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Mechanical Performance of Volcanic Ash Concrete Showing Modulus Reduction with Strength Retention

Carlos Pinto-Almeida [1], Andrés Abril-Camino [1*], Daniel Abril-Camino [2]

[1] Faculty of Engineering, Universidad Tecnológica Indoamérica, Agramonte, Ambato 180204, Ecuador.

[2] Faculty of Engineering, Universidad San Francisco de Quito, Diego de Robles, Quito 17901, Ecuador.

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Abstract

This study aims to evaluate the mechanical behavior of concrete that incorporates 51.3% raw volcanic ash into its structure, focusing on its static elasticity modulus and compressive strength. Cylindrical concrete samples were prepared via the mix design commonly used in practice in Baños, Tungurahua, Ecuador. Three curing methods were applied: immersion, water spraying, and no curing. Compressive strength tests were conducted at 3, 7, 14, 21, and 28 days, whereas the static modulus was measured at 28 days following ASTM C469. Despite the high use of ash in the mixture, the mixtures achieved adequate compressive strengths for structural applications, reaching 28.05 MPa. However, a significant reduction in the static modulus was observed, with experimental values of approximately 7.06 GPa, whereas the value of 24.89 GPa was predicted by the equations given in ACI318. The use of raw volcanic ash in structural mixes requires modifications to deformation and stiffness calculations to ensure seismic performance, suggesting the need to review local regulations on traditional mixes. Based on the experimental data, an alternative empirical model, the VAM model, was proposed to better predict the elastic modulus of concrete with high volcanic ash content. The findings reveal a dual function of ash, acting as a pozzolanic material and as a low-density aggregate, highlighting the need to adjust the design equations when raw volcanic ash is used. This work contributes to the sustainable design of concrete mixtures in seismic regions.

Keywords: Elastic Modulus; Concrete Resistance; Volcanic Ash; Modulus; Stress–Strain Curve.

1. Introduction

Concrete is one of the most widely used materials in construction [1]. It is used for its mechanical, physical, chemical, and thermal properties, which make it present in buildings, bridges, pavements, and dams [2]. Its characteristics, such as compressive strength, fire resistance, and ability to protect reinforcing steel, make it a widely used material in construction around the world [3]. In Ecuador, concrete is the most widely used construction material, according to the National Building Survey by the National Institute of Statistics and Censuses (INEC) [4]. Local regulations govern the quality, strength, and curing time of concrete depending on the type of cement used. However, there are processes in which there are no regulations for concrete mixed design. In certain cases, the regulations include control procedures that are limited to the extraction and testing of concrete cores to verify the in situ strength against the design specifications. Nonetheless, even under these frameworks, there are cases where there is a complete lack of oversight due to clandestine construction and informal building practices [5].

In Tungurahua Province, which is characterized by volcanic activity from homonymous volcanoes, volcanic ash is widely incorporated into concrete mixtures [6], mainly for economic reasons and local availability. Previous

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* Corresponding author: andresabril@uti.edu.ec

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studies have shown that volcanic ash can act as a pozzolanic material, improving long-term durability, reducing permeability, and contributing to the sustainable development of concrete [7-9]. In the studies presented, the use of ash is typically limited to partial replacement in proportions usually below 30%, often with processed or calcined additions to maximize its reactivity. In the present study, raw volcanic ash—without calcination—was used in a mixture with 51.3% cement replacement, [10] and its mechanical performance was evaluated, especially with respect to the modulus of elasticity of hardened concrete. Despite the high replacement level, the design-required strength was maintained in the fabricated cylindrical samples, which raises questions about the optimal structural design when a minimum strength that can be achieved with this mixture is specified. However, a deeper evaluation of its physical and chemical properties is needed.

Since the required strength specified by the structural designer is maintained, an examination of the characteristics of the concrete developed by adding this ash is needed. In Chapter 19.2.2.2, local regulations and ACI 318 present two mathematical expressions to determine the static modulus of concrete: one for typical weight concrete and the other for a lightweight mix [10]. The measured value depends on the compressive strength in the case of a typical mix and on both the compressive strength and density of lightweight concrete [11].

Young's modulus, or the static modulus of elasticity, is an essential characteristic of the concrete mix that describes the stiffness or resistance to elastic deformations of a material [12]. In a seismic region such as Ecuador, it is a crucial factor when performing seismic-resistant structural design, which is generally determined via the equations provided by local regulations for concrete [13].

This study aims to assess the elastic modulus of concrete containing a high proportion of volcanic ash in its mixture [14]. This study aims to analyze the correspondence between the experimentally obtained results and the expressions proposed in this study, as well as those established by local and international standards. Additionally, the evolution of the concrete strength over the curing time is examined to identify the mechanical development of the material at different ages. The behavior of volcanic ash is analyzed not only as a supplementary cementitious material but also in its functional transition toward the role of an aggregate.

In the study *"Effect of Volcanic Ash on the Properties of Cement Paste and Mortar"* [15], it was established that volcanic ash, owing to its pozzolanic effect, can partially replace cement because of its binding properties. However, the scope of that research was limited to mortar, with a focus on comparisons between volcanic ash mortar and cement mortar. The present article extends the analysis to concrete, not only mortar but also coarse aggregate, and compares the compressive strength and elastic modulus of conventional concrete and lightweight concrete with the elastic modulus of the new concrete incorporating volcanic ash.

In the article *"Mechanical Properties of Volcanic Ash-Based Concrete"* [16], it is established that up to 25% of cement can be replaced with volcanic ash. This study considers an analysis of the compressive strength of concrete with varying replacement percentages of ash; however, key factors, such as the elastic modulus, which directly influences the stiffness of structural elements, are not addressed in terms of providing data on the static elastic modulus of volcanic ash concrete. Instead, the research has focused primarily on sustainability as well as the potential of the material as an alternative to conventional concrete. The present study proposes a methodology for the determination and evaluation of concrete incorporating volcanic ash.

Research *"Strength, Durability and Microstructural Aspects of High-Performance Volcanic Ash Concrete"* [17] is consistent with the findings presented in this research, namely, that the incorporation of volcanic ash reduces the compressive strength of concrete and that volcanic ash concrete requires longer curing periods than conventional concrete does. Therefore, this work may serve as a foundation for future studies aimed at determining the relationship between the percentage of volcanic ash incorporated and the curing time required to achieve adequate compressive strength.

This research article was structured by first determining the empirical use of concrete with volcanic ash as a fine aggregate. A review of previous studies on the use of volcanic ash in concrete was subsequently conducted, with a focus on aspects such as strength, testing methods, and results obtained by other authors. The methodology involved obtaining materials from the region to ensure similar physical and mechanical properties of gravel, cement, sand, ash, and water, which were used in the preparation of the concrete test samples. The mix design was based on surveys conducted with constructors, engineers, and workers. At this stage, the materials were characterized through granulometric analysis and ASTM soil classification.

The methodology also included testing the concrete samples, which were subjected to different curing times—some in curing pools and others without curing. Comparisons were then made with formulas provided in the construction codes. A total of 24 cylindrical samples were tested via a hydraulic compression press in accordance with established standards. The results allowed comparisons between samples with different curing times, particularly in terms of compressive strength, stress–strain curves, and elastic zone characteristics.

Additionally, the static modulus of elasticity was compared among traditional concrete, lightweight concrete, and volcanic ash concrete samples. The test results were used to propose a trend through the volcanic ash modulus (VAM) model. On the basis of this tendency, an empirical equation was proposed to estimate the static elastic modulus of volcanic ash concrete. Finally, the discussion was developed considering the experimental results, the experience of the researchers, and the bibliography consulted, leading to the final conclusions of this study.

2. Research Methodology

The research methodology follows a systematic sequence designed to ensure the rigorous characterization and evaluation of volcanic ash as a partial replacement material in concrete. Initially, raw volcanic ash is collected and subjected to particle size analysis in accordance with ASTM C33, followed by physicochemical characterization through X-ray fluorescence (XRF) and X-ray diffraction (XRD) tests to identify oxides and mineral phases such as plagioclase and pyroxenes. A concrete mix design is subsequently developed, and test samples are prepared, incorporating controlled curing regimes. Mechanical testing is then conducted according to ASTM C39, assessing the compressive strength at 7, 14, and 28 days, as well as the elastic modulus at 28 days, with failure modes recorded and classified. The results are further analyzed through evaluation of the strength activity index (SAI), which provides insights into the pozzolanic reactivity of volcanic ash. Finally, statistical analysis and modeling are performed to compare the experimental outcomes with those of the ACI 318 equations, leading to the development of an empirical volcanic ash modulus (VAM) model that estimates the elastic modulus of volcanic ash concrete, thereby contributing to both theoretical understanding and practical applications in sustainable construction materials. Figure 1, shows the flowchart of the research methodology through which the objectives of this study were achieved.

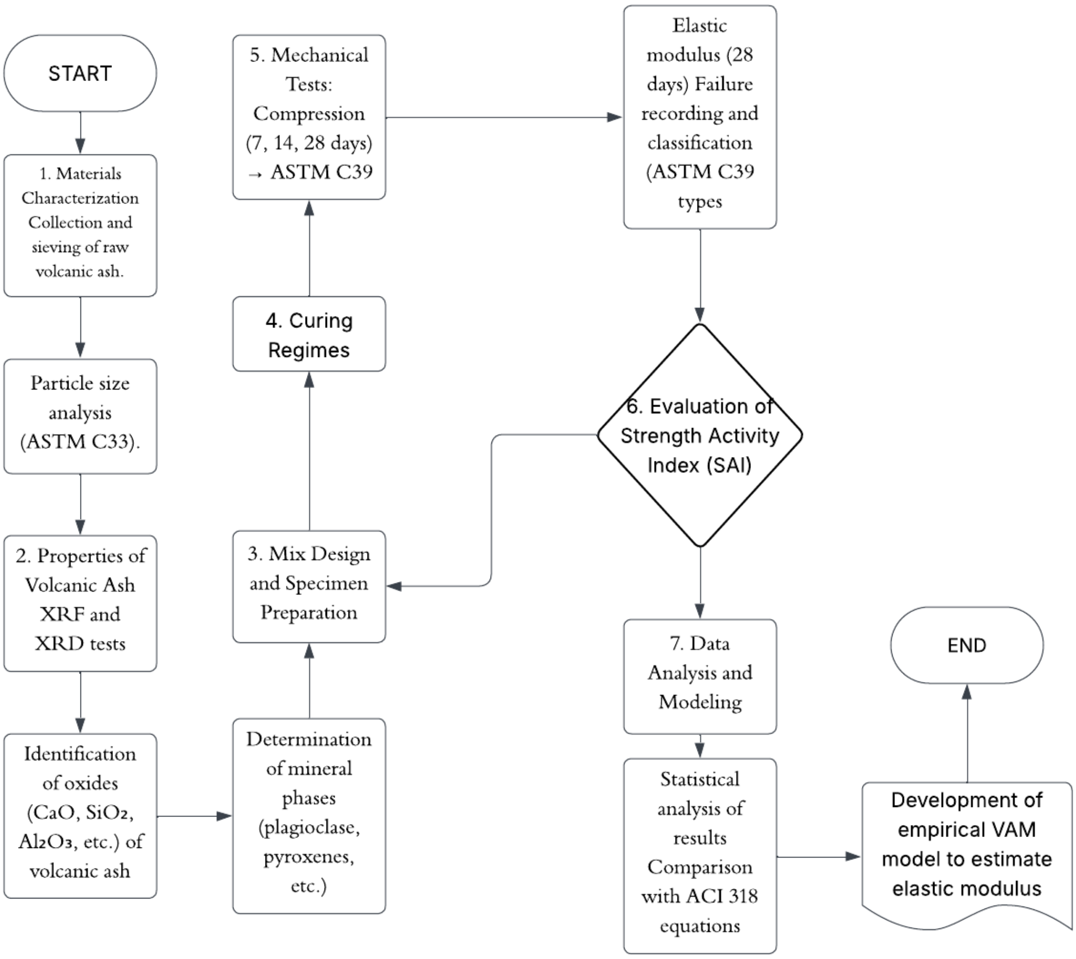


Figure 1. Workflow of the methodology used in the current research

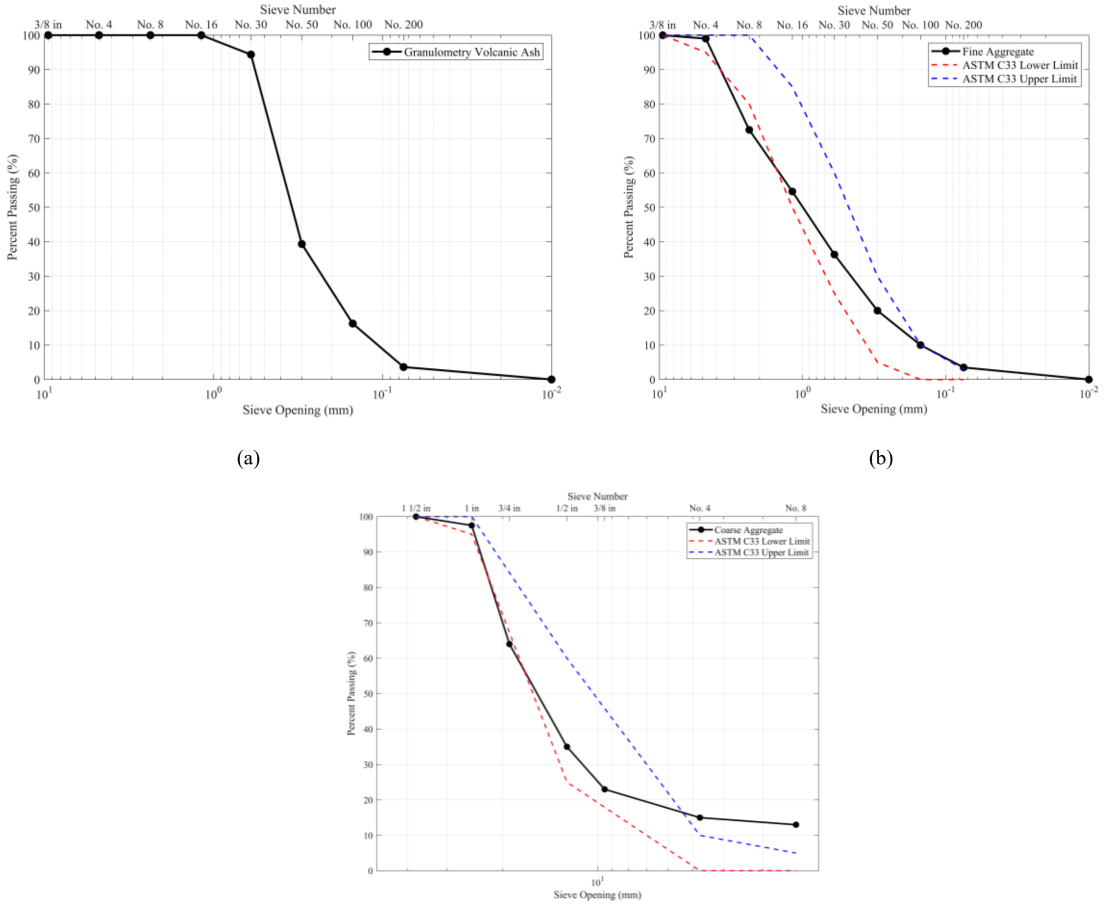
The present study was performed in three phases. The first stage examines the evolution of concrete strength over the curing time. For this purpose, 24 cylindrical samples with a diameter of 150 mm and a height of 300 mm were produced using a cement replacement of 51.3%, with the following mix design.

For the current study, the mix design used in the production of the samples is characterized by the high use of volcanic ash, as shown per cubic meter in Table 1.

Table 1. Mix design used per m³

Mix design per m³					
	Water	**Cement**	**Volcanic Ash**	**Fine aggregate**	**Coarse aggregate**
Mass (kg)	164.3	279.1	294.6	294.6	900.8

This mix design is similar to that used in construction projects in Baños - Tungurahua. The particle size distribution of the materials used is shown in the Figure 2, which details the following components.



(a)

(b)

(c)

Figure 2. Particle size distribution of the materials used: a) Volcanic ash b) Fine aggregate c) Coarse aggregate

2.1. Volcanic Ash

Volcanic ash is defined as a natural pozzolan produced by the fragmentation of magmatic rock during a volcanic eruption, where the particle size is less than 2 mm in diameter [18, 19]. When weathered, this material forms natural pozzolanic deposits of various colors ranging from light gray to black [19]. The type of ash used is Class N according to ASTM C618 (Table 2), as this type of ash is raw and of natural origin. [20].

Table 2. Classification, ASTM C 618 [20]

Categories of Fly Ash according to ASTM C618 standard		
CLASS		
N	Materials that require calcination to develop satisfactory properties	Raw or calcined pozzolans, chalks, and shales, calcined or uncalcined.
F	Fly ash possesses pozzolanic qualities.	Combustion of anthracite or bituminous coal. [20]
C	Fly ash possesses not only pozzolanic but also cementitious properties	Combustion of various coal types including lignite, sub- bituminous, anthracite, and bituminous.

Note: The total calcium content in Class C fly ashes is usually higher than that in Class F fly ashes.

2.2. Curing

The samples were subjected to three diverse types of curing: curing in a specialized curing pool (CP), curing by water sprinkling (like what is done at construction sites) (CRA), and not curing (SC). For the analysis, fifteen samples with different curing times and curing types were used: five samples cured in a curing pool, five samples cured by sprinkling water once every 8 hours, and five samples without any curing. Additionally, six extra samples were compressed over 28 days, resulting in a total of twenty-four samples. These samples underwent periodic compression tests at 3, 7, 14, 21, and 28 days.

During the curing phase, the ambient temperature and humidity were continuously monitored with a digital therm hygrometer located in the laboratories of Indoamérica University. The cylindrical CRA and SC samples were stored at an average temperature of 21 ± 2 °C and a relative humidity of 65 ± 5%. For the CRA samples, water was applied every 8 hours, with a volume of 750 mL per cylinder used in each spray.

2.3. Concrete Resistance

The compression test of the concrete samples allows for the evaluation of the mechanical strength of the material under axial loading [21]. To characterize the mechanical performance of concrete, deformation data were collected from each sample [22].

2.4. Elasticity Modulus (Static)

The second part of the study is based on obtaining the modulus of elasticity determined from the stress–strain curve of the mixture containing volcanic ash and cured for 28 days [23], as explained in ASTM C469 [24]. The tangent modulus is calculated from the stress–strain curve, and on the basis of the experimental data, a formula is proposed and compared with the expressions stated in the local regulations and ACI 3-18 [25, 26]. For this calculation, the method described in ASTM C469 was used, where the modulus of elasticity was calculated as [27]:

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - 0.000050} \tag{1}$$

The elasticity modulus, denoted as E, is determined via specific stress and strain values. σ_2 represents the stress corresponding to 40% of the ultimate load, whereas σ_1 corresponds to the stress at a longitudinal strain of fifty microstrains. The longitudinal strain produced by the stress σ_2 is represented as ε_2 [25, 26].

The Equation given by the ACI for determining the static elasticity modulus calculated according to the compressive strength of normal-weight concrete in MPa is as follows [28]:

$$E = 4700 \times \sqrt{f_c'} \tag{2}$$

For lightweight concrete:

$$E = wc^{1.5} \times 0.043 \times \sqrt{f_c'} \tag{3}$$

where E is the elasticity modulus (s) and wc = the density of the concrete [29].

In the third phase of the study, the chemical and mechanical attributes of the volcanic ash used as a supplementary cementitious material (SCM) were characterized, along with its potential behavior as a fine aggregate. The ash, sourced from the province of Tungurahua, exhibited fine granulometry, a porous texture, and a silica-rich composition—characteristics that give it a certain pozzolanic potential [30]. Under controlled curing conditions, 51.3% cement replacement with ash resulted in a compressive strength of up to 28.05 MPa, meeting conventional structural requirements. This difference suggests a dual role of the ash within the mixture: while it contributes to the mechanical strength, its physical behavior reduces the structural stiffness of the concrete.

3. Results

3.1. Average Density of the Samples

The pressure method of ASTM C231 was employed to determine the air content [31]. The air content in the mixture was 2.4%, and the applied dosage was used. After the samples were prepared, their weights were recorded before being subjected to axial loading in the compression machine, with an average weight of 9.71 kg. The average density of the samples is 1831.58 kg/$m^{3.}$

3.2. Evolution of the Compressive Strength Over Time

Although fly ash demonstrates compressive behavior superior to that of volcanic ash, a reduction in the cement content inevitably results in a decrease in the compressive strength [32]. Furthermore, as the replacement level of fly ash increases, the strength development of the material tends to diminish. Consequently, compared with conventional concrete, volcanic ash concrete has an even lower compressive response [33].

The cylinders made with a 51.3% replacement of cement with raw volcanic ash achieved compressive strengths of up to 28.05 MPa at 28 days, meeting the minimum structural design requirements for conventional concrete (see Figure 3). During the early ages (3–14 days), a slower strength development was observed, especially in the samples without curing, where the increase practically stabilized after 14 days. This behavior aligns with reports by Oner *et al.* (2005) [7] and Nayak *et al.* (2022) [9], who indicate that uncooked natural pozzolans show limited initial reactivity, acting partly as fine aggregates until the pozzolanic reactions progress.

The samples with pooled curing (PC) had the greatest strength growth, highlighting the importance of maintaining continuous hydration conditions to activate the ash–calcium hydroxide ($Ca(OH)_2$) reaction. In contrast, the samples without curing (NC) reached only approximately 70% of the maximum strength achieved by the PC group, confirming that the volcanic ash matrix is more sensitive to moisture loss than ordinary concrete is. This finding aligns with the observations of Mohamad *et al.* (2020) [30], who reported that the microstructure of concrete with natural ash is more porous and requires greater water retention to develop stable hydration products. Once the samples were prepared, their compressive strength was recorded periodically for three samples for each curing method [34].

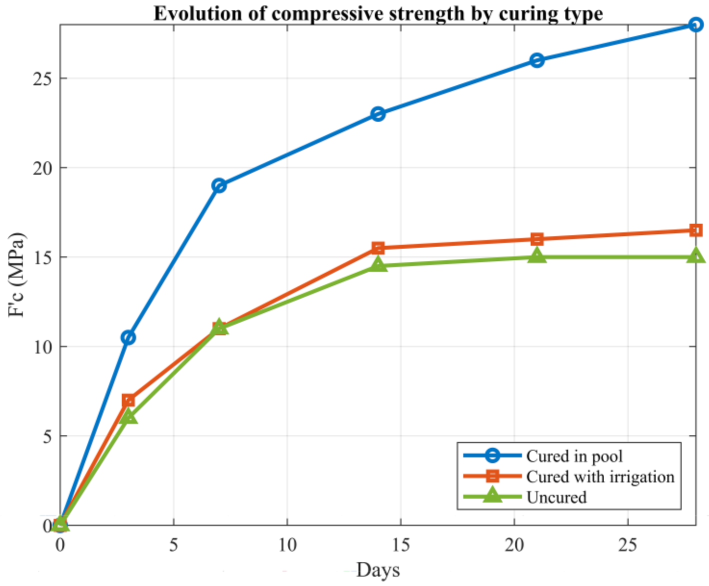


Figure 3. Compression resistance (MPa) vs. time (s)

The failure patterns exhibited by the cylindrical samples correspond to types 1, 2, 3 and 6, according to the classification established in the ASTM C39 standard. Among the samples cured in a pool (CP), the type 1 pattern (compression cone) predominated, characterized by the formation of a defined cone at the ends of the cylinder. This type of failure indicates that the load was distributed relatively evenly across the cross-section. The samples subjected to spray curing (CRA) exhibited failures of types 2 and 3, indicating a slightly more heterogeneous response in the compressed zone (see Figure 4).

Figure 4. Compression test failure patterns of the concrete samples

3.3. Elasticity Modulus

In *"Volcanic Ash as a Sustainable Binder Material: An Extensive Review"* [35], it is explicitly reported that the elastic modulus of volcanic ash concrete is markedly lower than that of unmodified cementitious concrete. The mechanical characterization indicates an elastic modulus of 43.5 GPa for conventional concrete, whereas it is 10.67 GPa for volcanic ash concrete, corresponding to a reduction factor of approximately 4.06. This finding indicates substantial stiffness degradation associated with the incorporation of volcanic ash. Moreover, the analysis highlights the reduced density of cylindrical samples containing volcanic ash, which aligns with the theoretical predictions derived from the proposed equation in the referenced study, as discussed below.

Twenty-eight days after specimen preparation, the following curves illustrating the stress and strain behavior were obtained (Figure 5):

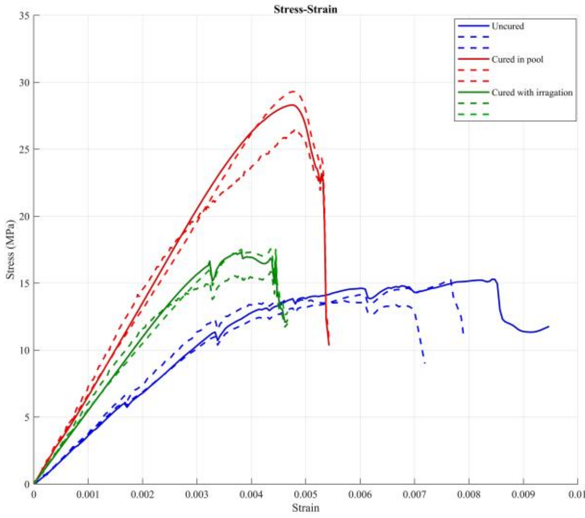


Figure 3. Representative stress–strain curves

In this study, an evaluation of the static elasticity modulus of the concrete was performed on the basis of the experimentally obtained stress–strain curves via two commonly accepted methods: the one provided by ASTM C469, detailed below, and the tangent modulus. This value represents the average stiffness of the material up to the point of maximum recorded strain. On the other hand, the initial tangent modulus is obtained as the slope between the first two points of the curve, reflecting the stiffness of the concrete during the initial stages of loading when its behavior is linear (Figure 6).

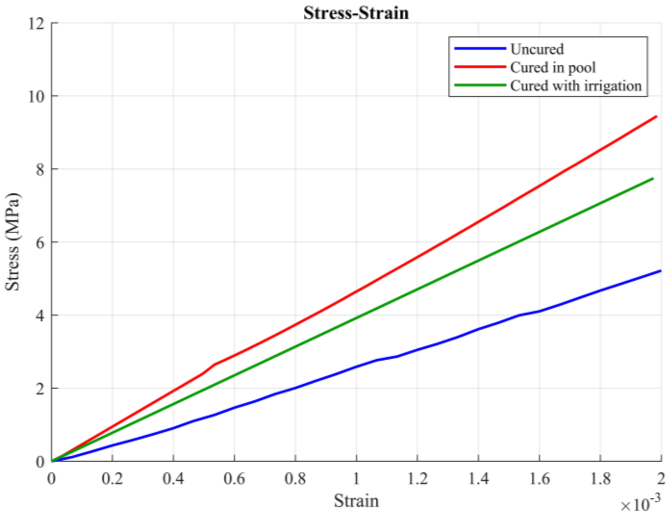


Figure 4. Characteristic elastic zone

By calculating the static elasticity modulus in accordance with ASTM C469 and the tangent modulus, the following results were obtained. The curing of the samples in the curing pools is defined as CP, the curing by water sprinkling is defined as CRA, and the curing of the samples without any curing is defined as SC (see Figure 7).

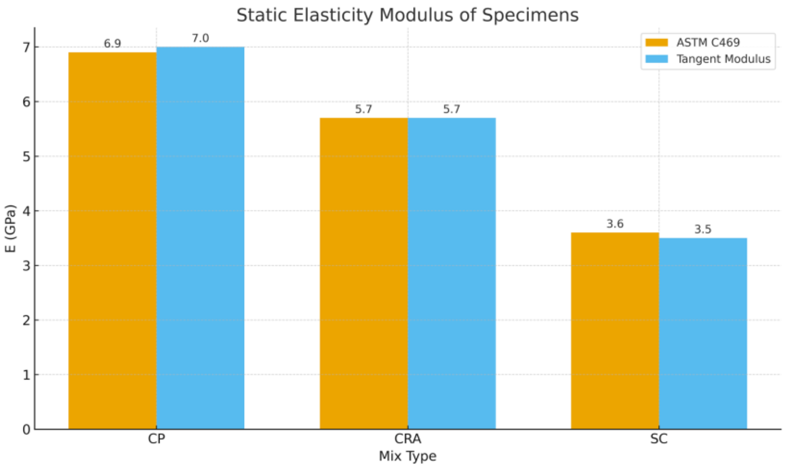


Figure 5. Static elasticity modulus of the samples

The values obtained from ASTM C469 do not differ significantly from those calculated via the tangent modulus method. However, when the empirical formula provided by ACI 318 is used as a valid approximation based on compressive strength, the results differ notably. The average density of the samples is shown in the Figure 8.

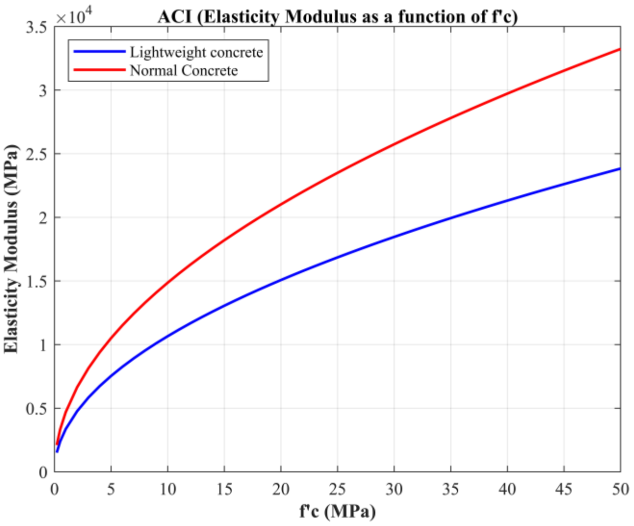


Figure 6. ACI (Elasticity Modulus as a function of *f'c*)

By obtaining compressive strength data covering a range from 14.5 to 28 MPa, modulus of elasticity (E) values between 17.9 and 24.9 GPa are calculated, which overestimate the experimental results for this type of material by 2.5--4 times (Figure 9).

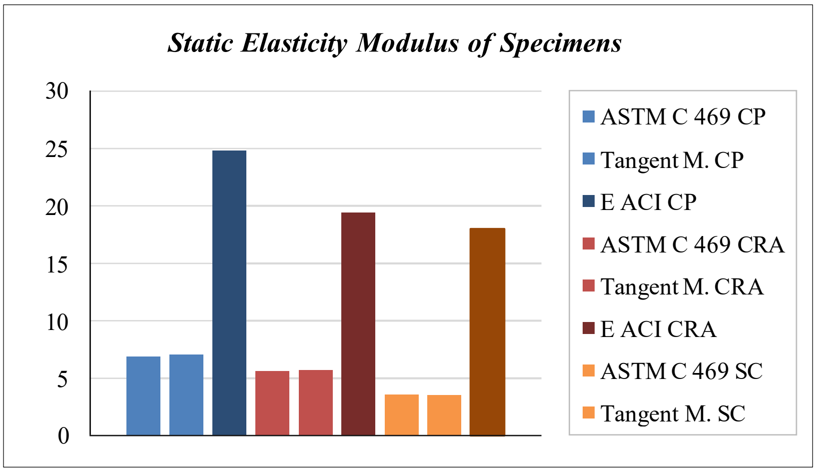


Figure 7. Static elasticity moduli of the samples, including the ACI equation results

When the elastic modulus is plotted as a function of the concrete compressive strength and compared with the experimental results, a notable difference is observed (Figure 10).

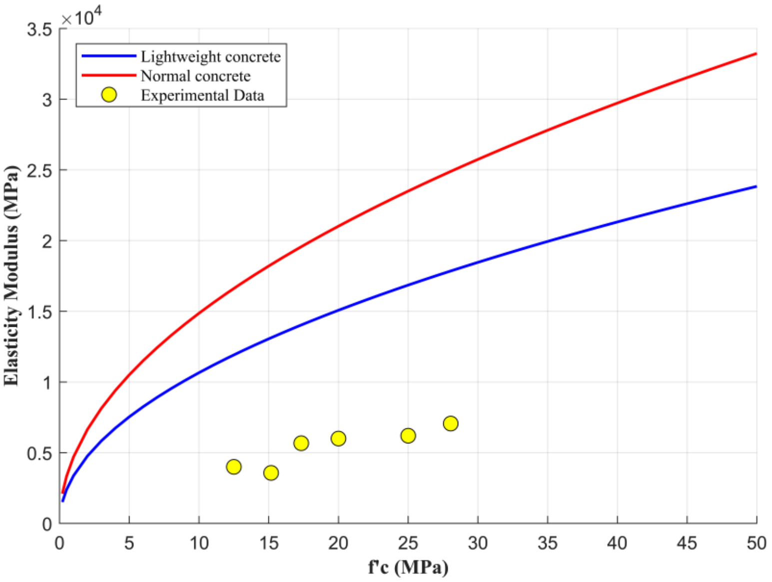


Figure 8. ACI elasticity modulus - experimental results

The static modulus of elasticity, measured at 28 days according to ASTM C469, had an average value of 7.06 GPa, which was significantly lower than the value of 24.89 GPa estimated via the empirical expressions of ACI 318 for the same compressive strength. This difference between 250% and 400% highlights that the conventional relationship between f'c and E is not valid for mixes with a high content of raw ash. Noguchi et al. (2009) [12] reported that concrete with unconventional aggregates or low-density matrices may exhibit much lower stiffness for the same compressive strength, a phenomenon that is experimentally confirmed here.

The reduction in the modulus can be attributed to two main factors: (i) the low density and high porosity of the volcanic ash used, which reduces the stiffness of the interfacial transition zone (ITZ), and (ii) the ash fraction, which, owing to its granulometry, behaves more like a fine aggregate than a cementing material at early ages. The granulometric analysis revealed that 100% of the ash passed through the No. 16 sieve (1.18 mm), but only 3.6% passed through the No. 200 sieve (0.075 mm), confirming that a sizable portion behaves physically as a filler rather than undergoing an immediate chemical reaction.

The empirical mathematical model, considering that it is a lightweight matrix, is expressed as follows:

Empirical Modulus Model for Volcanic Ash Concrete (VAM Model):

$$E = wc^{1.4} \times 0.03 \times \sqrt{f_c'} \tag{4}$$

The model, called the VAM (Volcanic Ash Modulus) model, was calibrated on the basis of actual laboratory values and showed a nonlinear trend with respect to compressive strength. The model predicts values significantly lower than those estimated by the traditional ACI 318 expressions, with a closer correlation to the measured results, especially within the strength range of 14.5–28 MPa. A fitted curve was obtained that reduces the modulus estimation error by more than 80%, validating its applicability for concrete with a high volcanic ash content. Noticing a significant difference from the equation given by ACI 318, an empirical model is proposed on the basis of the experimental data obtained (Figure 11).

Given the evident overestimation of the modulus by ACI 318, an alternative model called the VAM (Volcanic Ash Modulus) was proposed, which was calibrated with experimental values. This model reduced the prediction error by more than 80%, achieving a closer correlation between strength and stiffness for mixtures with a high content of raw ash. This adjustment is crucial in seismic zones such as Ecuador, where the modulus of elasticity directly influences the overall stiffness of the structure and, therefore, the vibration periods and seismic design forces.

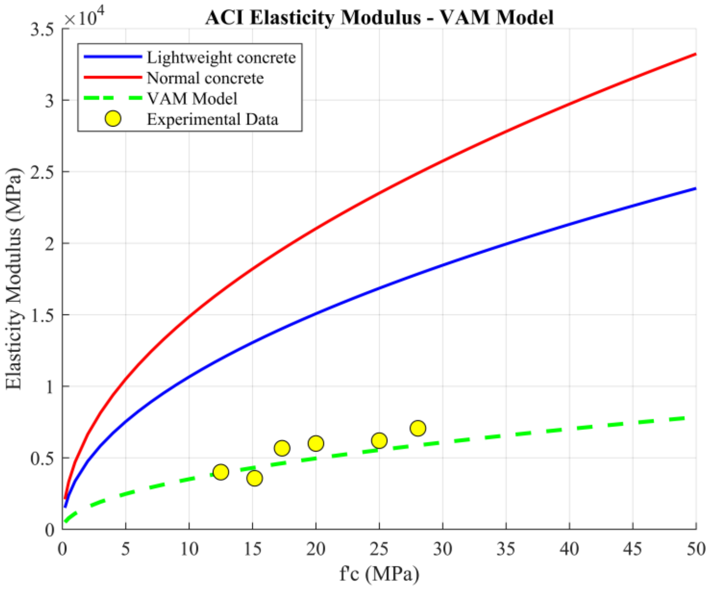


Figure 9. ACI elasticity modulus - VAM model

The study *"Comportamiento del concreto ante la fibra y ceniza volcánica"*[36] clearly revealed a reduction in the elastic modulus when recycled aggregates such as volcanic ash were incorporated, thereby corroborating the results reported in the referenced article. Taken together with the findings of Andrés Játiva and the present investigation, these works stand in contrast to the assertions of Hussein M., suggesting a divergent perspective in the literature. These discrepancies reinforce the notion that comprehensive laboratory testing is indispensable for establishing a more consistent understanding of the mechanical response of volcanic ash concrete.

3.4. Properties of the Volcanic Ash

Main Components Identified

Two X-ray analysis techniques, fluorescence and diffraction, were used, and it was determined that the volcanic ash used in this study was composed of aluminates and silicates. In its reaction with calcium oxide (CaO), it helps to maintain the strength of the concrete.

Reactivity and Cementitious Behavior

Volcanic ash by itself cannot form a cementitious paste independently. When combined with calcium hydroxide ($Ca(OH)_2$), which is a product of cement hydration, its pozzolanic potential is activated, promoting the development of mechanical strength in the material [18, 37].

Chemical Composition

In terms of its chemical composition, the ash analyzed comes from a volcano in the Andes Mountain range and therefore presents high contents of calcium oxide (CaO), silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3). In smaller proportions, it contains magnesium oxide (MgO), sodium oxide (Na_2O), and titanium dioxide (TiO_2) [38, 39].

Mineralogical Phase and Crystal Structure

In the crystalline phase, the following minerals were identified: plagioclases, pyroxenes, olivine, magnetite, and a significant fraction of amorphous material. Andesine was the main constituent of the samples, followed by enstatite, pigeonite, and, in smaller proportions, albite.

Structural Nature of the Minerals

The minerals andesine and albite belong to the tectosilicate group (plagioclases), characterized by strong and stable structures due to the orderly arrangement of their tetrahedra at elevated temperatures. Enstatite and pigeonite are inosilicates from the pyroxene group, featuring single-chain structures with a stable, refractory nature.

These results are consistent with those of previous studies on volcanic ash [8, 40].

4. Discussion of Findings

When analyzing the results, it is evident that samples cured in a curing pool show a considerable increase in compressive strength, with the strength continuing to improve even at 28 days. This contrasts with the results of the samples cured only by water sprinkling and those without any curing, which exhibit similar compressive strength values, with a slightly greater strength in the water-sprinkled samples. However, in both cases, the strength reaches its limit of approximately 14 days, after which no significant increase occurs. Although this study focused primarily on mechanical behavior, particularly compressive strength and static modulus of elasticity, the observed reduction in stiffness and sensitivity to curing conditions suggest an internal microstructure that may also affect durability-related properties. While no standardized permeability, water absorption, or shrinkage tests were conducted, the high cement replacement ratio and the lower elastic modulus are consistent with a more porous and less cohesive matrix. Similar findings have been reported in previous studies using volcanic ash from Tungurahua, where increased capillary absorption and drying shrinkage were observed compared with those of conventional concrete. In this work, indirect indicators—such as density values and moisture loss patterns—suggest similar tendencies. Further testing of these properties is recommended as part of future research.

In the cylinders with no curing (SC), the type 3 curing pattern was observed, and in several cases, the type 6 pattern was characterized by longitudinal cracks running through much of the cylinder's height. This pattern may be associated with either an internally nonhomogeneous stress distribution or variations in the alignment or rigidity of the loading ends. In this study, the specimens with type 6 failure did not exhibit detachment of the nonadhered caps or visible deformation of the compression plates, so this phenomenon cannot be attributed solely to an issue with the nonadhered caps but also to the internal configuration of the material itself.

For samples without curing, a characteristic axial stress is maintained at a certain strain level, suggesting that after reaching approximately 85% compressive strength, the internal matrix no longer behaves as a cohesive and monolithic system. The lack of adequate curing prevents optimal hydration development, resulting in an internal structure with higher porosity and susceptibility to microcracking. Consequently, the ability to redistribute stresses is compromised, causing remarkably high strain values beyond the peak strength without a corresponding increase in stress.

The application of the VAM model highlights the limitations of traditional empirical models such as ACI 318 when applied to concrete with unconventional supplementary cementitious materials. The considerable overestimation of the elastic modulus by ACI (up to four times greater than the experimental values) suggests that the inclusion of volcanic ash—especially raw, noncalcined ash at high replacement percentages—significantly alters the stiffness–strength relationship. This may be attributed to the higher porosity, lower density, and incomplete hydration of the material within the first 28 days. The VAM model accounts for these conditions, providing a more accurate prediction of the material's actual stiffness, which is critical in seismic regions such as Ecuador, where the elastic modulus directly influences structural design. Additionally, although developed for academic purposes, the VAM model addresses real needs in Ecuador, where raw volcanic ash is widely used without regulation. Given the importance of accurate stiffness estimation in seismic design, this model could serve as a basis for future validation studies and, eventually, support the adaptation of national building codes.

The results indicate that raw volcanic ash does not act solely as a supplementary cementitious material during the first 28 days of curing. Although it possesses pozzolanic potential, its reaction appears insufficiently active within this period, hindering the full development of hydration products that contribute to material stiffness. Part of the ash behaves more like a low-density, highly porous fine aggregate, affecting the internal structure of the concrete and reducing the elastic modulus even while maintaining compressive strength. This functional transition, between a cementitious and inert role, strongly depends on the curing method applied. Continuous immersion promotes greater hydration and better matrix–ash integration, whereas intermittent or absent curing limits this interaction. Although the ash used has potential as a pozzolanic material, its contribution at early ages appears insufficient. The simulated strength activity index (SAI) values, which are based on experimental compressive strength data, indicate values below the 75% threshold set by ASTM C618 at 28 days. Specifically, an SAI of approximately 71.1% suggests that the volcanic ash behaves more as a fine aggregate than as a reactive cementitious material within this curing period. This aligns with previous findings on natural pozzolans with limited short-term reactivity.

These findings emphasize the need to consider volcanic ash not only as a chemical reactive but also as a physical component of the granular skeleton of concrete. Future research should include microstructural and supplementary pozzolanic reactivity tests to quantify the degree of functional transition of ash depending on the curing time [41].

5. Conclusion

The integration of volcanic ash as a partial replacement for more than half of the cement demonstrated that it is possible to achieve compressive strengths suitable for structural applications even under variable curing conditions. However, the experimental results revealed a significant discrepancy between the measured static modulus of elasticity and the values estimated via empirical models such as those referenced in the Ecuadorian construction code and ACI 318. This finding highlights the limitations of applying standard correlations between the modulus of elasticity and compressive strength in concretes incorporating unconventional supplementary cementitious materials. To address this, an alternative empirical equation (VAM) was developed on the basis of the experimental data, providing a more accurate fit and reducing prediction errors by more than 80% compared with traditional formulas. This model offers a useful tool for estimating stiffness in mixtures with high volcanic ash content.

The study also identified a dual role of volcanic ash: beyond its pozzolanic reactivity, a significant portion of the material behaves as a low-density fine aggregate owing to its particle size distribution and porosity. This dual behavior directly influences the elastic properties of the mixture and explains the observed sensitivity of the mechanical performance to the curing method. Continuous immersion promoted better integration of the ash within the matrix, whereas intermittent or absent curing limited stiffness development despite maintaining compressive strength.

These results underscore the need for specific curing protocols and microstructural analyses to characterize the performance of volcanic ash fully and optimize its use. Future research should expand the validation of the VAM model to a broader range of mixes and field applications, supporting its potential adaptation to local construction codes in Ecuador, where volcanic ash-based concretes are commonly used in seismic regions.

6. Declarations

6.1. Author Contributions

Conceptualization, C.P.A.; methodology, D.A.C.; software, C.P.A. and D.A.C.; validation A.A.C.; formal analysis, A.A.C.; investigation, C.P.A. and D.A.C.; resources, D.A.C.; data curation, C.P.A. and D.A.C.; writing—original draft preparation, C.P.A. and D.A.C.; writing—review and editing, A.A.C.; visualization, A.A.C. and D.A.C.; supervision, A.A.C.; project administration, A.A.C.; funding acquisition, C.P.A. and A.A.C. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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