ash fluid soil cement

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## ABSTRACT

The excessive global use of Portland cement (PC) accounts for approximately 8% of anthropogenic CO<sub>2</sub> emissions. Coupled with the underutilization of volcanic materials in construction, this raises significant environmental and economic challenges. A promising alternative to address this issue is the use of soil cement mixtures (SCMs) incorporating volcanic ash. This study evaluates the geotechnical performance of these SCMs as a sustainable solution; SCMs samples of volcanic ash were prepared with Portland cement contents ranging from 0 to 40%. The experimental design included unconfined compressive strength testing, chemical analysis, X-ray fluorescence (XRF), and mineralogical characterisation through X-ray diffraction (XRD). The results showed that SCMs with 20% volcanic ash by mass, replacing Portland cement (PC), achieved compressive strengths of 2.5 MPa, compared to 1.8 MPa for conventional mixtures with PC alone, while also allowing a 10% reduction in CP content. Microstructural analyses confirmed that volcanic ash diminishes pore structure and matrix densification through pozzolanic reactions, forming calcium silicate hydrate (CSH) gels, also known as tobermorite gel, which is the core of PC-based concretes and is responsible for many of their strength and durability properties. An optimal mass replacement level of volcanic ash for PC was identified between 15% and 25%, balancing strength, workability, and sustainability. The reduction in PC cement usage, together with the beneficial incorporation of volcanic ash, offers a practical solution to lower atmospheric emissions and production costs. These findings support the application of volcanic ash-based soil-cement mixtures (SCMs) in infrastructure projects, particularly in volcanic regions. This approach promotes circular economy principles by transforming volcanic ash conventionally regarded as a low value waste material in to an environmentally viable construction resource.

**Keywords:** Strength percentage, compressive strength, Portland cement, carbon dioxide, circular economy.

## Introduction

Sustainable construction practices are essential to mitigate environmental impacts without sacrificing structural reliability. Soil stabilization techniques, especially those using soil cement mixtures, have proven effective for improving geotechnical properties in infrastructure projects<sup>1-3</sup>. However, the high carbon footprint associated with PC production drives the need for alternative solutions that maintain construction material performance while reducing construction costs. Volcanic ash, a natural pozzolanic material, can enhance SCMs by refining their microstructure and strengthening mechanical behaviour, offering a viable path toward sustainable geotechnical applications<sup>4-10</sup>.

Soil stabilization with cement is a standardized geotechnical engineering method for improving bearing capacity, reducing compressibility, and enhancing durability<sup>11-17</sup>. On the contrary, extensive PC use raises environmental concerns due to the CO<sub>2</sub> emissions generated during its production<sup>18</sup>. Incorporating volcanic ash into soil cement mixtures, MSCs, presents a promising alternative<sup>19</sup>, leveraging its pozzolanic reactivity to optimise PC hydration and improve mechanical properties<sup>20-22</sup>. Despite these potential benefits, research on the geotechnical behaviour of fluid soil cement volcanic ash mixtures remains limited, particularly regarding their classification, microstructural evolution, and compressive strength<sup>23</sup>. Addressing these research gaps is essential for advancing sustainable soil stabilisation practices.

Pozzolanic reactions have been extensively studied in cementitious systems, demonstrating their capacity to refine pore structure and enhance long-term mechanical properties<sup>24</sup>. While prior research has explored the influence of volcanic ash in conventional concrete and mortar applications, indicating improvements in strength and durability<sup>25,26</sup>, its role in soil stabilisation remains understudied<sup>27,28</sup>. Building on this background, the present study investigates how volcanic ash modifies interactions in MSCs, thereby contributing to a broader understanding of sustainable soil improvement techniques.

This study aims to evaluate the geotechnical performance of MSCs with varying PC contents, incorporating volcanic ash, PC, water, and admixtures. This research aims to determine the influence of volcanic ash on soil classification<sup>29</sup>, compressive strength, and microstructural properties, thereby assessing its suitability for geotechnical applications. The central hypothesis is that volcanic ash interacts with cement hydration products, refining the matrix structure and enhancing mechanical performance<sup>30,31</sup>, ultimately providing a cost-effective and environmentally responsible stabilization alternative.

The geotechnical behaviour of these mixtures is analysed using a methodology that includes soil classification under the Unified Soil Classification System (USCS), unconfined compressive strength (UCS) tests, and chemical characterisation with X-ray fluorescence (XRF) and X-ray diffraction (XRD) to evaluate material composition and performance<sup>32–34</sup>. To contribute to the field of geotechnics and material strength involving volcanic ash based soil cement<sup>35,36</sup>, this work assesses the mechanical properties of mixtures of ash, cement, water, and admixtures using 192 cylindrical specimens prepared with volcanic ash from the Paricutin volcano in Michoacan, Mexico. The findings of this study contribute to optimising sustainable soil stabilisation practices, providing valuable insights for engineers seeking to balance performance, cost, and environmental responsibility in construction applications.

## Results

For this research, volcanic ash, from the Paricutin Volcano<sup>37</sup> was used, following the testing program outlined in Table 1. Based on the Unified Soil Classification System (USCS), it is classified as silty sand (SM). Its index properties, were: specific gravity soil solids  $G_s=2.46$ , maximum dry density of the soil  $\gamma_{dmax}=15.69$  kN/m<sup>3</sup>, optimum moisture content=19.19%, California bearing-ratio CBR=30%, liquid limit LL=Not appreciable (INAP), plastic limit PL=Not appreciable (INAP), behaving as a friction, inert, non-cohesive material, according to Table 2 and figure 5.

The CP used was a gray cement from the brand CEMEX, Tolteca Extra CPC 30R, in accordance with NMX C 414 ONNCCE. Likewise, a MAXEh brand additive was employed. It is an additive that, when mixed with inorganic, silty sandy soils, PC, and water, produces a resistant construction material. The main differences lie in the characteristics of the aggregate and in the way the MAXEh additive influences the adhesion and hardening (petrification) of the mixtures.

The optimum mass percentage of PC for a fluid soil cement mix without the MAXEh additive, under saturated conditions is 15.80%, which meets the design strength of 2.45 MPa (design load 5126.80 N) and the resistance percentage (100%). The optimum PC percentage for a fluid soil cement mix without the MAXEh additive, under unsaturated conditions, is 13.85%. Additionally, the optimal mass percentage of CP for a fluid soil-cement mixture with 0.5% MAXEh additive was determined, under saturated conditions, is 17.58%, which meets the design strength of 2.45 MPa. For specimens under unsaturated conditions, it is 16.58%.

The best performance in terms of PC consumption is observed in the unsaturated specimens. Based on the standard NMX-C-441-ONNCCE-2013<sup>38</sup>, it complies with the requirements for artisanal brick type, non-structural use (minimum strength 2.35 MPa).

For the standard NMX-C-404-ONNCCE-2012<sup>38</sup>, for the solid brick type, structural use with a minimum strength of 6.86 MPa, in this case it complies using an optimum mass percentage of PC of 30%. For the standard NMX-C-486-ONNCCE-2014<sup>39</sup>, for Mortar Type III, structural use with a minimum strength of 3.92 MPa, in this case, it complies by using an optimum cement percentage of 22% by mass.

Finally, this article aims to promote the use of volcanic ash as a construction material, in this particular case as an aggregate for fluid soil-cement. Once the MSCs mixtures were prepared for each mass percentage of PC, specifically for 5%, 10%, 15%, 20%, 30%, and 40%, and the specimens with and without the MAXEh additive were fabricated, the following behaviour was observed: for unsaturated specimens, the loads, percentages, and strengths are higher than for saturated specimens, which is consistent with the results. Figure 1 show the behaviour of the different specimens with the aforementioned additive percentages.

**Table 1.** Testing program

| n  | Soil         | Cement | Additive (%) | Curing Conditions | Duplicated test |
|----|--------------|--------|--------------|-------------------|-----------------|
| 48 | volcanic ash | 6      | 0 and 0.5    | sat/unsat         | A and B         |

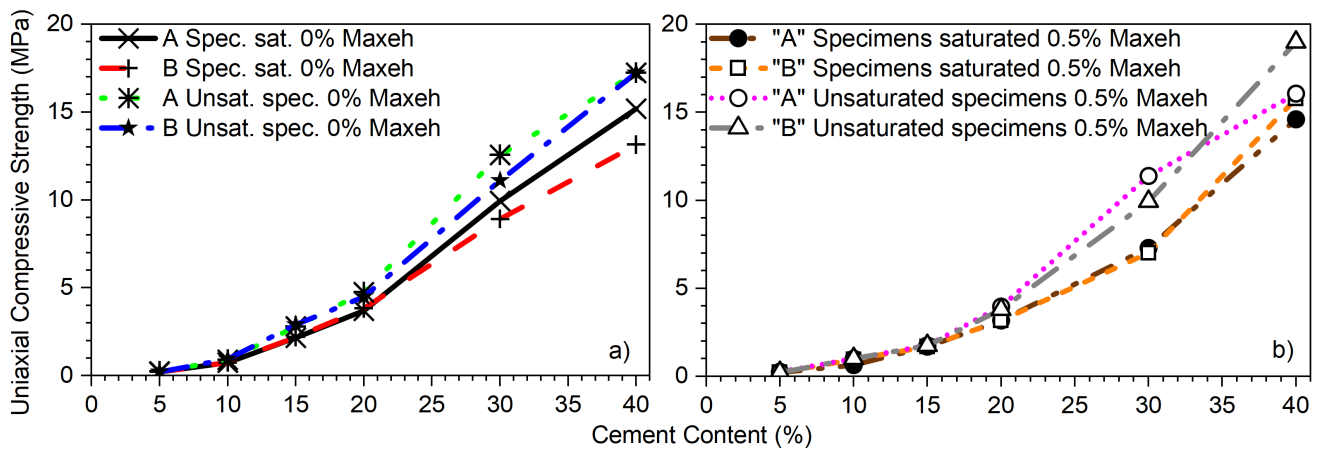
Cement (5%, 10%, 15%, 20%, 30% and 40%), A=4 test (3, 7, 14 and 28 days), B=4 test (3, 7, 14 and 28 days)

## Discussion

The volcanic ash in this research, referred to as soil, according to its particle size distribution, is classified as silty sand (SM), according to the USCS. According to the results, it is suitable for producing fluid soil-cement mixes because, in its hardened state, it meets the strength requirements specified by the Mexican standards NMX-C-441-ONNCCE-2013<sup>40</sup>. For this reason,

**Table 2.** Index properties of soil or soil quality<sup>1</sup>

| Soil properties                                                       | Value |
|-----------------------------------------------------------------------|-------|
| Specific gravity                                                      | 2.46  |
| Grain size analysis                                                   |       |
| Gravel (%)                                                            | 0     |
| Sand (%)                                                              | 85    |
| Silt (%)                                                              | 14    |
| Clay, particle size <0.002 mm (%)                                     | 1     |
| Consistency limit                                                     |       |
| Liquid limit (%)                                                      | INAP  |
| Plastic limit (%)                                                     | INAP  |
| Plastic index (%)                                                     | 0     |
| Density of the soil                                                   |       |
| Minimum dry density of the soil, $\gamma_{dmin}$ (kN/m <sup>3</sup> ) | 14.37 |
| Maximum dry density of the soil, $\gamma_{dmax}$ (kN/m <sup>3</sup> ) | 15.69 |
| Optimum moisture content (%)                                          | 19.19 |
| Soil expansion (%)                                                    | 0     |
| CBR (%)                                                               | 30    |
| USCS Classification                                                   | SM    |

**Figure 1.** Unconfined compressive strength test (MPa) at 28 days<sup>1</sup>

this study aims to promote the use of volcanic ash as a construction material for manufacturing: fluid soil-cement bricks, fluid soil-cement retaining walls, and restoration mortars for historical monuments, as well as for cyclopean mortars and cyclopean soil-cements, among other applications.

Despite its limitations for predicting mechanical behavior, the USDA textural classification system remains a highly viable and useful tool for the preliminary characterization of Parícutin volcanic ash. By accurately placing the aggregate within the loamy sand class (85% sand, 14% silt, and 1% clay), this system provides a standardized and intuitive physical description based on particle-size distribution. This granulometric characterization greatly facilitates the initial assessment of the potential compactability of the matrix in flowable soil-cement mixtures. Rather than being obsolete, the USDA soil texture triangle provides a universally recognized and readily accessible framework that, when combined with Atterberg limits, enables efficient and reproducible preliminary screening of precursor materials for geotechnical engineering and the development of sustainable, low-cost construction materials.

Furthermore, another potential application is in the archaeological zones of the Malpaís, where pyramids are located. These structures require a binding material to join pieces of basic extrusive igneous volcanic rock (basalts) and carry out restoration work. Finally, the structural properties of soil cement depend mainly on the type of soil (preferably an inert or non-cohesive silty sand), the type of PC, the type of additive, and the curing conditions. Therefore, the intention is to continue researching soil cement mixes for the restoration of the aforementioned archaeological zones, following the intervention guidelines established

in Mexico by the National Institute of Anthropology and History (INAH).

## Methods

To systematically evaluate the feasibility of volcanic ash-derived soils for flowable fill applications in restoration contexts, we designed an experimental framework comprising three sequential phases: material characterisation, mechanical testing, and performance optimisation. The methodology integrates field sampling, laboratory synthesis of MSCs, and analysis based on mechanical compressive strength to determine optimal compositions that meet the structural requirements for the conservation of historical monuments.

**Phase 1: Literature review** A comprehensive review of soil cement slurry (flowable fill) SCMs technology was conducted, examining its origins, development, and applications in construction practices.

**Phase 2: Experimental program** **Sample collection and characterisation:** Field samples were collected from the extraction site for laboratory testing. Index properties and material quality were determined through standard geotechnical tests.

**Mix preparation and curing:** The SCM soil-cement slurry mixtures were prepared using PC from the brand CEMEX (Tolteca Extra, CPC type with 30R strength) and the MAXEh additive. Specimens were fabricated under both saturated and unsaturated conditions.

**Mechanical testing:** Unconfined compression tests were performed on specimens cured for 3, 7, 14, and 28 days.

**Phase 3: Analysis and application assessment** Geotechnical test results and unconfined compressive strength data were analysed to determine the optimal cement content. The target strength was set at a minimum of 2.45 MPa. The feasibility of applying the optimised mixture to historical monument restoration was evaluated.

## Material sampling

The soil Samples, consisting of volcanic ash, were collected randomly throughout the site near the Paricutin volcano, as the area exhibited homogeneous geotechnical characteristics throughout. The material was placed in polypropylene bags and transported to the Soil Mechanics Laboratory within the Materials Laboratory at Universidad Michoacana de San Nicolas de Hidalgo for subsequent analysis. The total mass sample collected from the field trip was 170kg, sufficient to conduct all planned laboratory tests.

The material used in this project is a soil composed of volcanic ash. It originates from the area of the ruins buried by the lava of the Paricutin Volcano<sup>41–45</sup>. In the Purhepecha language, its name derives from the word parhikutini, meaning "place on the other side"<sup>46</sup>. It is associated with the villages of San Juan Viejo Parangaricutiro and San Salvador Combtzio, in the municipality of Uruapan, Michoacan, Mexico. Physiographically, it is located within the Trans-Mexican Volcanic Belt province, in the Purepecha Plateau region.

The soil was sampled using a shovel and stored in raffia sacks for transport to the laboratory, where quality tests were performed. Figure 2 shows the location sketch and the sampling site.



**Figure 2.** Panoramic view of the Paricutin Volcano and site for material extraction and storage in raffia sacks<sup>1</sup>

## Index property determination

The extracted material was spread and air-dried at ambient temperature in the drying yard. Quartering was subsequently performed to obtain representative samples for geotechnical testing figure 3. Index properties were determined following standard procedures, including: natural moisture content, grain-size distribution, see figure 5, Atterberg limits, dry unit weight, maximum dry unit weight, and specific gravity of solids. Chemical composition was analysed by wavelength-dispersive X-ray fluorescence (WDXRF) spectroscopy using a BRUKER AXS S8 TIGER spectrometer (certified under QUALITATS MANAGEMENT SYSTEM ISO 9001:2008, Reg. Nr. 052928 QM08), in accordance with ASTM E1621-22<sup>47</sup>, Table 3.

The United States Department of Agriculture (USDA) Soil Textural Classification<sup>48</sup>, presented in Figure 6, provides a strictly physical description based on the particle-size distribution of the fine-earth fraction (<2 mm). Under this classification scheme, the fine-earth fraction is divided into three fundamental particle-size classes: sand (50–2000 µm), silt (2–50 µm), and clay (<2 µm)<sup>48,49</sup>. For the Paricutin volcanic ash, laboratory particle-size analyses revealed a composition of 85% sand, 14% silt, and 1% clay (particles <0.002 mm). When these percentages are plotted on the USDA soil texture triangle (Figure 6), the volcanic ash sample falls within the loamy sand (LoSa) textural class, located near the base of the triangle and adjacent to the boundary of the sand (Sa) class<sup>49</sup>. According to the USDA Soil Survey Manual, loamy sand is defined, among other criteria, by a sand content ranging from approximately 70 to 90%, and the percentage of silt plus 1.5 times the percentage of clay is equal to or greater than 15% ( $\text{Silt} + 1.5 \times \text{Clay} \geq 15\%$ )<sup>48</sup>. Applying these criteria to the experimental data obtained for the volcanic ash gives:

Sand=85% (within the 70–90% range)

$\text{Silt} + 1.5 \times \text{Clay} = 14\% + 1.5 \times 1\% = 15.5\% (\geq 15\%)$

This quantitative agreement confirms the graphical assignment of the sample to the loamy sand domain of the USDA textural classification<sup>48</sup>. Nevertheless, the USDA textural classification has important conceptual limitations when applied to the assessment of mechanical behavior in geotechnical engineering and materials science. Particle-size-based classification systems implicitly assume that the fine fraction (<2 µm) exhibits the plasticity and cohesive properties inherently associated with clay minerals; however, this assumption is physically incorrect and may lead to critical classification errors<sup>50</sup>. In the specific case of this volcanic ash, mineralogical characterization by X-ray diffraction (XRD) indicates that the material consists predominantly of anorthite (59.9%), albite (39.0%), and quartz (1.1%), with no detectable active phyllosilicate or clay-mineral phases. Therefore, the presence of 1% of particles smaller than 2 µm is attributable to the extreme physical fragmentation of quartz and feldspar particles during volcanic activity rather than to the presence of plastic clay minerals. This mineralogical distinction explains why, despite containing minor proportions of silt- and clay-sized particles according to the USDA classification, the material exhibits negligible intrinsic cohesion and non-plastic behavior (NP). From a geotechnical perspective, it is therefore classified as silty sand (SM) according to the Unified Soil Classification System (USCS). The non-plastic fines contribute to a predominantly frictional response and facilitate effective compaction<sup>50</sup>. This distinction is particularly relevant to understanding the behavior of flowable soil–cement mixtures incorporating volcanic ash. The strength development associated with pozzolanic reactions does not arise from clay-induced cohesion; rather, it is governed by the reactivity of volcanic glass and reactive aluminosilicate phases with the hydration products of Portland cement (PC), leading to the formation of calcium silicate hydrate (C–S–H) and related calcium aluminosilicate hydrate phases. Thus, while the USDA textural classification (Figure 6) provides a standardized physical description of particle-size distribution, the complementary engineering characterization based on the USCS classification (SM) and Atterberg limits provides a more meaningful basis for interpreting the material's mechanical behavior and its suitability for low-cost, sustainable flowable soil–cement mixtures. The distinction between particle size and plasticity is also consistent with the broader scientific discussion in clay-mineral classification, in which plasticity is regarded as a more appropriate diagnostic property than particle size alone for identifying clay-like behavior.

**Table 3.** Chemical composition of Paricutin volcanic ash determined by X-ray fluorescence (XRF) spectroscopy using a BRUKER AXS S8 TIGER spectrometer.

| Component Unit | SiO <sub>2</sub> (%) | Al <sub>2</sub> O <sub>3</sub> (%) | Fe <sub>2</sub> O <sub>3</sub> (%) | CaO (%) | MgO (%) | TiO <sub>2</sub> (%) | K <sub>2</sub> O (%) | Na <sub>2</sub> O (%) | P <sub>2</sub> O <sub>5</sub> (%) | MnO (%) | SrO (%) |
|----------------|----------------------|------------------------------------|------------------------------------|---------|---------|----------------------|----------------------|-----------------------|-----------------------------------|---------|---------|
| Content        | 48.40                | 15.70                              | 15.20                              | 11.20   | 2.30    | 1.80                 | 1.77                 | 1.66                  | 1.37                              | 0.22    | 0.16    |

| Component Unit | ZnO (ppm) | ZrO <sub>2</sub> (ppm) | MoO <sub>3</sub> (ppm) | BaO (ppm) | Rb <sub>2</sub> O (ppm) |
|----------------|-----------|------------------------|------------------------|-----------|-------------------------|
| Content        | 286       | 241                    | 76.1                   | –         | –                       |

### Preparation of specimens for X-ray diffraction analysis

X-ray diffraction (XRD) analysis was performed to determine the crystalline phases present in the sample; results are shown in figure 4. For natural materials, the presence of  $\text{SiO}_2$  in its quartz phase is common, alongside feldspars such as albite ( $\text{NaAlSi}_3\text{O}_8$ ) and anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ), and clay minerals including illite ( $(\text{K},\text{H}_3\text{O})(\text{Al},\text{Mg},\text{Fe})_2(\text{Si},\text{Al})_4\text{O}_{10}[(\text{OH})_2,(\text{H}_2\text{O})]$ ). As shown in figure 4, only quartz, albite and anorthite phases were identified in the volcanic material. Peaks beyond  $60^\circ$  in  $2\theta$  were not assigned to specific phases due to database limitations, as reference cards for clay minerals typically report only low-angle reflections. The quantification of each crystalline phase is reported in Table 4.

Phase quantification reveals quartz as the dominant crystalline component, consistent with the siliceous nature of volcanic ashes<sup>27</sup>. The absence of detectable clay minerals, despite their common occurrence in natural soils, may reflect either concentrations below the XRD detection limit or the aforementioned database limitations at higher diffraction angles. This mineralogical assemblage aligns with previously reported compositions for volcanic-derived geomaterials in the region<sup>25</sup>, though with distinct proportions, particularly in the albite-to-anorthite ratio.



**Figure 3.** Index properties were determined following standard geotechnical procedures, including: natural moisture content, grain-size distribution, specific gravity of solids, and soil unit weights<sup>1</sup>

### Preparation of specimens with fluid soil-cement and MAXEh additive

To determine the optimal mass percentage of fluid soil-cement, several mixtures with varying cement percentages were prepared. Specifically, mixtures were produced with cement contents of 5%, 10%, 15%, 20%, 30%, and 40%. For each of these fluid soil-cement mixtures, multiple specimens were fabricated. The fluid soil-cement mixture SCMs consisted of a soil—in this case, the volcanic ash—Portland grey cement (CEMEX Tolteca Extra CPC 30R), and the MAXEh additive (Figure 7), in accordance with the Mexican standard NMX-C-159-ONNCCE-2016<sup>51</sup>. Furthermore, the slump was determined following the Mexican standard NMX-156-ONNCCE-2010<sup>52</sup>. The cylindrical specimens produced measured 5 cm in diameter and 10 cm in height. For each mixture and PC percentage, 8 specimens were made. These were tested as follows: 2 specimens to determine compressive strength at 3 days of curing, a further 2 specimens at 7 days, another 2 at 14 days, and the final 2 at 28 days of curing. Duplicate specimens were prepared because soils are inherently variable; this duplication ensured sufficient specimens for a reliable determination of strength and mitigated the risk of anomalies in individual specimens. Compressive strength testing was also conducted according to standard NMX-083-ONNCCE-2014<sup>53</sup>. In this investigation, specimens were studied under both saturated and unsaturated conditions (as soil behaviour varies significantly with saturation); that is, the effect of curing conditions on the strength of the fluid soil-cement was investigated. Saturated specimens were submerged in tap water (curing in tap water, TW), whereas unsaturated specimens were not submerged; instead, they were cured by wrapping them in moist plastic bags (curing in plastic wrapping, PW)<sup>54</sup> until the testing date, see figure 8.

### Unit Cost Analysis of Fluid Soil-Cement Specimen Manufacturing

A direct economic cost analysis was conducted to evaluate the feasibility of using fluid soil-cement as an alternative construction material, considering current prices as of June 2026. The study focused exclusively on material costs, excluding labor, machinery, and equipment, with an exchange rate of MXN 17.52 per USD 1.00 as of 26 June 2026. The methodology consisted of determining the volume of aggregates required for each mixture, calculating the proportions of soil, cement, additive, and water based on their densities and unit masses. Subsequently, the unit price per piece of each component was analyzed, including the unit cost of Portland cement per unit mass, which allowed the total material cost per unit to be obtained. Finally, the expenses associated with the manufacturing of the fluid soil-cement were accounted for. The comparison of unit costs between a conventional mortar mixture (mortar-sand 1:6) and the fluid soil-cement mixtures with various material combinations is shown in Figure 9. The results indicate that reductions in Portland cement consumption and additive usage have a direct impact on lowering the unit cost. The mixture with the optimal cost corresponds to a Portland cement content between 10% and 15%, which achieves a minimum compressive strength of 2.4 MPa. The use of fluid soil-cement with reduced Portland cement contents represents an economically viable option, achieving competitive unit costs compared to traditional mortar, without compromising the mechanical performance required for non-critical structural applications.

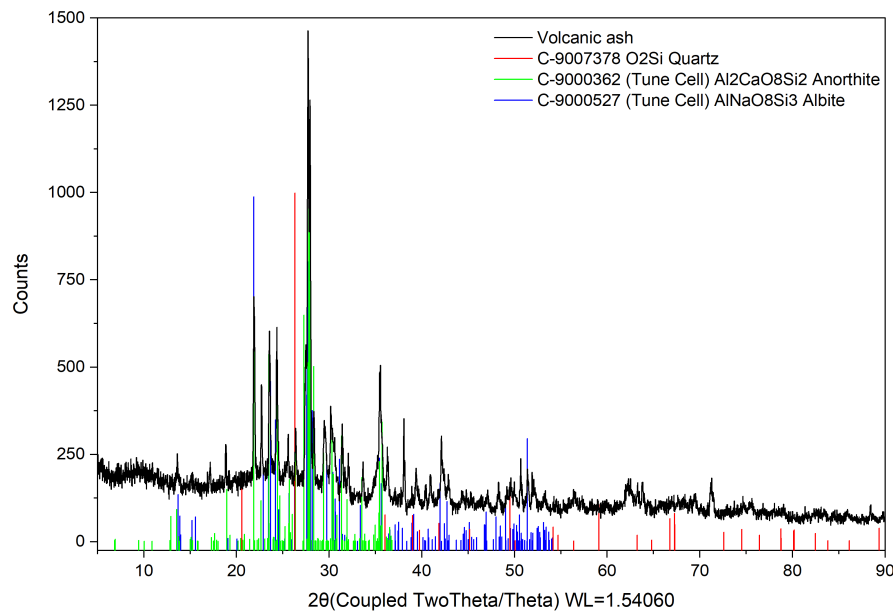


**Figure 4.** X-ray diffraction (XRD) pattern of volcanic ash from the Parícutín volcano.

**Table 4.** Mineralogical composition of volcanic ash from Parícutín volcano.

| Crystalline phase                                  | Mass (%) |
|----------------------------------------------------|----------|
| Quartz ( $\text{SiO}_2$ )                          | 1.1      |
| Albite ( $\text{NaAlSi}_3\text{O}_8$ )             | 39.0     |
| Anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ) | 59.9     |

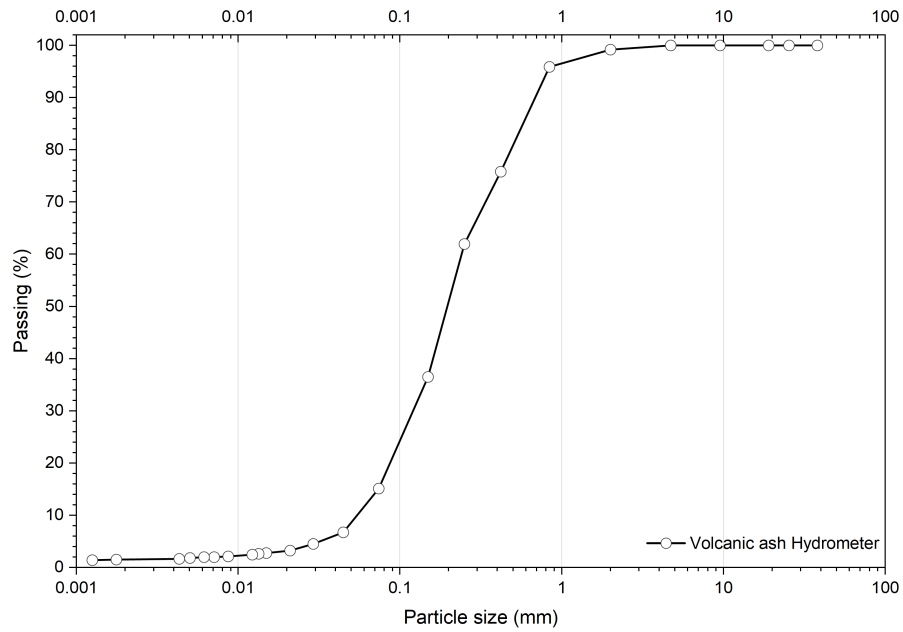


**Figure 5.** Soil quality with the geotechnical parameters of the index properties (N-CMT-4-02-002/22, 2023)<sup>1</sup>

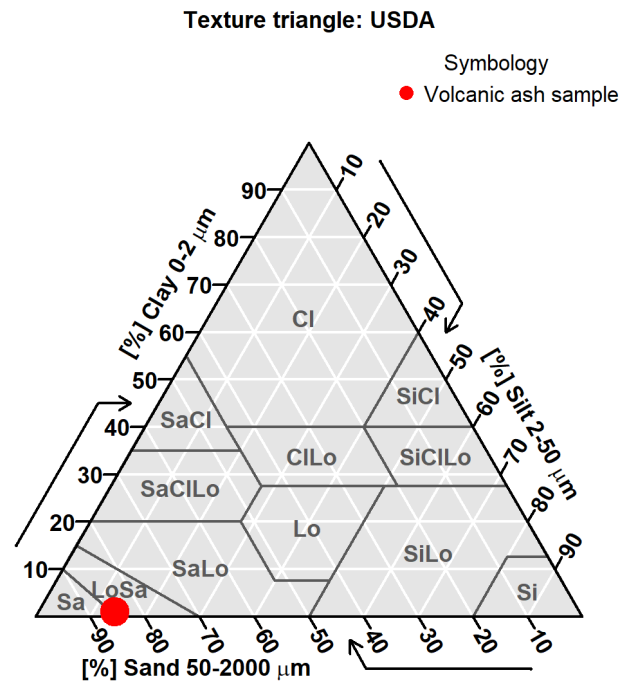


**Figure 6.** Soil classification according to the USDA Soil Classification System



**Figure 7.** Mix with the additive for obtaining soil-cement samples<sup>1</sup>

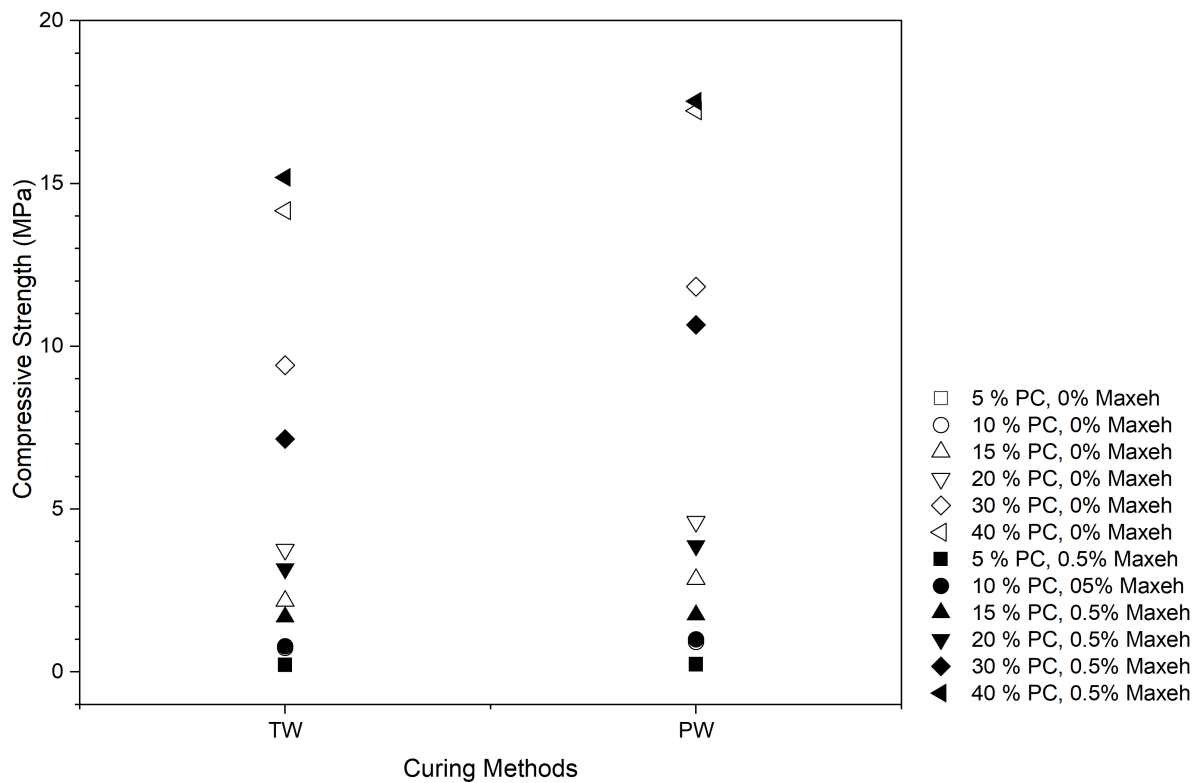


**Figure 8.** Compressive strength of soil-cement samples at 28 days, with curing in tap water (TW) and curing in plastic wrapping (PW)<sup>1</sup>

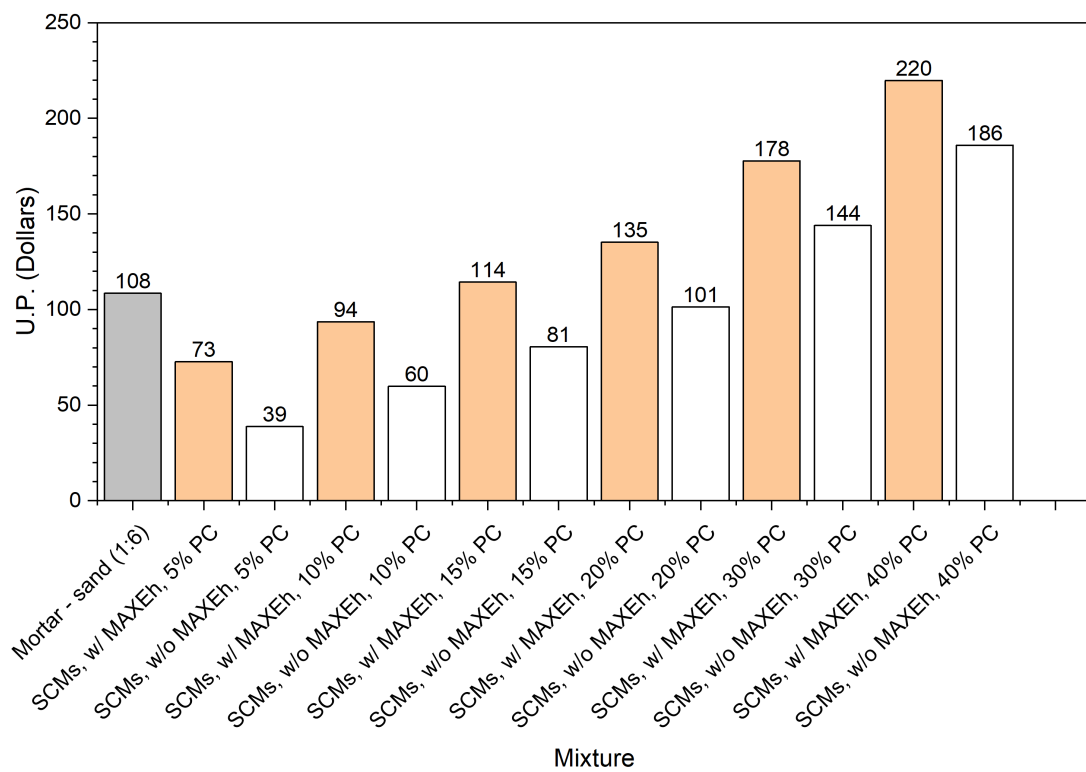


**Figure 9.** Comparison of the unit price of the study mixtures without considering labor costs

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## Author contributions statement

F. J. J-R.: writing and testing, V. L-L.: testing, W. M-M.: reviewing, E. M. A-G.: conceptualization, A. I. C-S.: writing original draft, H. L. C-G.: methodology, M. A. N-S.: supervision, M. A-S.: editing. All authors reviewed the manuscript.

## Competing interests

The authors declare no competing interests.

## Data Availability

Full data availability and author contribution statements are included in the manuscript file, and is also available upon request to the author.