Revista ALCONPAT
www.revistaalconpat.org
eISSN 2007-6835
Revista de la Asociación Latinoamericana de Control de Calidad, Patología y Recuperación de la Construcción

Systematic review on the use of volcanic ash as a supplementary cementing material: mechanical and durability properties for applications in Ecuador.

L. J. Fernández-Sánchez[1]*, L. M. Fernández-Delgado[2], D. E. Fernández-Sánchez[3], R. S. Quintana-Vásconez[1], Y. Díaz-Cárdenas[4], S. G. Castro-Angulo[1,5]
*Contact author: ljfernandez@pucesa.edu.ec
DOI: https://doi.org/10.21041/ra.v16i3.1010

Received: 05/01/2026 | Received in revised form: 12/08/2026 | Accepted: 21/08/2026 | Published: 01/09/2026

ABSTRACT

This systematic review evaluates volcanic ash as a supplementary cementitious material in mortars and concretes, emphasizing its applicability to the Ecuadorian context. Indexed studies were analyzed through a bibliometric strategy and a technical synthesis of mechanical performance, durability, and pozzolanic mechanisms. Results show favorable replacement ranges of 10–25%, associated with pore refinement and C-S-H/C-A-S-H formation. However, wider implementation is limited by chemical variability, fineness, $Ca(OH)_2$ availability, and the need for local characterization. The originality of this review lies in discussing these technical limits in relation to clinker factor reduction. It is concluded that its application requires technical, normative, logistical, and industrial validation.
Keywords: volcanic ash; supplementary cementitious material; durability; pozzolanic reaction; clinker factor.

Cite as: Fernández-Sánchez, L. J., Fernández-Delgado, L. M., Fernández-Sánchez, D. E., Quintana-Vásconez, R. S., Díaz-Cárdenas, Y., Castro-Angulo, S. G. (2026), *"Systematic review on the use of volcanic ash as a supplementary cementing material: mechanical and durability properties for applications in Ecuador."* ALCONPAT Journal, Volume (Issue), pp. 372 – 410, DOI: https://doi.org/10.21041/ra.v16i3.1010

[1] Pontifical Catholic University of Ecuador, Ambato Campus, Ambato, Ecuador.
[2] Indoamérica Technological University, Ambato, Ecuador.
[3] Independent researcher, Ambato, Ecuador.
[4] Marta Abreu Central University of Las Villas, Villa Clara, Cuba.
[5] Autonomous University of Nuevo León, Faculty of Civil Engineering (FIC-UANL), Av. Universidad S/N, Ciudad Universitaria, San Nicolás de los Garza, Nuevo León 66455, Mexico.

Contribution of each autor
In this study, author L.J. Fernández-Sánchez led and contributed to the search, selection, extraction, and organization of scientific literature (50%), the synthesis of information and final integration of the results (60%), and the drafting and critical review of the content and manuscript (70%); author R.S. Quintana-Vásconez contributed to the search, selection, extraction, and organization of the literature (35%) and to the thematic analysis and interpretation of the included studies (60%); Author D.E. Fernández-Sánchez contributed to the search, selection, extraction, and organization of the literature (15%) and to the definition, verification, and validation of methodological consistency (35%); Author L.M. Fernández-Delgado contributed to the definition of the methodological criteria (35%) and to the drafting and critical review of the content and manuscript (15%); Author Y. Díaz-Cárdenas contributed to the thematic analysis and interpretation of the included studies (40%); and S.G. Castro-Angulo contributed to the methodological validation (30%), the drafting and critical review of the content and manuscript (15%), and the synthesis of the information and final integration of the results (40%).

Revisión sistemática sobre el uso de ceniza volcánica como material cementante suplementario: propiedades mecánicas y de durabilidad para aplicaciones en Ecuador.

RESUMEN

Esta revisión sistemática evalúa el uso de ceniza volcánica como material cementante suplementario en morteros y concretos, con énfasis en su aplicabilidad al contexto ecuatoriano. Se analizaron estudios indexados mediante una estrategia bibliométrica y una síntesis técnica de desempeño mecánico, durabilidad y mecanismos puzolánicos. Los resultados muestran rangos favorables de sustitución entre 10–25%, asociados al refinamiento poral y a la formación de C-S-H/C-A-S-H. No obstante, su ampliación está limitada por la variabilidad química, la finura, la disponibilidad de $Ca(OH)_2$ y la caracterización local. La originalidad radica en discutir estos límites frente a la reducción del factor clínker. Se concluye que su aplicación requiere validación técnica, normativa, logística e industrial.

Palabras clave: ceniza volcánica; material cementante suplementario; durabilidad; reacción puzolánica; factor clínker.

Revisão sistemática sobre o uso de cinzas vulcânicas como material cimentício suplementar: propriedades mecânicas e de durabilidade para aplicações no Equador.

RESUMO

Esta revisão sistemática avalia o uso de cinza vulcânica como material cimentício suplementar em argamassas e concretos, com ênfase em sua aplicabilidade ao contexto equatoriano. Estudos indexados foram analisados por meio de uma estratégia bibliométrica e de uma síntese técnica sobre desempenho mecânico, durabilidade e mecanismos pozolânicos. Os resultados indicam faixas favoráveis de substituição entre 10–25%, associadas ao refinamento dos poros e à formação de C-S-H/C-A-S-H. Contudo, sua ampliação é limitada pela variabilidade química, finura, disponibilidade de $Ca(OH)_2$ e caracterização local. A originalidade está em discutir esses limites frente à redução do fator clínquer. Conclui-se que sua aplicação requer validação técnica, normativa, logística e industrial.

Palavras-chave: cinza vulcânica; material cimentício suplementar; durabilidade; reação pozolânica; fator clínquer.

Discussions and subsequent corrections to the publication
Any dispute, including the replies of the authors, will be published in the second issue of 2027 provided that the information is received before the closing of the first issue of 2027.

Legal Information
Revista ALCONPAT is a quarterly publication by the Asociación Latinoamericana de Control de Calidad, Patología y Recuperación de la Construcción, Internacional, A.C., Km. 6 antigua carretera a Progreso, Mérida, Yucatán, 97310, Tel. +52 1 983 419 8241, alconpat.int@gmail.com, Website: www.alconpat.org
Reservation of rights for exclusive use No.04-2013-011717330300-203, and ISSN 2007-6835, both granted by the Instituto Nacional de Derecho de Autor. Responsible editor: Pedro Castro Borges, Ph.D. Responsible for the last update of this issue, Informatics Unit ALCONPAT, Elizabeth Sabido Maldonado.
The views of the authors do not necessarily reflect the position of the editor.

1. LIST OF ABBREVIATIONS

Acronym	Meaning
C-S-H	Calcium Silicate Hydrate
C-A-S-H	Calcium Aluminum Silicate Hydrate
$Ca(OH)_2$	Calcium Hydroxide
CO_2	Carbon Dioxide
SCM	Supplementary cementitious materials
GWP100	Global Warming Potential
TAP100	Terrestrial acidification potential
FEP	Freshwater eutrophication potential
MEP	Marine eutrophication potential
ODP_{inf}	Ozone Depletion Potential
POFP	Potential for the formation of photochemical oxidants
PMFP	Particulate Matter Formation Potential
FDP	Fossil Fuel Depletion Potential
EC	Ecuador
GLO	Global
CV	Volcanic Ash
SiO_2	Silicon Dioxide
Al_2O_3	Aluminum Oxide
Fe_2O_3	Iron(III) Oxide
CaO	Calcium Oxide
PRISMA	Preferred reference items for systematic reviews and meta-analyses
MgO	Magnesium Oxide
K_2O	Potassium Oxide
Na_2O	Sodium Oxide
SO_3	Sulfur Oxide
D_{50}	Average particle size
BET	Brunauer-Emmett-Teller
ITZ	Interfacial transition zone
AFm	Aluminate ferrite monosulfate
XRF	X-ray fluorescence
LOI	Loss on Ignition
LCA	Life Cycle Assessment

2. INTRODUCTION

The cement industry is one of the most carbon-intensive industrial sectors, primarily due to the production of Portland clinker. Globally, cement manufacturing accounts for approximately 7% to 8% of anthropogenic CO_2 emissions, while the direct emissions intensity of cement has remained close to 0.6 t r CO_2 per metric ton of cement produced in recent years (Garces-Vargas et al., 2024;

Rovnaník et al., 2007; N. Singh et al., 2023). This is due to the dual contribution of limestone calcination and kiln energy consumption, making the reduction of the clinker factor a priority strategy for decreasing the environmental footprint of concrete. In this context, the use of supplementary cementitious materials (SCMs) allows for the partial replacement of Portland cement, reduces clinker content, and enables the utilization of mineral resources or byproducts with a lower environmental impact (Fernández-Jiménez et al., 2023; A. Rajesh et al., 2023; Sharma et al., 2021). Volcanic ash, due to its natural origin, potential availability in volcanic regions, and pozzolanic behavior, constitutes a relevant alternative for sustainable cementitious systems, especially in the Andean context, where Ecuador offers favorable geological conditions for the study of natural pozzolans of volcanic origin (Cascone et al., 2025; M. U. Hossain et al., 2021; Pinto-Almeida et al., 2025; Sokołowska, 2025).

Traditionally, the reduction of the clinker factor has relied on the use of SCMs such as industrial byproducts and natural pozzolans, including fly ash, granulated blast furnace slag, silica fume, and natural pozzolans. However, the future availability of these materials is limited both by supply constraints and by structural changes associated with the energy transition, particularly the decline in coal use for electricity generation and the progressive decarbonization of the metallurgical sectors. This situation underscores the need to identify alternative sources of SCMs that do not rely exclusively on carbon-intensive industrial chains. In this regard, natural pozzolans and volcanic ash take on strategic importance, as they can help reduce clinker content without relying on the future availability of fly ash or slag.

In the case of Ecuador, clinker production accounts for the largest environmental impact within the evaluated cement system, exceeding 90% in several impact categories reported for the analyzed functional unit, as shown in Figure 1. This impact is particularly significant for GWP100, PMFP, and POFP due to calcination and kiln combustion. Petroleum coke production (GLO) is primarily responsible for fossil fuel depletion (FDP) and contributes to terrestrial acidification (TAP100). Electricity supply and the extraction of natural resources have an impact on freshwater eutrophication (FEP) and marine eutrophication (MEP). To reduce the most significant impacts of the cement manufacturing process, the following priority measures are proposed: optimizing energy consumption, incorporating alternative fuels, advancing the decarbonization of the electricity grid, and reducing the clinker factor through SCMs (especially volcanic ash).

From a physicochemical perspective, the efficiency of SCMs depends on their chemical and mineralogical composition, amorphous fraction, fineness, specific surface area, and ability to react with the portlandite $Ca(OH)_2$ generated during the hydration of Portland cement. In cement systems containing volcanic ash, the reactive silico-aluminate phases do not act in isolation but interact with the calcium available in the matrix. This pozzolanic reaction can promote the secondary formation of C-S-H and C-A-S-H gels, which have a cementitious function similar to the main hydration products of Portland cement, contributing to the refinement of the porous network, the reduction of capillary connectivity, and the improvement of mechanical and chemical performance against the ingress of aggressive agents. However, at high substitution levels, the reduced amount of clinker limits the generation of $Ca(OH)_2$, which can restrict the pozzolanic reaction and leave fractions of ash unreacted (Fernandes et al., 2025; Játiva et al., 2025; Kupwade-Patil, De Wolf, et al., 2018; Shahjalal et al., 2025; S. Singh et al., 2026; Tomoyose et al., 2020).

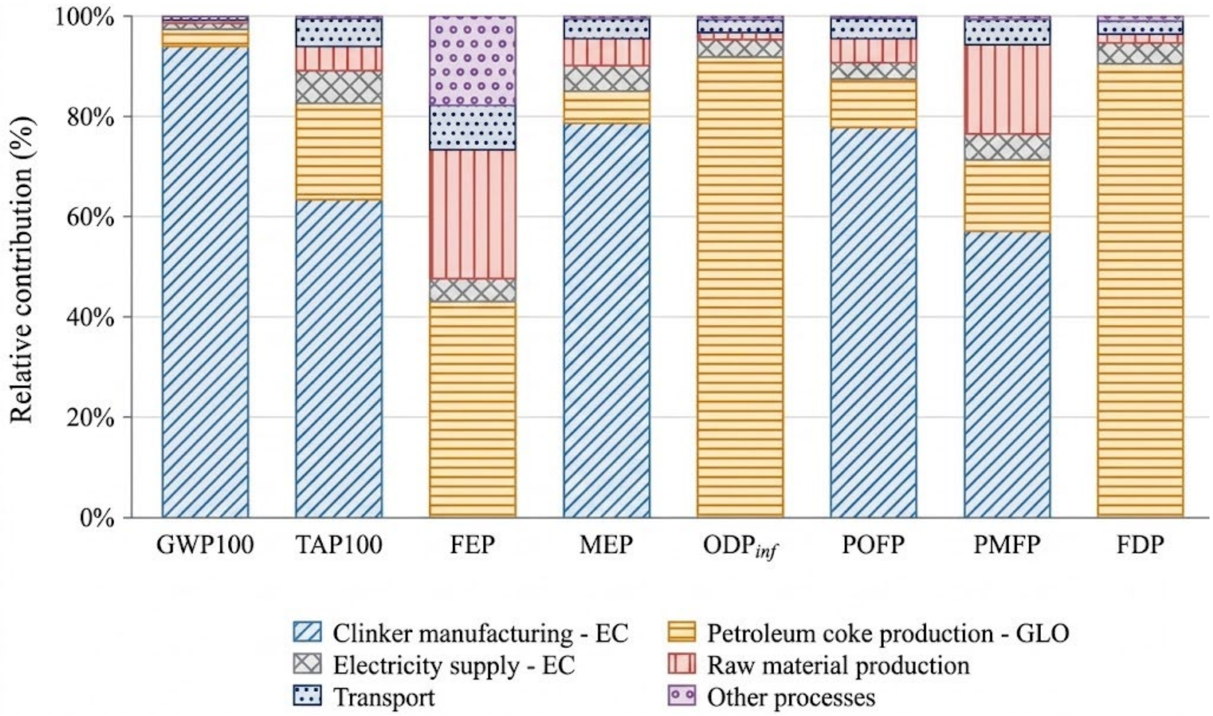

Figure1 . Relative contribution of production processes to environmental impact categories per metric ton of clinker (functional unit). GWP100: global warming potential; TAP100: terrestrial acidification potential; FEP: freshwater eutrophication potential; MEP: marine eutrophication potential; ODPinf: ozone depletion potential; POFP: photochemical oxidant formation potential; PMFP: particulate matter formation potential; FDP: fossil fuel depletion potential; EC: Ecuador; GLO: global. Source: adapted from (Petroche & Ramirez, 2022).

Ecuador is located in the Pacific Ring of Fire and is part of an Andean region characterized by recurring volcanic activity, ash emissions, and the presence of pyroclastic deposits. This geological condition suggests the existence of potential sources of volcanic materials of interest for cementitious applications; however, their use as SCMs cannot be assumed solely based on their volcanic origin. Technical feasibility depends on the chemical composition, mineralogy, amorphous fraction, fineness, pozzolanic reactivity, material accessibility, continuity of supply, and compatibility with local cements and aggregates (Pinos-Velez et al., 2024; Toulkeridis & Zach, 2017).

In the Ecuadorian context, the use of volcanic ash as an SCM faces limitations that go beyond geological availability. These include the need for specialized laboratories for physical-chemical and mineralogical characterization, the costs associated with drying, grinding, and classifying the material, the spatial and temporal variability of the ash, restrictions on access to certain areas due to geographic or environmental conditions, and the distance between potential sources and cement or concrete plants. Furthermore, the potential location of deposits in protected areas or areas that are difficult to access may limit their extraction and industrial use. Therefore, the application of volcanic ash in Ecuador requires an integrated assessment of technical performance, environmental impact, processing costs, logistics, and regulatory compliance (Cavalieri et al., 2024; Mohamad et al., 2020).

Although there is a growing body of research on the use of volcanic ash in construction materials, there is still no clear consensus on the optimal substitution ranges or on its effect on mechanical and durability properties. The evidence is scattered due to the chemical and physical variability of VA depending on its origin, which makes it difficult to establish sound technical recommendations for safe and efficient industrial-scale application; this variability manifests itself in significant

differences in the content of SiO_2, Al_2O_3, Fe_2O_3, CaO, alkalis, amorphous phase, crystalline phases, particle size, and specific surface area. These parameters influence the pozzolanic reaction rate, water demand, the filler effect, the availability of calcium for the formation of C-S-H/C-A-S-H, and, consequently, mechanical performance and resistance to chemical attack. (Gil-Martín et al., 2025; Shahjalal et al., 2025; Sokołowska, 2025). Therefore, it is necessary to consolidate the findings to establish a knowledge base that facilitates their adoption in building codes and construction practices, especially in a context such as Ecuador's.
Within this framework, the objective of this systematic review is to critically evaluate the use of volcanic ash as a supplementary cementitious material in mortars and concretes, considering: (i) its effect on compressive and flexural strength; (ii) its influence on durability, particularly on permeability, chloride transport, sulfate attack, and carbonation; (iii) the pozzolanic and microstructural mechanisms that explain its performance; and (iv) the technical limits of replacement ranges in relation to clinker reduction and its potential application in Ecuador. Unlike reviews focused solely on substitution percentages or mechanical properties, this study integrates a bibliometric analysis of the scientific literature, a technical synthesis of mechanical and durability properties, the physicochemical characterization of volcanic ash, and a critical discussion of the conditions necessary for its utilization in the Ecuadorian context.

3. PROCEDURE

3.1 Description of the methodological approach, search strategy, and selection

This study was conducted as a systematic literature review with complementary bibliometric analysis, aimed at synthesizing scientific evidence on the use of volcanic ash as a supplementary cementitious material in mortars and concrete. The methodological procedure was organized into five stages: definition of research questions, literature search, application of inclusion and exclusion criteria, extraction of technical data, and bibliometric-thematic analysis.
The review was not designed as a statistical meta-analysis due to the heterogeneity of the included studies regarding the origin of the volcanic ash, chemical composition, fineness, substitution percentage, water-to-cement ratio, curing age, type of mixture, and experimental method—all of which are relevant data points that allow for critical analysis. Therefore, the synthesis was conducted in a narrative and comparative manner, identifying trends, performance ranges, reported mechanisms, and technical limitations for its application in the Ecuadorian context.
Only articles indexed in Scopus were considered, due to its prestige, editorial rigor, and broad coverage of construction materials, civil engineering, and sustainability. The process was organized into three phases—search, filtering, and final selection—guided by three specific research questions.

1. How does the volcanic ash content influence the compressive and flexural strength of mortars and concretes?
2. What effect does volcanic ash have on the durability of mortars and concretes against sulfates and on their permeability?
3. What are the optimal ranges of volcanic ash content for sustainable and efficient use?

These questions helped define the search descriptors and Boolean or logical operators used in Scopus, combining terms such as "volcanic ash," "supplementary cementitious materials," "compressive strength," "flexural strength," "durability," "sulfate resistance," and "permeability." Filters were applied to restrict the results to peer-reviewed articles published between 2011 and 2025, in English or Spanish, within the subject areas of engineering, materials science, and environmental science.

3.2 Information Source and Search Strategy

The literature search was conducted in the Scopus database, selected for its coverage of civil engineering, materials science, concrete technology, sustainability, and cementitious materials. The search was aimed at identifying scientific articles and reviews related to volcanic ash, natural pozzolans, and supplementary cementitious materials used in mortars and concrete.

The search string used was: TITLE-ABS-KEY(("volcanic ash" OR "natural pozzolan" OR "natural pozzolans" OR "volcanic pozzolan" OR "volcanic pozzolans") AND ("supplementary cementitious material" OR "supplementary cementitious materials" OR SCM OR pozzolan) AND (concrete OR mortar) AND (strength OR durability OR permeability OR "sulfate resistance" OR "pozzolanic activity" OR "pozzolanic reactivity" OR microstructure OR "chemical composition" OR XRD OR XRF OR SEM OR "particle size" OR fineness OR "specific surface area")) AND (DOCTYPE(ar) OR DOCTYPE(re)) AND PUBYEAR > 2010

This decision allowed for the maintenance of a consistent and traceable document base for the bibliometric analysis; however, it is acknowledged that the use of a single database may limit the comprehensiveness of the review and introduce coverage bias. Therefore, the absence of complementary databases such as Web of Science is stated as a methodological limitation of the study and should be considered in future expanded reviews.

3.3 Inclusion and Exclusion Criteria

The identified records were evaluated at two levels. The first level corresponded to the bibliometric analysis, in which all documents retrieved through the search string and filters applied in Scopus were considered. The second level corresponded to the technical synthesis, for which only studies providing verifiable information on mortar or concrete mixtures with volcanic ash as a SCM were selected.

Studies that met the following criteria were included:

- Evaluate mortars, pastes, or concretes containing volcanic ash, volcanic pozzolan, volcanic slag, or natural volcanic material used as SCM.
- Report the substitution percentage, dosage, or incorporation ratio of the volcanic material.
- Present at least one mechanical, durability, microstructural, or physicochemical property.
- Include information on compressive strength, flexural strength, permeability, sulfate attack, transport of aggressive agents, pozzolanic activity, chemical composition, mineralogy, fineness, or particle size.
- Be scientific articles or indexed reviews published within the defined search period.
- Include studies on pastes, mortars, or concretes based on Portland cement or comparable cementitious systems, in which volcanic ash, volcanic pozzolan, or natural volcanic material is used as a cementitious material (SCM).

Documents were excluded if:

- Studies in which volcanic ash was part of multicomponent mixtures but did not report results that allowed for distinguishing its individual effect or specific contribution within the cementitious system.
- Did not report comparable technical data on composition, dosage, performance, or characterization.
- Were non-peer-reviewed documents, abstracts, editorials, technical notes, or communications lacking experimental data.
- Contained duplicate documents or insufficient information for data extraction.

3.4 Study Screening and Selection Process

The initial search identified 422 records in Scopus. These documents formed the basis for the general bibliometric analysis, including the temporal evolution of publications, subject areas, sources, countries, and keywords. However, not all records were used for technical data extraction, as several documents pertained to general studies on natural pozzolans, supplementary cementitious materials, or applications not directly comparable to mortars and concretes containing volcanic ash.

Subsequently, the records underwent a screening process based on title, abstract, and keywords. At this stage, 262 documents were excluded because they did not directly address the use of volcanic ash as a supplementary cementitious material in cementitious systems, because they dealt with applications unrelated to mortars or concretes, or because they did not provide technical information relevant to the objectives of the review. Next, 160 documents were evaluated in full text, and 50 documents were excluded for failing to report sufficient data on dosage, mechanical performance, durability, physicochemical characterization, or pozzolanic mechanisms. Finally, 110 studies were included in the technical synthesis of results.

To improve the traceability of the process, a flowchart (Figure 2) of the study selection process and a supplementary table listing the documents included in the technical synthesis were incorporated, indicating the author, year, type of volcanic material, substitution percentage, type of cementitious matrix, evaluated properties, and main findings.

The process of identification, screening, full-text evaluation, and inclusion is summarized in Figure 2. Of the 422 records identified, 110 studies met the criteria established for the technical synthesis.

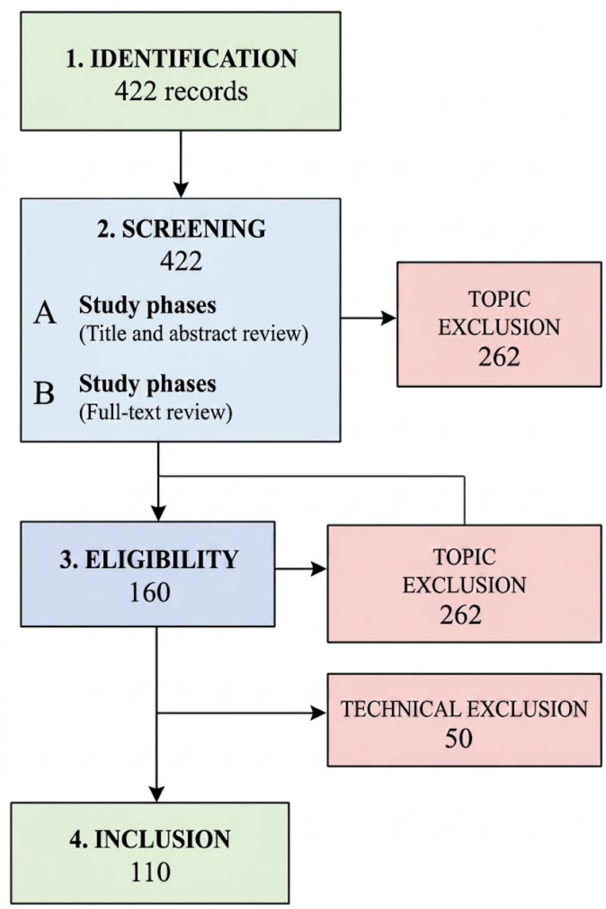

Figure 2. Flowchart of the study search, screening, and inclusion process.
Source: author's own work.

The 422 records retrieved from Scopus were used for the bibliometric analysis. The technical synthesis was conducted exclusively on the 110 studies that met the inclusion criteria and provided verifiable information on dosage, mechanical performance, durability, physicochemical characterization, or pozzolanic mechanisms of volcanic ash as a supplementary cementitious material.

3.5 Data extraction and synthesis.

Data extraction was performed exclusively on the 110 studies included in the technical synthesis. For each study, bibliographic, methodological, and technological variables were recorded. Bibliographic variables included author, year, and publication source. Methodological variables considered the type of cementitious matrix, substitution percentage, water-to-cement ratio, test age, and curing conditions. Technological variables included compressive and flexural strength, permeability, sulfate resistance, chloride transport, chemical composition, mineralogy, fineness, particle size, specific surface area, pozzolanic activity, and reported hydration products.
The synthesis was conducted through narrative comparison and thematic analysis, grouping the findings into four categories: mechanical performance, durability, physicochemical mechanisms, and feasibility of application (Figure 3). Due to the heterogeneity of materials, experimental designs, and test conditions, a quantitative meta-analysis was not performed.
The general sequence of the search, bibliometric processing, variable selection, and presentation of results is illustrated in Figure 3.

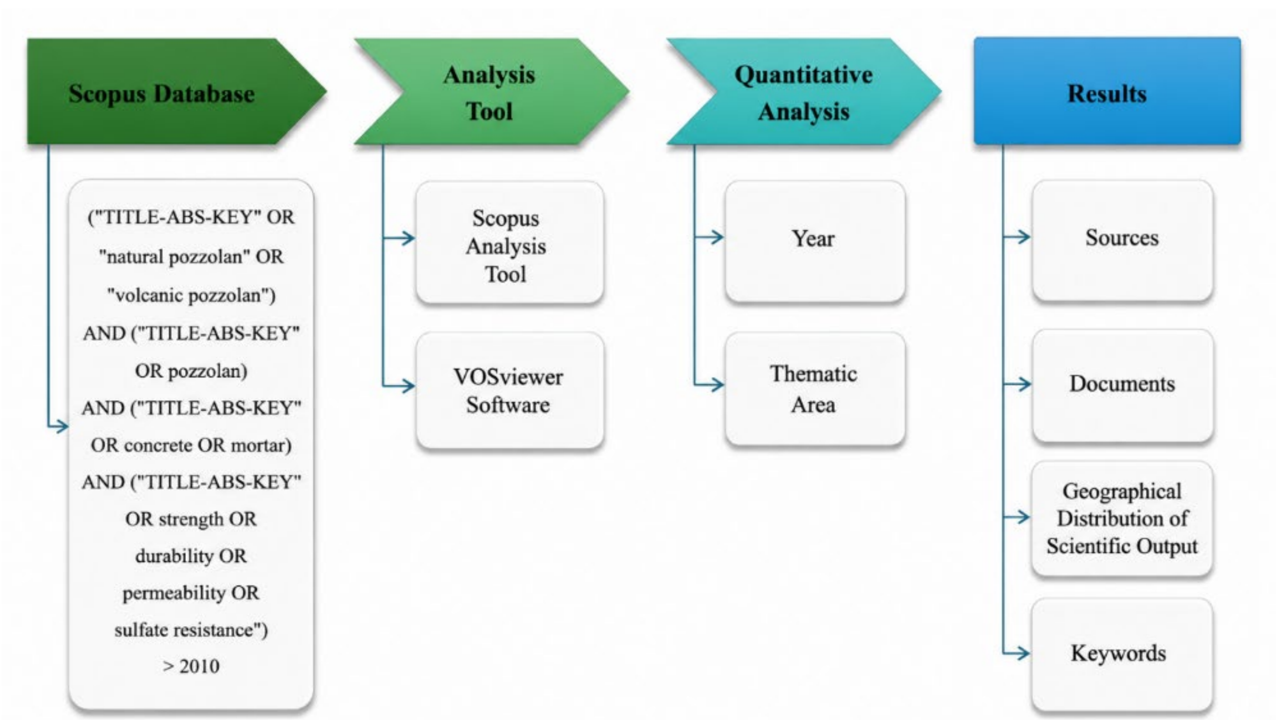

Figure 3. Search methodology
Source: Author's own work.

3.6 Bibliometric Analysis and Technical Analysis

The bibliometric analysis and technical synthesis were conducted as separate components. The bibliometric analysis was applied to the complete set of records retrieved from Scopus, with the aim of identifying publication trends, subject areas, primary sources, geographic distribution, scientific collaboration, and keyword co-occurrence. VOSviewer and Scopus export tools were used for this analysis.

The technical synthesis, on the other hand, was limited to studies that met the inclusion criteria for data extraction regarding mechanical performance, durability, physicochemical characterization, and pozzolanic mechanisms. Therefore, the initial 422 records should not be interpreted as the number of studies included in the technical discussion, but rather as the documentary basis for the bibliometric analysis.

3.7 Methodological limitations.

The exclusive use of Scopus constitutes a limitation of the study, as it may restrict the scope of the literature compared to reviews that incorporate complementary databases such as Web of Science. This decision was made to maintain bibliometric homogeneity and traceability in the analyzed metadata; however, the results should be interpreted with this potential coverage bias in mind. Furthermore, the study was not registered under a PRISMA protocol nor was it designed as a meta-analysis, due to the heterogeneity of the available studies regarding ash origin, chemical composition, fineness, cementitious matrices, curing conditions, test ages, and evaluation methods. For this reason, a systematic review with bibliometric analysis and narrative synthesis was chosen, aimed at identifying trends, mechanisms, and technical limitations rather than estimating a statistical effect size.

Since the objective of the article includes discussing the applicability of volcanic ash in Ecuador, a complementary contextual search was conducted to identify literature and documents related to volcanic activity, ash deposits, natural pozzolans, and volcanic materials in the Ecuadorian context. This search was not used to construct the overall bibliometric analysis but rather to support the applied discussion on opportunities, constraints, and the need for local validation (Figure 4).

Thus, the technical review was based on international evidence regarding the performance of volcanic ash as SCM, while the Ecuadorian perspective was incorporated as a focal point for contextual discussion and technology transfer.

Figure 4 distinguishes between the two components of the study: the bibliometric analysis applied to the 422 records retrieved from Scopus and the technical synthesis developed using the 110 studies ultimately included.

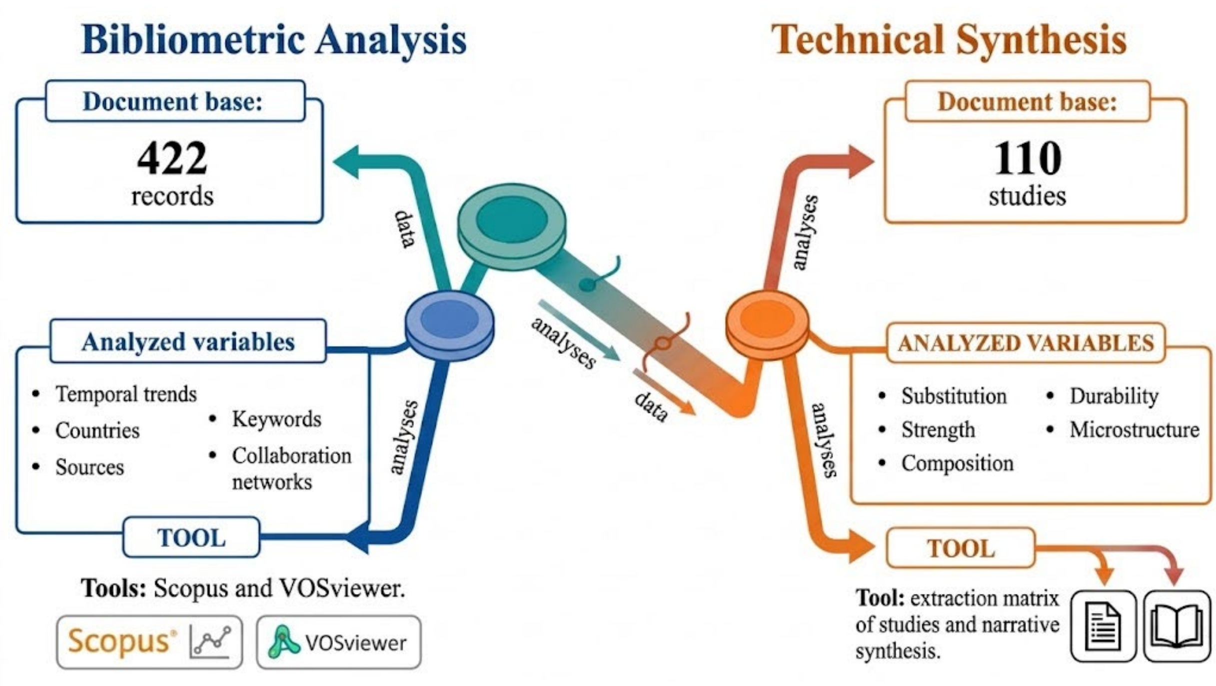

Figure 4. Distinction between bibliometric analysis and technical synthesis
Source: author's own work.

4. RESULTS

The results are presented on two complementary levels. First, the bibliometric analysis of the records retrieved from Scopus is presented, with the aim of characterizing the temporal evolution, subject areas, publication sources, geographic distribution, and keywords associated with the study of volcanic ash and natural pozzolans as supplementary cementitious materials. Second, a technical synthesis of the studies selected for data extraction is presented, focusing on mechanical performance, durability, pozzolanic mechanisms, physicochemical characterization, and feasibility of application. Therefore, the bibliometric records should not be interpreted as equivalent to the number of studies included in the technical discussion.

4.1 Bibliometric analysis of the scientific output identified in Scopus.

4.1.1 Quantitative análisis.

The number of documents per year related to the use of volcanic ash and natural pozzolans as supplementary cementitious materials is presented in Figure 5. The general trend shows a sustained increase in scientific interest between 2011 and 2025, with more pronounced growth beginning in 2015. This trend coincides with the intensification of research on clinker factor reduction, the valorization of natural mineral resources, and the development of cementitious materials with a lower environmental impact.

Figure 5 shows a first significant increase in 2018, followed by more pronounced growth until reaching a peak in publications in 2022. Although a slight decline is observed in 2023 and 2024, the rebound in 2025 indicates that the topic remains scientifically relevant. This trend confirms that volcanic ash is not a marginal area of research but rather an emerging field within SCM research. However, the quantitative increase in publications does not necessarily imply technological maturity, as industrial application continues to be constrained by the material's physicochemical variability, the standardization of testing, and regulatory validation.

The temporal evolution of scientific output is presented in Figure 5, which shows sustained growth since 2015 and the highest number of publications in recent years.

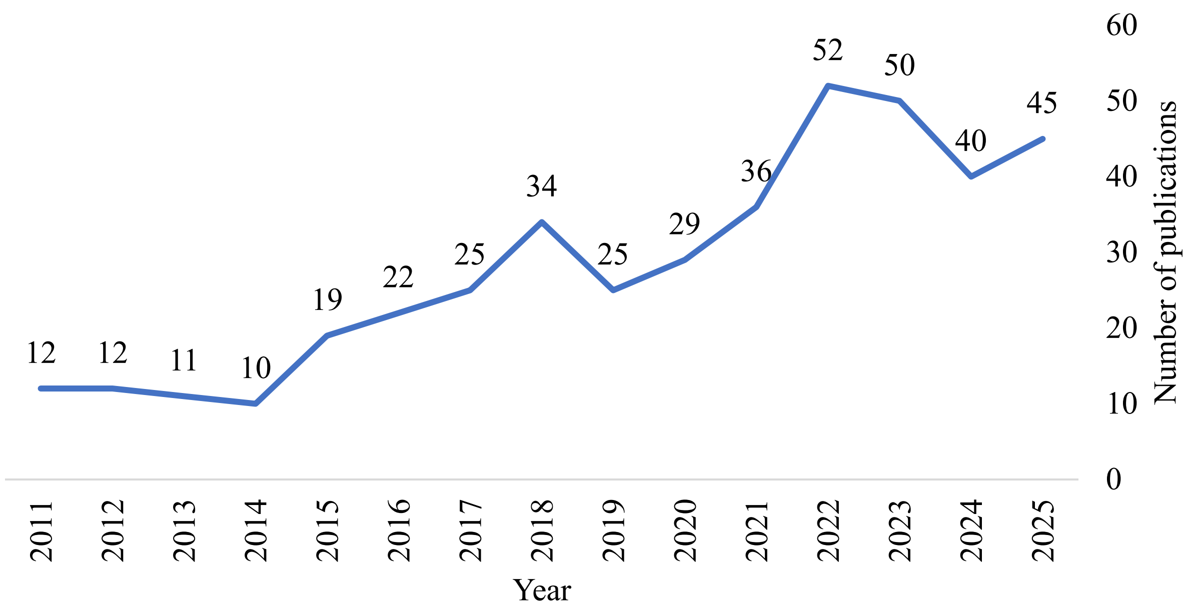

Figure 5. Annual trend in publications on volcanic ash and natural pozzolans as SCMs.
Source: Author's own compilation based on data exported from Scopus.

Figure 6 shows that most of the scientific output is concentrated in the fields of Materials Engineering and Materials Science, highlighting the field's predominantly technical orientation. This distribution is consistent with the objective of this review, which focuses on the mechanical performance, durability, microstructure, and feasibility of using volcanic ash in cementitious matrices. The presence of complementary fields, such as Environmental Sciences, Chemical Engineering, and Earth Sciences, confirms the interdisciplinary nature of the topic, particularly given its relationship to sustainability, mineralogical characterization, reduction of environmental impacts, and the valorization of natural resources.
As shown in Figure 6, scientific output is concentrated primarily in Materials Engineering and Science, followed by Environmental Sciences, Physics and Astronomy, and Earth Sciences.

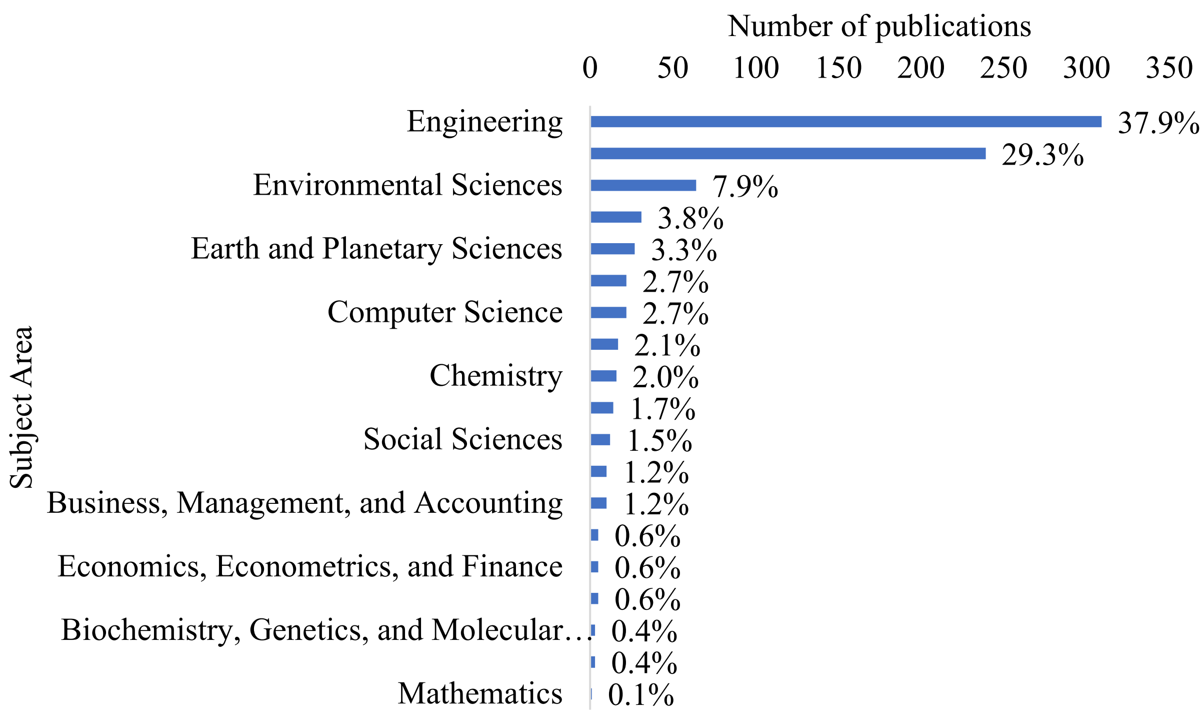

Figure 6. Number of publications by subject area
Source: Author's own analysis based on data exported from Scopus.

4.1.2 Publication sources.
The data were processed using VOSviewer software, selecting the "bibliographic coupling" option as the type of analysis. The unit of analysis was defined as "sources," and a minimum of 2 documents was established for a journal to be included in the analysis. The main journals accounting for the majority of the analyzed scientific output are presented in Figure 7. *Construction and Building Materials* has the highest number of documents, followed by *Materials* and other sources specializing in cementitious materials and sustainable construction. The graph includes only those sources with four or more publications. Therefore, 201 additional articles, which belong to journals with lower publication frequencies, are not shown in the graph (Figure 8).
This indicates a significant concentration in a few specialized journals as well as considerable dispersion among many sources with a small number of contributions. The structure of the relationships among the sources is depicted in Figure 8, obtained through a bibliographic coupling analysis in VOSviewer. The size of each node represents the journal's output, and the links express the strength of the bibliographic relationships between sources.

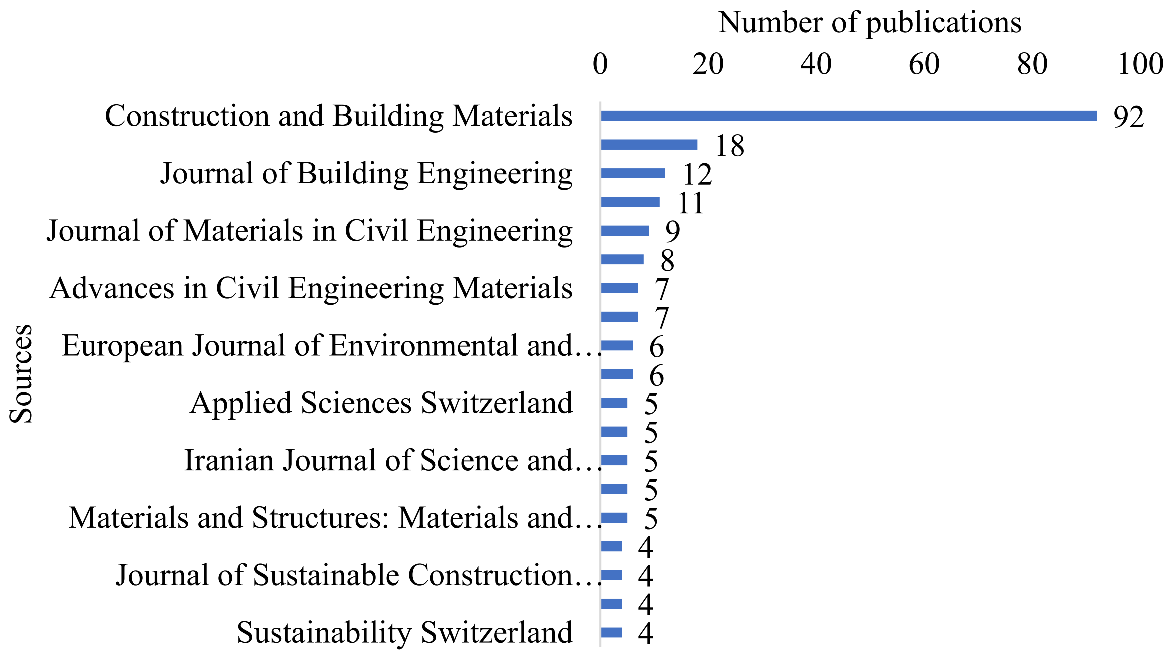

Figure 7. Major publication sources on volcanic ash and natural pozzolans as SCMs.
Source: Author's own work based on data exported from Scopus.

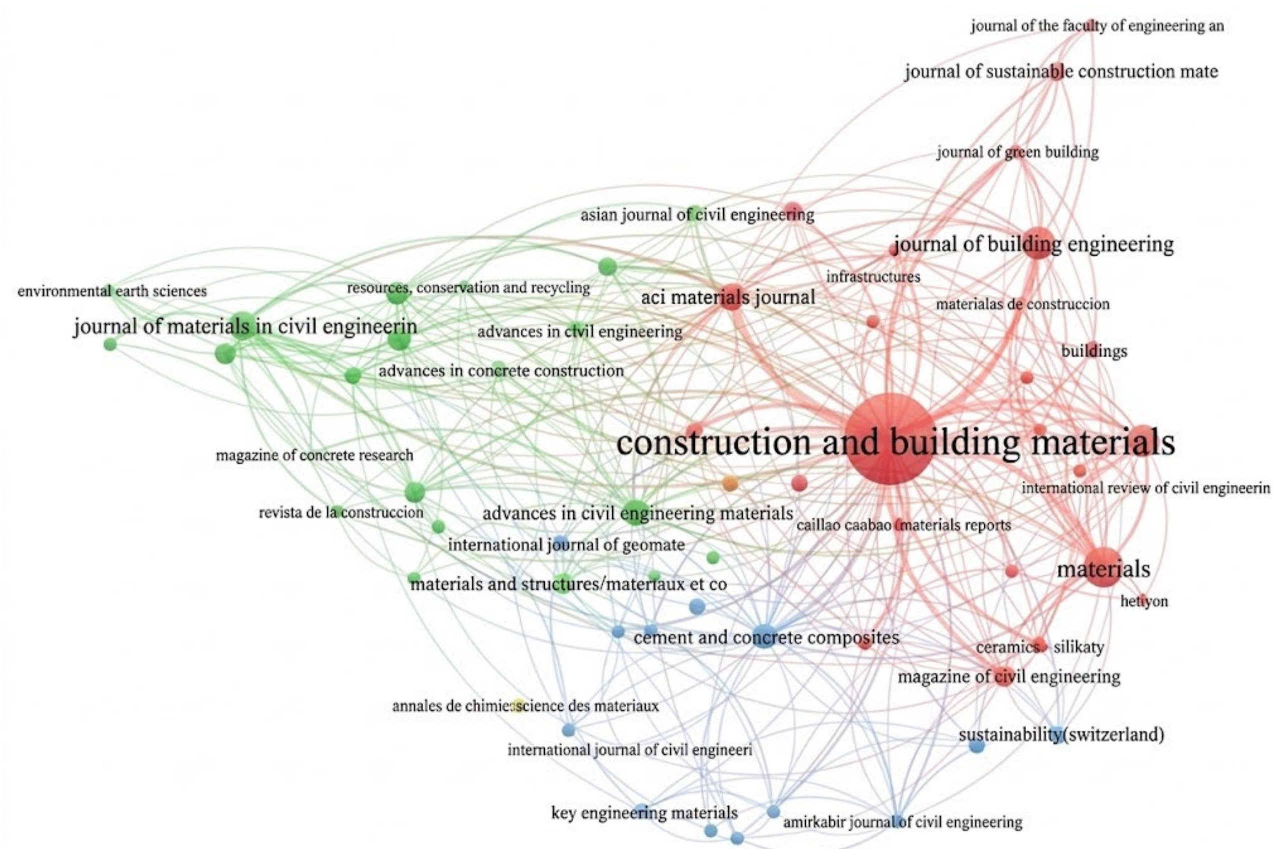

Figure 8. Bibliographic citation network among publication sources.
Source: Created by the author using VOSviewer, based on records retrieved from Scopus.

The network highlights the formation of thematic clusters associated with cementitious materials, civil engineering, and sustainability. Some journals with fewer articles exert significant influence within the network, indicating that bibliometric relevance depends not only on the volume of publications but also on their connections and the impact of the published articles.

4.1.3 Geographic distribution of scientific output.

The analysis by country reveals a significant geographic concentration of scientific output on volcanic ash and natural pozzolans as SCMs. As shown in Figure 9, Saudi Arabia, Iran, and Turkey rank among the countries with the highest number of publications, followed by China, Spain, Greece, and Egypt. This distribution reflects the existence of established research groups in regions with a long tradition of studying natural pozzolans, alternative cementitious materials, and concrete durability.

It is important to note that Figure 9 represents scientific output by affiliation or country of publication, not the geological availability of the resource. Therefore, Ecuador's low presence in bibliometric output should not be interpreted as an absence of volcanic ash, but rather as a gap in applied research. This distinction is relevant because the potential for using volcanic ash as an SCM depends not only on its territorial presence but also on its chemical composition, amorphous phase, fineness, accessibility, logistics, pretreatment, and regulatory validation. The geographic distribution of scientific output is presented in Figure 9. The map represents the number of publications by the authors' country of affiliation and not the availability of volcanic ash reserves or deposits.

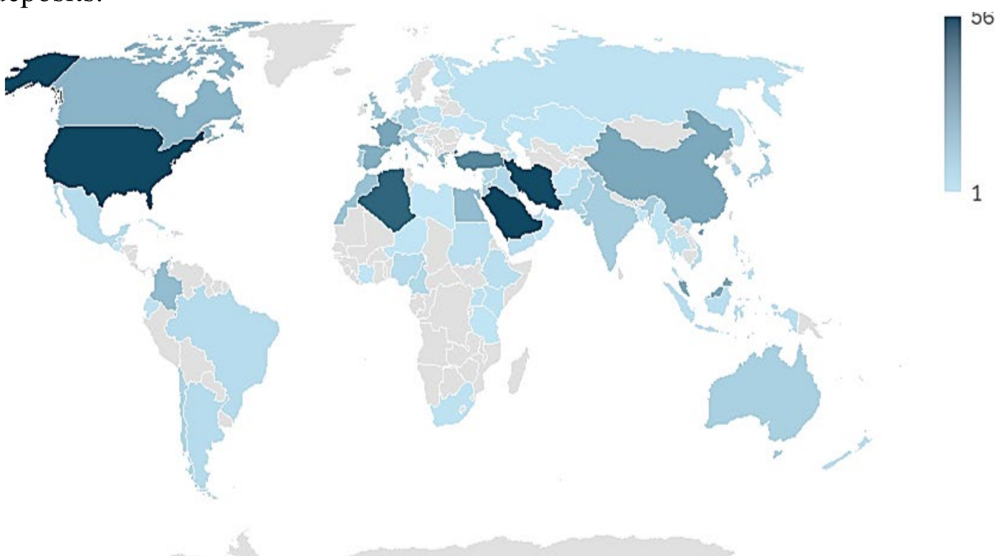

Figure 9. Geographic distribution of scientific output
Source: Author's own work based on data exported from Scopus.

Figure 10 shows the international collaboration network generated using VOSviewer. The size of the nodes represents the relative volume of scientific output, while the links indicate co-authorship relationships between countries. The presence of regional clusters suggests that the development of knowledge regarding volcanic ash as a cementitious material is associated with established research networks, particularly in Asia, the Middle East, and Europe. For Ecuador, this bibliometric analysis highlights a strategic opportunity: to strengthen international collaborations that enable the transfer of methodologies for characterization, durability assessment, and validation of cementitious mixtures with natural pozzolans. Figure 10 shows the international co-authorship network. The size of the nodes represents each country's scientific output, while the links show collaborative relationships between authors from different countries.

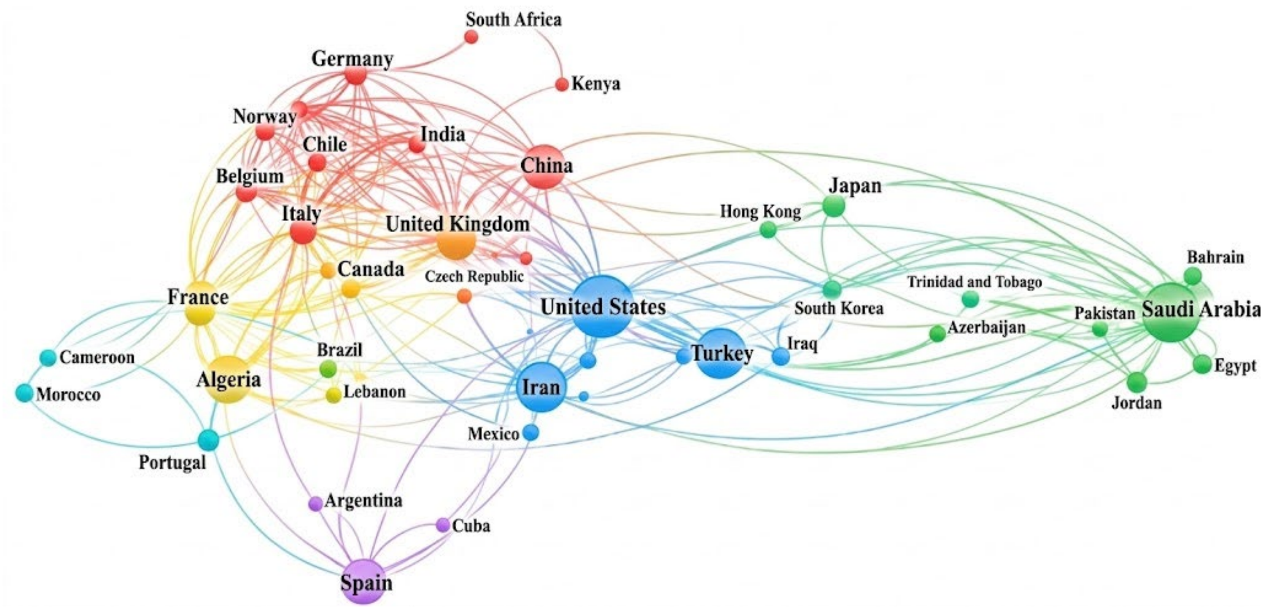

Figure 10. Visualization of the collaboration network among countries
Source: created by the authors using VOSviewer, based on records retrieved from Scopus.

4.1.4 Keyword co-occurrence.

The keyword analysis conducted using VOSviewer included the consolidation of similar terms to prevent duplicates and represent the most prominent concepts with greater accuracy. Figure 11 presents the keyword co-occurrence network, after merging synonyms and terminological variants. The main thematic clusters relate to mechanical performance, durability, pozzolanic activity, chemical characterization, and sustainability.

The co-occurrence of keywords made it possible to identify the central themes regarding the use of volcanic ash as a supplementary cementitious material. Figure 11 shows a network highlighting terms associated with mechanical performance—particularly compressive and flexural strength—and with comparisons of volcanic ash to other pozzolans. Also prominent are concepts related to Portland cement and material durability, such as permeability, resistance to chlorides and sulfates, and freeze-thaw effects. In addition, terms related to its chemical and mineralogical characterization appear, highlighting interest in its pozzolanic reactivity. Finally, the presence of words associated with geopolymers, alkaline activation, and carbon footprint indicates their relevance in research aimed at developing more sustainable materials.

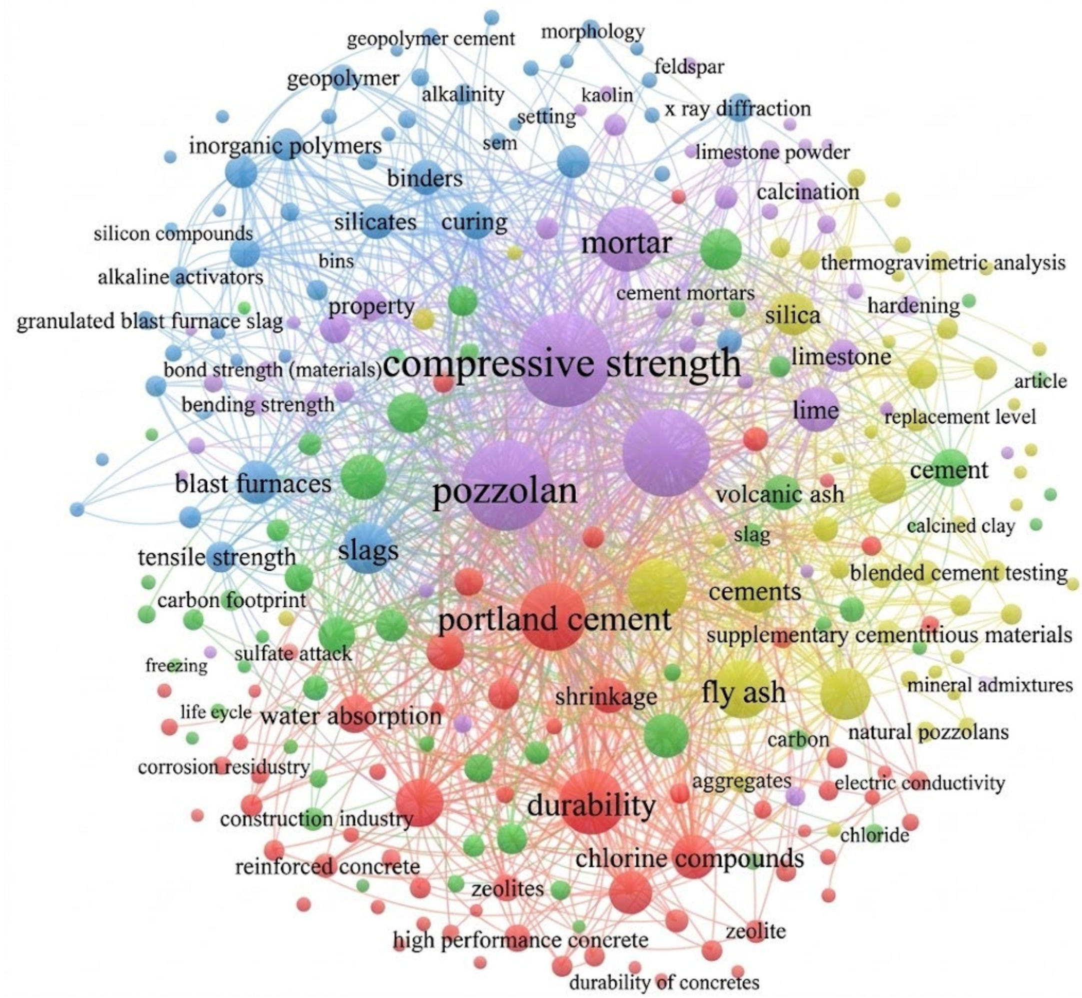

Figure 11. Overlaid visualization of keywords by cluster
Source: Created by the authors using VOSviewer, based on records retrieved from Scopus.
Note: The keywords are retained in English, as they were retrieved and indexed in Scopus and processed in VOSviewer, in order to preserve traceability, terminological consistency, and the reproducibility of the bibliometric analysis.

4.2 Mechanical performance and factors controlling the reactivity of volcanic ash.

The mechanical performance of mortars and concretes containing volcanic ash does not depend solely on the percentage of cement substitution, but rather on the interaction between chemical composition, amorphous fraction, fineness, particle size, specific surface area, availability of portlandite, and curing conditions. These factors control the rate and magnitude of the pozzolanic reaction. In particular, the content of reactive SiO_2 and Al_2O_3, together with the amorphous fraction, determines the ash's ability to react with the $Ca(OH)_2$ released by the hydration of Portland cement. Fineness and specific surface area increase the contact area and can promote both the filler effect and the nucleation of hydration products. As a result, when sufficient calcium is available in the matrix, the secondary formation of C-S-H and C-A-S-H gels is promoted, which are responsible for pore refinement, matrix densification, and improved mechanical and durability performance. Conversely, high substitutions can reduce the amount of hydratable clinker, limit the availability of portlandite, and intensify the dilution effect, leaving fractions of the ash partially unreacted (Khan et al., 2019, 2022; S. Singh et al., 2026).

The reviewed evidence shows that volcanic ash contents between 10% and 20% typically offer the most favorable balance between early strength, long-term strength, and workability. Within this range, volcanic ash can act simultaneously through a physical filling effect, nucleation of hydration products, and pozzolanic reaction, promoting the secondary formation of C-S-H and C-A-S-H. These products contribute to the refinement of the porous network, the densification of the matrix, the reduction of capillary connectivity, and the development of medium- and long-term mechanical strength (Hasan et al., 2024; K. M. A. Hossain & Lachemi, 2007; Lo et al., 2009; Özen & Uzal, 2021). At these levels, the pozzolanic reaction of fly ash promotes the additional formation of C-S-H and C-A-S-H gels, densifying the microstructure and improving durability (Y. Cao et al., 2025; Jackson et al., 2017; Wei et al., 2005). At moderate replacement levels (5–10%), simultaneous increases in strength, durability, and workability are even observed (Hossain, 2005; Shahjalal et al., 2025), whereas replacements exceeding 20–30% tend to reduce early strength and workability due to cement dilution and incomplete pozzolanic reaction (Edris et al., 2021; Hasan et al., 2024; Zhou et al., 2021).

However, at high replacement levels (>30%), long-term strength can be maintained or even increased through activation methods and synergistic blends with other byproducts (slag, other supplementary cementitious materials, and nanoadditives), as well as through optimized curing regimens (Ababneh et al., 2024; Bawab et al., 2024; Díaz et al., 2013; Khan & Amin, 2017; Martín-Rodríguez et al., 2024; Zhou et al., 2021). The fineness, chemical composition, and amorphous content of fly ash are key factors that control its reactivity and its effect on strength (M. Cao & Zhang, 2023; Hazarika et al., 2025; Kupwade-Patil, Tyagi, et al., 2016; Masmoudi et al., 2017). Furthermore, in aggressive environments, such as marine environments or at high temperatures, concretes containing 10–20% CV exhibit better residual mechanical performance and greater durability compared to conventional Portland cement (A Lachemi, 2004; Anwar Hossain, 2006; Demirel & Keleştemur, 2010; Jackson et al., 2017; Wahyuni et al., 2025). Overall, the literature supports the view that VA is an effective cementitious material for improving compressive strength when dosed within optimal ranges and its activation and curing are properly controlled (Bawab et al., 2024; Hasan et al., 2024; Zhou et al., 2021). Overall, the literature supports the finding that volcanic ash can improve compressive strength when incorporated within appropriate replacement ranges and when its reactivity, fineness, and curing conditions are controlled. Table 1 provides a comparative summary of the main effects of volcanic ash content on early strength, long-term strength, and workability.

Table1 . Effect of volcanic ash content on compressive strength

VA Content (% replacement)	**Early-age strength**	**Long-term strength**	**Workability**	**Activation effects / mixtures**
5–10	Comparable / ↑	↑	↑	Better for workability and durability (A Lachemi, 2004; Hossain, 2005; Bashir & Elahi, 2023; Bawab et al., 2025b; Dahiru et al., 2019; Klausen et al., 2025; Shahjalal et al., 2025; Uzbaş & Aydın, 2019)
10–20	Slight ↓ / ≈	↑	≈	Optimal for strength and workability (Hasan et al., 2024; K. M. A. Hossain & Lachemi, 2007; Kupwade-Patil, Chin, et al., 2018; Lo et al., 2009)
20–30	↓	≈ / ↑	↓	Requires activation or synergistic mixtures (Hasan et al., 2024; Kupwade-Patil, Chin, et

				al., 2018; Martín-Rodríguez et al., 2024; Zhou et al., 2021)
>30	↓↓	≈ / ↑ (with activation)	↓↓	Synergistic mixtures and activation are essential (Bawab et al., 2024; Hasan et al., 2024; Khan et al., 2022; Kupwade-Patil, Chin, et al., 2018; Uzbaş & Aydın, 2019; Zhou et al., 2021; Zhuginissov et al., 2026)

Legend: ↑ = Improved; ↓ = Reduced; ≈ = Comparable to control.
Source: Prepared by the authors based on the scientific evidence cited for each replacement range.

4.2.1 Chemical and physical variability of volcanic ash.

The chemical and physical variability of volcanic ash is one of the factors that most strongly influences its performance as a SCM. Unlike more tightly controlled industrial materials, volcanic ash can exhibit significant differences in the content of SiO_2, Al_2O_3, Fe_2O_3, CaO, alkalis, loss on ignition, amorphous phase, crystalline phases, fineness, particle size, and specific surface area. This variability explains why the optimal substitution ranges reported in the literature cannot be generalized without prior characterization of the material.

From a chemical standpoint, ashes with a higher proportion of amorphous silicoaluminate phases tend to exhibit greater pozzolanic potential, provided there is sufficient $Ca(OH)_2$ available in the cementitious matrix. In these cases, the reaction with portlandite can promote the formation of C-S-H and C-A-S-H, products responsible for microstructural densification. In contrast, fly ash with high crystalline content, low fineness, or a limited reactive fraction may act predominantly as a filler, providing physical benefits but making a lesser chemical contribution to strength development. The chemical and physical variability identified in the reviewed studies is presented in Table 2. The information was extracted from the original articles and organized comparatively to show the differences in chemical composition, mineralogy, fineness, particle size, and specific surface area of the evaluated volcanic ashes.

Table 2. Chemical and physical variability of volcanic ash.

Author / year	Country or source of the material	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	$Na_2O + K_2O$ (%)	SO_3 (%)	Loss on ignition (%)	Amorphous phase / reported mineralogy	Fineness / particle size (D_{50}, percentage retained, or mesh size)	Specific surface area (m²/kg or m²/g, Blaine method)	Evaluated application
(K. M. A. Hossain, 2003)	Papua New Guinea (Mt. Tavurvur)	59.34	17.54	7.06	6.12	2.55	5.83	0.7	1.03	—	Retained on 75 µm sieve: 42%	242 m²/kg	Cement mixtures, mortar, and concrete
(Hazarika et al., 2025)	Iceland (VM 1)	43.8	14.6	13.3	11.95	7.44	2.24	—	-0.51	Albite, Anorthite, Andesine, Oligoclase	D50: 9–37 µm	4–13 m²/g (BET)	Reactivity MR3 (SCM)
(Hazarika et al., 2025)	Iceland (VM 2)	47	12.75	17.2	9.31	4.92	3.96	—	-0.7	Albite, Anorthite, Andesine, Oligoclase	D50: 9–37 µm	4–13 m²/g (BET)	Reactivity MR3 (SCM)
(Hazarika et al., 2025)	Iceland (VM 3)	65.6	14.9	7.7	3.62	0.83	6.71	—	1.44	Olivine, Albite, Oligoclase	D50: 9–37 µm	4–13 m²/g (BET)	Reactivity MR3 (SCM)
(Hazarika et al., 2025)	Iceland (VM 4)	61.7	14.05	6.04	6.61	2.86	5.35	—	2.45	Albite, Anorthite, Oligoclase	D50: 9–37 µm	4–13 m²/g (BET)	Reactivity MR3 (SCM)
(Flores Medina et al., 2015)	Natural Pozzolan	55	15.9	4.2	2.2	1.5	9.5	—	11.2	—	—	—	Concrete

(Edris et al., 2021)	Jordan (North)	34.39	4.59	31.5	24.11	0.49	1.30 (K_2O)	—	—	Volcanic tuff	< 75 µm	—	Concrete
(Demirel & Keleştemur, 2010)	Turkey (Mt. Meryem)	49.52	16.72	11.3	8.26	4.54	—	—	1.68	Pumice	—	—	Concrete
(Amine et al., 2017)	Pozzolan 1 (Pz1)	49.5	18	10	7.5	5.5	7	0.1	1.6	—	—	—	Mineral supplementatio n
(al-Swaidani et al., 2016)	Syria (Dirat-at-Tulul)	46.52	13	11.4	10.1	9.11	2.91	0.3	2.58	Slag; Olivine, Plagioclase, Glass	D50: 17.5 µm (inter-ground)	3,200 cm²/g	Mortar and concrete
(Dahiru et al., 2019)	Nigeria (Jos Plateau)	28.1	18	35.1	0.29	0.26	0.28	—	15.9	—	< 75 µm	—	Concrete
(Zunino & Scrivener, 2024)	Natural Pozzolan (NP)	68.97	13.92	2.09	1.51	0.73	7.01	0.1	4.27	—	—	2.89 m²/g (BET)	Low-clinker cement paste
(Letelier et al., 2018)	Chile (Calbuco Valley)	57.76	14.54	11	8.27	2.44	4.55	—	—	Volcanic glass (~57%)	< 75 µm	285 m²/kg	Concrete
(Kupwade-Patil, Al-Aibani, et al., 2016)	Saudi Arabia (Basalt)	38.89	13	12.4	9.09	6.16	4.43	0.1	1.8	Amorphous phase: 71.7%; Anorthite, Forsterite	D50: 10.0 µm; Mean: 17.14 µm	—	Cement paste

(Djon Li Ndjock et al., 2017)	Cameroon (P1)	40.1	16.3	13.5	6.3	5.3	1.3	—	11.1	Amorphous: 42.5%; Muscovite, Hematite	—	7,319 cm²/g	Geopolymer
(Hossain, 2005)	Mexico	68.2	11.2	1.8	1	0.2	0.20 (Na_2O)	0	—	—	—	—	Marine concrete
(Jackson et al., 2017)	Italy (Neapolitan)	38.9–60.2	18.6–30.7	—	0.4–10.7	0.0–0.2	7.9–19.0	—	—	Phillipsite (Zeolite)	—	—	Mineral cement
(Jubera-Pérez et al., 2024)	Spain (La Palma)	38.2	14.1	18.6	11.2	6.5	4.5	0.2	—	Amorphous: 63.5–72.5%	D: 23, 28, and 45 µm	—	Mortar (SAI)
(Yu et al., 2015)	China (Jiangxi - NQ)	74.81	11.15	1.87	1.39	0.16	7.72	—	1.71	Amorphous: 76.8%; Quartz, Labradorite	90% < 45 µm	—	Mortar
(Zeyad et al., 2023)	VPD (Pumice Powder)	48.06	16.83	7.63	12.52	6.59	3.65	0.3	1.61	Quartz, amorphous aluminosilicate phase	1.0–15 µm	4090 cm²/g	Concrete
(Keshta et al., 2022)	Egypt (Wadi El-Anbgy)	67.04	14.9	2.59	3.27	1.72	6.54	0.3	2.83	—	Passes through #170 sieve	—	Concrete
(Martín-Rodríguez et al., 2024)	Spain (La Palma)	41.56	14.49	14.7	11.92	5.57	5.96	0.2	—	Diopside, Augite, Magnetite, Bytownite	96% < 45 µm; 91% < 32 µm	—	Hybrid and alkaline cement

Source: Compiled by the authors based on data reported in the studies cited in the first column.
Note: VM1–VM4, MR3, and Pz1 correspond to the identification codes used by the authors of the original studies; "—" indicates information not reported.

4.3 Effect on flexural strength.

Scientific evidence shows that the flexural strength of concrete and mortar containing volcanic ash (VA) depends heavily on the percentage of cement replacement. Consistently, the studies agree that replacement ranges between 10–20%, with 15% being the most common value, allow for maximizing flexural strength, with significant increases compared to control mixtures (Al-Swaidani, 2017; Bawab et al., 2024; Hasan et al., 2024; A. Hossain et al., 2006; Keshta et al., 2022; Shahjalal et al., 2025). This behavior is attributed to the pozzolanic reaction of CV, which generates additional C-S-H and C-A-S-H gels, promoting the densification of the cementitious matrix and the refinement of the interfacial transition zone (ITZ) (Bawab et al., 2024; Khan et al., 2022; Nováková et al., 2024; Peng et al., 2024; Wang et al., 2025). At substitution levels above 20%, strength tends to stabilize or decrease, primarily due to cement dilution effects and incomplete pozzolanic reaction, although prolonged curing can partially mitigate this loss (Ali et al., 2023; Anwar Hossain, 2006; Hasan et al., 2024; Keshta et al., 2022; Mohamad et al., 2020; Zeyad et al., 2023; Zhuginissov et al., 2026).

Likewise, the fineness of the volcanic ash and the activation methods play a decisive role: finer particles and physical or chemical treatments increase reactivity and enhance flexural strength (al-Swaidani et al., 2016; Begaye et al., n.d.; Khan et al., 2019; Khan & Amin, 2017; J. Liu et al., 2017; L. P. Singh et al., 2017; Xiong et al., 2022; Zhang et al., 2025). However, high CV contents affect workability and setting time, especially at replacement rates above 25–35% (Bawab et al., 2024, 2025b; Hasan et al., 2024; K. M. A. Hossain, 2003), which requires the use of additives and pretreatment strategies (Keshta et al., 2022; Ogunbode & Hassan, 2011; Zhang et al., 2025).

Table 3 summarizes the effect of the volcanic ash replacement percentage on the flexural strength of mortars and concretes. The analyzed data indicate that the greatest increases are typically achieved in the 10–15% range, while contents exceeding 25–35% tend to reduce performance due to the dilution effect and the reduced availability of hydration products.

Table 3. Effect of volcanic ash (VA) replacement on the flexural strength of mortars and concretes.

Percentage of VA replacement	Trend in flexural strength	Dominant mechanism	Effect on workability/ setting	References
0% (control)	Reference value	Normal cement hydration	Normal	(Al-Swaidani, 2017; Hasan et al., 2024)
5%	↑ Moderate increase (up to +15–17%)	Micro-filler and early activation	Slight decrease	(Shahjalal et al., 2025; L. P. Singh et al., 2017)
10%	↑↑ High increase	Optimal formation of C-S-H and C-A-S-H, refinement of the ITZ	Acceptable	(Al-Swaidani, 2017; Hasan et al., 2024; A. Hossain et al., 2006; Shahjalal et al., 2025)
15%	↑↑ Maximum increase (optimal)	Densification of the matrix and ITZ	Slight reduction	(Al-Swaidani, 2017; Bawab et al., 2024; Hasan et al., 2024; A. Hossain et al., 2006)
20%	↑ / ↔ Plateau	Maximum pozzolanic benefit with onset of dilution	Moderate reduction	(Bawab et al., 2024; Hasan et al., 2024; A. Hossain et al., 2006)

25–35%	↓ Decrease	Cement dilution and incomplete hydration	Significant decrease	(Ali et al., 2023; Hasan et al., 2024; Zeyad et al., 2023)
>40%	↓↓ Severe decrease	Excessive dilution, low reactivity	Slow setting, low workability	(Bawab et al., 2024; K. M. A. Hossain, 2003)

Source: Prepared by the author based on the scientific evidence cited for each replacement range. Note: ↑ indicates an increase; ↓ indicates a decrease; ↔ indicates stable behavior relative to the control mix.

4.4 Optimization strategies to expand the use of volcanic ash.

To expand the use of volcanic ash beyond conventional replacement ranges, simply increasing its dosage is not enough. Its performance must be optimized through beneficiation strategies and mix design. Controlled grinding can increase the specific surface area and accelerate the pozzolanic reaction, although this must be balanced against water demand, compatibility with superplasticizers, and the potential increase in energy consumption associated with processing the material. Particle size classification helps reduce coarse particles with low reactivity and improve the filler effect, while thermal or chemical activation can increase the availability of reactive phases. However, these strategies must be evaluated using technical, energy, economic, and environmental criteria, as intensive treatments could diminish some of the benefits associated with reducing clinker content (Khan et al., 2022; J. Rajesh & Kandasamy, 2025; Zhao et al., 2018).

Another strategy involves formulating binary or ternary systems that combine volcanic ash with other SCMs or with cements of different compositions, seeking to balance $Ca(OH)_2$ availability, reactive alumina content, pore refinement, and mechanical performance. These alternative could allow for greater reductions in the clinker factor without compromising durability; however, they require specific experimental validation for each ash source, especially in contexts such as Ecuador, where mineralogical and logistical variability limits the standardization of the material (Bawab et al., 2024; de Siqueira & Cordeiro, 2022; Rodrigues et al., 2022).

4.5 Impact on durability: sulfate resistance.

The incorporation of volcanic ash (VA) significantly improves the resistance of concrete and mortar to sulfate attack, primarily due to its pozzolanic activity, which reduces the calcium hydroxide content and refines the pore structure, thereby limiting the ingress of sulfate ions and the formation of expansive ettringite (Bawab et al., 2025b; Canpolat et al., 2007; Das Gupta et al., 2025). Optimal replacement levels range from 10–20%, where an adequate balance between early mechanical strength and long-term durability is achieved, although replacement levels of up to 40% can be used when sulfate resistance is prioritized over early strength (Das Gupta et al., 2025; A. Hossain et al., 2006; Kupwade-Patil, De Wolf, et al., 2018).

From a microstructural perspective, CV reduces porosity, increases the ultrasonic pulse velocity, and densifies the cementitious matrix, thereby hindering sulfate diffusion and internal expansion (Al-jabali et al., 2025). Furthermore, the consumption of reactive aluminates and $Ca(OH)_2$ decreases the nucleation and growth of ettringite, thereby reducing microcracking (Amine et al., 2017; Bawab et al., 2025a; Khan et al., 2022; Rols et al., 2000; Souza et al., 2023; Zunino & Scrivener, 2025). The fineness and amorphous content of the CV have a decisive influence on its effectiveness, since finer particles with a higher amorphous phase accelerate the pozzolanic reaction and enhance sulfate resistance (Djon Li Ndjock et al., 2017; Jaturapitakkul et al., 2007; Jubera-Pérez et al., 2024; Shahjalal et al., 2025; Suraneni et al., 2019; Yu et al., 2015). Under severe environmental exposure conditions, such as wetting–drying cycles, CV performs better than

conventional Portland cement, especially at replacement rates of 20–30% (Gao et al., 2010; Omikrine Metalssi et al., 2024). Overall, the evidence supports the conclusion that CV is a highly effective material for increasing the durability of concrete in sulfate-containing environments, provided that its dosage, fineness, and curing regimen are optimized (Al-jabali et al., 2025; Bawab et al., 2025b; Das Gupta et al., 2025; Hasan et al., 2024; Kiran Kumar et al., 2024; Nair & Viswanathan, 2023; Wang et al., 2023).
Replacement levels of 10–20% have proven particularly effective in improving this property, although good performance has been reported at levels as high as 40% (K. M. A. Hossain & Lachemi, 2004; Sideris & Savva, 2001). The performance of CV in this area is comparable to and even superior to that of other conventional SCMs (Khan et al., 2022; Siddique, 2012).

4.6 Impact on durability: permeability.

Permeability, which measures the ease with which fluids and aggressive agents (such as water and chlorides) can penetrate concrete, is a key indicator of its durability. The incorporation of volcanic ash (VA) as a partial cement replacement significantly reduces the permeability of concrete, primarily due to the refinement of the porous structure and the densification of the matrix resulting from its pozzolanic reaction (A. Lachemi, 2004; Darwis et al., 2018; Edris et al., 2021; K. M. A. Hossain & Lachemi, 2007; Vedalakshmi et al., 2003). The most consistent results are reported in the 10–20% substitution range, where the lowest values of water absorption and permeability are achieved, along with a substantial improvement in resistance to chloride penetration, with reductions of up to 80–90% in diffusivity (Altimari et al., 2025; Anwar Hossain, 2006; Edris et al., 2021; Ibrahim et al., 2025). For higher replacement levels (20–40%), permeability continues to decrease, although with losses in e r early strength; these levels are appropriate when long-term durability is prioritized over initial mechanical performance (Al-Swaidani, 2017; Anwar Hossain, 2006; A. Hossain et al., 2006; K. M. A. Hossain & Lachemi, 2007). However, replacement rates exceeding 40% can lead to increased porosity and unreacted ash, compromising both mechanical strength and carbonation resistance (Kupwade-Patil, Al-Aibani, et al., 2016; Lammertijn & De Belie, 2008).
From a microstructural perspective, CV reduces pore connectivity, decreases the dominant pore diameter, and promotes the formation of pozzolanic products (C-S-H, Al-tobermorite, phillipsite), which limits the transport of water and chlorides (Elshinawy et al., 2025; A. Hossain, n.d.; Hu & Du, 2013; Jackson et al., 2017; Játiva et al., 2025; Vedalakshmi et al., 2003). The fineness, origin, and activation of fly ash directly influence its effectiveness, with better results observed for fine fly ash with a high amorphous content (Khan et al., 2019; Mitrović, 2011). Friedel salt formation further contributes to the immobilization of chlorides (A. Lachemi, 2004; K. M. A. Hossain & Lachemi, 2004; J. C. Liu et al., 2023; Tomoyose et al., 2020). In aggressive environments, such as marine areas or those with wet–dry cycles, CV-based concretes exhibit superior performance compared to conventional Portland cement (Ho et al., 2023; A. Hossain, n.d.). However, at high replacement levels, the increase in carbonation depth poses a limitation that must be mitigated through optimized mix design, proper curing, and combined use with other SCMs or nano-additives (Flores Medina et al., 2015; A. Hossain et al., 2006; Ibrahim et al., 2025). Overall, the evidence confirms that CV is highly effective in improving the impermeability of concrete when dosed within optimal ranges and under appropriate curing conditions (Kupwade-Patil, Palkovic, et al., 2018; Sharfuddin Ahmed et al., n.d.; Vedalakshmi et al., 2003).
The identified effects on durability are summarized in Table 4. Generally speaking, ash contents between 10% and 20% yield the most favorable results regarding permeability, chloride ingress, and sulfate attack; however, performance depends on the composition and fineness of the ash, curing conditions, and the exposure environment. At high replacement rates, the lower alkaline reserve may increase the risk of carbonation.

Table 4. Summary of effects on durability.

Property	Optimal CV Range	Main effect	Dominant mechanism	Technical Limit	References
Sulfate resistance	10–20% / up to 40% in certain cases	Lower expansion and greater durability	Pore refinement, portlandite consumption, reduced expansive formation	Depends on aluminates, curing, and ash composition	(Bawab et al., 2025b; Canpolat et al., 2007; Das Gupta et al., 2025; A. Hossain et al., 2006; K. M. A. Hossain & Lachemi, 2004; Kupwade-Patil, De Wolf, et al., 2018; Sideris & Savva, 2001)
Microstructure in sulfate environments	10–30%	Denser matrix and reduced microcracking	Pore refinement and aluminate consumption		(Al-jabali et al., 2025; Amine et al., 2017; Bawab et al., 2025a; Khan et al., 2022; Rols et al., 2000; Souza et al., 2023; Zunino & Scrivener, 2025)
Water permeability	10–20%	Reduction in permeability	Densification and reduced capillary connectivity	Water demand may increase if the ash is very fine	(A Lachemi, 2004; Darwis et al., 2018; Edris et al., 2021; K. M. A. Hossain & Lachemi, 2007; Vedalakshmi et al., 2003)
Chloride diffusion	10–20%	Reduced chloride penetration	Pore refinement and possible chemical fixation	Requires evaluation of the Al_2O_3/AFm phases ratio	(Altimari et al., 2025; Anwar Hossain, 2006; Edris et al., 2021; Ibrahim et al., 2025; J.

					C. Liu et al., 2023; Tomoyose et al., 2020)
Aggressive environments (marine, wet–dry cycles)	20–30% in some systems	Better long-term performance	Prolonged curing and refined matrix	Do not extrapolate without local characterization	(Hossain, 2005; Gao et al., 2010; Ho et al., 2023; Omikrine Metalssi et al., 2024)
High replacement rates	>40%	Increased porosity and carbonation	Unreacted ash and dilution effect		(Flores Medina et al., 2015; Kupwade-Patil, Al-Aibani, et al., 2016; Lammertijn & De Belie, 2008)

Source: Author's own compilation based on the studies cited for each evaluated property.

Although moderate substitution ranges offer the best balance between mechanical properties and durability, their contribution to a significant reduction in the clinker factor remains limited. Therefore, Table 5 presents a critical interpretation of the substitution ranges, relating the expected technical performance to their potential for reducing the clinker factor, the associated risks, and the necessary optimization strategies.

Table 5. Critical interpretation of substitution ranges in relation to clinker factor reduction.

Substitution range	**Expected technical performance**	**Contribution to clinker factor reduction**	**Main risk**	**Optimization strategy**
5–10%	Moderate improvement due to filler and nucleation effects	Low	Limited environmental impact	Use in conventional cements without major changes
10–20%	Improved mechanical balance and durability	Moderate	Depends on reactivity and curing	Fineness control and chemical characterization
20–30%	Greater environmental potential	Medium-high	Lower early strength	Grinding, extended curing, additives
30–40%	Possible in optimized systems	High	Lack of portlandite and dilution effect	Ternary systems, activation, suitable cements
>40%	High environmental	Very high	Low early strength, unreacted	Strict experimental validation; no

	potential, but performance depends on activation and mix design		ash, and possible increased carbonation due to lower alkaline reserve	general recommendation

Source: Prepared by the authors based on a critical synthesis of the results reported in the included studies.

As shown in Table 5, contents between 10% and 20% offer the most favorable technical balance, although their impact on clinker factor reduction is moderate. Replacements between 20% and 40% present greater environmental potential but require fineness control, extended curing, additives, or ternary systems to compensate for lower early strength and reduced available portlandite. Above 40%, the use of volcanic ash cannot be generally recommended due to the risk of dilution, the presence of unreacted particles, and increased susceptibility to carbonation.

5. DISCUSSION OF RESULTS

5.1 Analysis of the findings.

Bibliometric results show that scientific interest in volcanic ash as a supplementary cementitious material has grown steadily since 2015, with research output concentrated primarily in the fields of Materials Engineering and Materials Science. This focus confirms that the literature has prioritized the evaluation of mechanical performance, durability, and the physical-chemical characterization of cementitious mixtures containing volcanic materials, as shown in Figures 5, 6, and 11.

The geographic distribution reveals a significant concentration of scientific output in countries such as Iran, Saudi Arabia, and Turkey, accompanied by well-established collaborative networks in Asia, the Middle East, and Europe, as shown in Figures 9 and 10. In contrast, Ecuador's participation remains limited, despite the fact that the country is located in a region of recurring volcanic activity and possesses potential sources of volcanic materials of interest for cementing applications (Pinos-Velez et al., 2024; Toulkeridis & Zach, 2017). This discrepancy between potential geological availability and scientific development represents a gap in applied research, although it does not, on its own, allow us to conclude that there is proven industrial availability of the resource.

Keyword analysis confirms that the literature centers on mechanical strength, durability, pozzolanic activity, chemical composition, and microstructure. These results provide the framework for critically interpreting substitution ranges, physicochemical mechanisms, and limitations associated with the variability of volcanic ash.

5.2 The optimal balance in mechanical performance.

Analysis of mechanical properties shows that volcanic ash can improve compressive and flexural strength when used within moderate replacement ranges and exhibits sufficient reactivity. In general, the 10–20% range offers the best balance between early-age strength and long-term strength development, as summarized in Table 1 (Hasan et al., 2024; K. M. A. Hossain & Lachemi, 2007; Kupwade-Patil, Chin, et al., 2018; Lo et al., 2009).

Within this range, the reactive silicoaluminate phases in the ash consume part of the portlandite generated during clinker hydration and promote the secondary formation of C-S-H and C-A-S-H, contributing to matrix densification and the refinement of the porous network (Y. Cao et al., 2025; Jackson et al., 2017; Wei et al., 2005). Conversely, substitutions exceeding 30% tend to reduce early strength due to the dilution effect, the reduced amount of hydratable clinker, and the possible presence of unreacted ash particles (Bawab et al., 2024; Hasan et al., 2024; Zhou et al., 2021).

The formation of C-A-S-H is influenced by the availability of reactive silicon and aluminum, the amorphous fraction of the ash, the presence of calcium from portlandite, the alkaline environment, particle size, and curing conditions. Consequently, the presence of volcanic ash alone does not guarantee the formation of these products; the mechanism depends on the interaction between the reactivity of the material and the chemical conditions of the cementitious matrix (Fernandes et al., 2025; Játiva et al., 2025; Kupwade-Patil, De Wolf, et al., 2018; Tomoyose et al., 2020).

This interpretation explains why moderate substitutions typically outperform high-level replacements. When there is sufficient hydratable clinker, the matrix has portlandite available to sustain the pozzolanic reaction; when the replacement is excessive, the calcium source decreases and the fraction of potentially unreacted ash increases. However, this limit can be shifted through grinding, activation, extended curing, or ternary cement systems, provided that their technical and environmental effectiveness is verified (Ababneh et al., 2024; Bawab et al., 2024; Khan & Amin, 2017; Martín-Rodríguez et al., 2024; Zhou et al., 2021).

For flexural strength, the evidence indicates that the most favorable range is between 10% and 15%, as shown in Table 3. This behavior is related to the refinement of the matrix and the interfacial transition zone, which improves aggregate–paste adhesion and the response to flexural tensile stresses (Bawab et al., 2024; Khan et al., 2022; Peng et al., 2024). However, further increases may reduce workability and delay setting, especially when the fineness of the material increases water demand or when the dilution effect predominates (Bawab et al., 2024; Hasan et al., 2024; K. M. A. Hossain, 2003).

Taken together, fineness, chemical composition, amorphous fraction, activation processes, and curing conditions determine whether a high replacement rate can maintain acceptable mechanical performance. Therefore, the percentage of volcanic ash should not be used as the sole design criterion (M. Cao & Zhang, 2023; Hazarika et al., 2025; Kupwade-Patil, Tyagi, et al., 2016; Masmoudi et al., 2017).

5.3 Durability: benefits and performance limits.

Scientific evidence confirms that volcanic ash (VA) significantly improves the durability of concrete, especially against sulfate attack and chloride penetration. Replacement rates of 10–20% are optimal for balancing mechanical performance and durability, although levels of up to 40% can be considered when long-term chemical resistance is prioritized; however, their performance depends on reactivity and mix design, as summarized in Table 4. This behavior is explained by the pozzolanic reaction of CV, which consumes portlandite ($Ca(OH)_2$), refines the pore structure, and limits the formation of expansive ettringite in sulfate-containing environments (Bawab et al., 2025b; Canpolat et al., 2007; Das Gupta et al., 2025).

Furthermore, in the 10–20% range, reductions of up to 80–90% in permeability and chloride diffusion have been reported, attributable to the densification of the matrix and the formation of Friedel's salt, which chemically immobilizes the chlorides (Anwar Hossain, 2006; Edris et al., 2021; Ibrahim et al., 2025). However, replacement rates exceeding 40% can increase the depth of carbonation and reduce mechanical strength due to a decrease in the concrete's alkali reserve (Flores Medina et al., 2015; Kupwade-Patil, Al-Aibani, et al., 2016; Lammertijn & De Belie, 2008). Therefore, the VA content should be defined as a critical design parameter, particularly relevant in contexts with high availability of volcanic resources, such as Ecuador.

5.4 Opportunities and conditions for the utilization of volcanic ash in Ecuador.

Ecuador offers favorable geological conditions for researching volcanic ash and natural pozzolans as potential supplementary cementitious materials, due to its location in a region of recurring

volcanic activity. However, this condition does not automatically equate to industrial availability, as utilization depends on the accessibility, continuity, volume, chemical composition, mineralogy, and reactivity of each source (Pinos-Velez et al., 2024; Toulkeridis & Zach, 2017).
The main opportunity for Ecuador lies in developing a technical framework that allows for distinguishing between ash with pozzolanic potential, materials requiring pretreatment, and sources that lack sufficient reactivity. This need is justified by the variability in the reported content of SiO_2, Al_2O_3, CaO, amorphous phase, mineralogy, fineness, and specific surface area for volcanic materials from different sources (Gil-Martín et al., 2025; Shahjalal et al., 2025; Sokołowska, 2025). Consequently, the substitution ranges obtained with ash from other regions should not be directly extrapolated to Ecuadorian materials.
Treatment processes should be defined according to the material's initial characteristics. Drying may be necessary to control dosage; grinding and particle size classification can increase the specific surface area and improve the filler effect; and mechanical, thermal, or chemical activation can be evaluated when reactivity is insufficient. However, these alternatives may increase energy demand, costs, and associated emissions; therefore, they must be justified through a technical, economic, and environmental assessment (Ababneh et al., 2024; Khan & Amin, 2017; Martín-Rodríguez et al., 2024; Zhang et al., 2025).
Logistics also influence industrial feasibility. The distance between sources, cement plants, concrete plants, and construction sites can alter the environmental and economic benefits obtained through clinker reduction. Therefore, a material that performs well in the laboratory may not be viable if it requires long-distance transport, energy-intensive processing, or lacks consistency in quality and supply (Cavalieri et al., 2024; Mohamad et al., 2020).
At the regulatory level, the incorporation of volcanic ash requires acceptance criteria related to chemical composition, fineness, loss on ignition, pozzolanic activity, relative strength, and durability, all of which must be adapted to the characteristics of the cements, aggregates, and local exposure conditions.
Consequently, the opportunities for Ecuador should be understood as an agenda for research, standardization, and technology transfer. Table 6 shows the main conditions for the utilization of volcanic ash as a supplementary cementitious material (SCM), including actual resource availability, characterization, treatment, performance, logistics, environmental impact, and regulatory control.

Table 6. Conditions for the utilization of volcanic ash as a supplementary cementitious material in Ecuador.

Dimension	Critical Aspect	Required Information	Implications for Ecuador
Availability of the resource	Presence of exploitable deposits or emissions	Geological inventory, volume, accessibility, and continuity	Industrial availability should not be assumed without data
Chemical characterization	SiO_2, Al_2O_3, CaO, alkalis, SO_3	XRF, LOI, chemical analysis	Determines whether the material can act as a pozzolan
Mineralogical characterization	Amorphous phase, crystalline phases, volcanic glass	XRD, quantification of the amorphous phase	Assesses pozzolanic reactivity
Physical properties	Fineness, particle size, specific surface area	Particle size distribution, Blaine/BET	Influences reactivity, water demand, and workability

Material processing	Drying, grinding, classification	Processing protocol	Improves uniformity and performance
Mechanical performance	Compression, flexural strength, relative strength	Mortar and concrete tests	Defines viable replacement ranges
Durability	Sulfates, chlorides, permeability, carbonation	Service Life and Exposure Tests	Determines safety for infrastructure
Logistics	Distance to cement plants/concrete plants, transportation, humidity	Technical-Economic Analysis	Can determine actual feasibility
National and international regulations	Acceptance criteria for natural pozzolans and SCM	Comparison with international requirements and adaptation to local cements and aggregates	Necessary for industrial adoption and quality control
Material processing	Drying, grinding, screening, and possible activation	Energy requirements, cost, improved reactivity, and environmental impact	Processing must improve performance without negating environmental benefits
Environmental impact	Clinker reduction vs. processing energy	LCA and economic analysis	Avoids false environmental improvements

Source: Prepared by the authors based on a critical analysis of international evidence and the conditions identified for the Ecuadorian context.

Table 6 shows that geological availability is only the first condition for potential industrial application. Actual feasibility will depend on whether the sources exhibit continuity, accessibility, and compositional uniformity; furthermore, the benefits derived from clinker reduction must outweigh the impacts and costs associated with drying, grinding, classification, and transportation. Therefore, prior to regulatory or industrial implementation, it will be necessary to validate Ecuadorian fly ash with local cements and aggregates under exposure conditions representative of the country.

In summary, the reviewed evidence indicates that substitutions between 10% and 25% offer the most consistent balance between mechanical performance, durability, and microstructural refinement, although these ranges do not constitute universal criteria. Their effectiveness depends on the amorphous fraction, fineness, availability of portlandite, curing conditions, and mix design; meanwhile, high replacement rates require activation or ternary systems to limit the dilution effect and the risk of carbonation (Bawab et al., 2024; Hasan et al., 2024; Kupwade-Patil, Al-Aibani, et al., 2016; Zhou et al., 2021). For Ecuador, the transfer of these results requires local characterization, logistical evaluation, environmental validation, and regulatory criteria prior to industrial implementation (Pinos-Velez et al., 2024; Toulkeridis & Zach, 2017).

6. CONCLUSIONS

The systematic review and complementary bibliometric analysis made it possible to evaluate the mechanical performance, durability, pozzolanic mechanisms, and application conditions of volcanic ash as a supplementary cementitious material. Based on the analyzed evidence, the following conclusions are drawn:

1. Volcanic ash contents between 10% and 25% generally offer the most favorable balance between mechanical strength, durability, and microstructural refinement. However, this range is indicative and does not constitute a universal dosing criterion, due to variability in chemical composition, mineralogy, amorphous fraction, fineness, cement type, water-to-cement ratio, and curing conditions.
2. The favorable performance of volcanic ash is related to its pozzolanic activity and the physical effect of its particles. The reaction of silico-aluminous phases with portlandite can promote the secondary formation of C-S-H and C-A-S-H, reduce capillary connectivity, and densify the matrix. At high replacement rates, the reduced availability of $Ca(OH)_2$ and the dilution effect may limit the reaction, reduce early strength, and leave a portion of the material unreacted.
3. Moderate substitutions can improve resistance to water, chloride, and sulfate ingress; however, high substitutions can reduce the alkali reserve and increase susceptibility to carbonation. Therefore, the contribution of volcanic ash to reducing the clinker factor must be evaluated in conjunction with mechanical strength, durability, and service life, and not solely based on the percentage of cement substituted.
4. For Ecuador, volcanic ash represents a potential alternative, but one that is still subject to local validation. Its application requires identifying and characterizing available sources, evaluating material variability, defining necessary treatments, testing its performance with local cements and aggregates, and analyzing logistics, costs, environmental impact, and regulatory criteria. Consequently, its industrial incorporation requires technical, regulatory, logistical, and environmental validation before establishing substitution ranges applicable to the country.

In other words, the utilization of volcanic ash in Ecuador should not be limited to the direct extrapolation of international optimal ranges but rather requires the establishment of a national agenda for applied research and technology transfer. To move from the territorial identification of the resource to its safe and viable incorporation into the construction industry, it is imperative to conduct detailed characterizations of local sources, evaluate treatment and controlled grinding processes, and carry out durability studies under real-world exposure conditions. Finally, the success of this sustainable alternative depends on the creation of regulatory frameworks and specific quality control criteria that ensure the logistical, environmental, and economic compatibility of volcanic ash as a SCM in the Ecuadorian context.

7. ACKNOWLEDGMENTS

Special thanks to the “School of Habitat, Infrastructure, and Creativity” and the “Research Directorate” of the “Pontifical Catholic University of Ecuador, Ambato Campus” for their support in conducting this research.

8. REFERENCIAS

A Lachemi, K. M. (2004). *Residual strength and durability of volcanic ash concrete exposed to high temperature.*

Ababneh, A. N., Matalkah, F., & Al-Akhras, M. (2024). *The use of graphene nanoplatelets for enhancement of the compressive strength of mortar containing high-levels of natural Pozzolan*. Construction and Building Materials, 449. https://doi.org/10.1016/j.conbuildmat.2024.138302
Ali, M. K., Kareem, Q., Ahmad, S., Shawkat, I. A., & Kassim, M. M. (2023). *Compressive and Flexural Strength of High-Volume Fly Ash Mortars Aged with Air-entraining Admixtures*. E3S Web of Conferences, 427. https://doi.org/10.1051/e3sconf/202342702017
Al-jabali, H. M., Edris, W. F., Al-Tamimi, M., Al Sayed, A. A. K. A., & Selouma, T. I. (2025). *Evaluation of the degradation of mortar with volcanic tuff replacement via destructive and non-destructive testing*. Case Studies in Construction Materials, 22. https://doi.org/10.1016/j.cscm.2025.e04308
Al-Swaidani, A. M. (2017). *Production of more durable and sustainable concretes using volcanic scoria as cement replacement*. Materiales de Construccion, 67(326). https://doi.org/10.3989/mc.2017.00716
al-Swaidani, A. M., Aliyan, S. D., & Adarnaly, N. (2016). *Mechanical strength development of mortars containing volcanic scoria-based binders with different fineness*. Engineering Science and Technology, an International Journal, 19(2), 970–979. https://doi.org/10.1016/j.jestch.2015.12.006
Altimari, F., Barbieri, L., Saccani, A., & Lancellotti, I. (2025). *Recycling Volcanic Lapillus as a Supplementary Cementitious Material in Sustainable Mortars*. Recycling, 10(4). https://doi.org/10.3390/recycling10040153
Amine, Y., Leklou, N., & Amiri, O. (2017). *Effect of supplementary cementitious materials (scm) on delayed ettringite formation in heat-cured concretes*. Energy Procedia, 139, 565–570. https://doi.org/10.1016/j.egypro.2017.11.254
Anwar Hossain, K. M. (n.d.). *Performance of Volcanic Ash Based Precast and In Situ Blended.* Cement Concretes in Marine Environment. https://doi.org/10.1061/ASCE0899-1561200517:6694
Anwar Hossain, K. M. (2006). *High strength blended cement concrete incorporating volcanic ash: Performance at high temperatures*. Cement and Concrete Composites, 28(6), 535–545. https://doi.org/10.1016/j.cemconcomp.2006.01.013
Bashir, M. I., & Elahi, A. (2023). *Micro Structural Study of Concrete with Indigenous Volcanic Ash* †. Engineering Proceedings, 44(1). https://doi.org/10.3390/engproc2023044019
Bawab, J., El-Hassan, H., El-Dieb, A., & Khatib, J. (2024). *Synergetic impact of volcanic ash and calcium carbide residue on the properties and microstructure of cementitious composites.* Construction and Building Materials, 439. https://doi.org/10.1016/j.conbuildmat.2024.137390
Bawab, J., El-Hassan, H., El-Dieb, A., & Khatib, J. (2025a). *Recycling of volcanic ash and carbide slag in blended mortars: A multi-criteria performance assessment.* Environmental Challenges, 20. https://doi.org/10.1016/j.envc.2025.101222
Bawab, J., El-Hassan, H., El-Dieb, A., & Khatib, J. (2025b, August). *Optimizing the Mix Design of Cementitious Composites Incorporating Volcanic Ash by Taguchi-TOPSIS Method.* Proceedings of the 11th World Congress on New Technologies. https://doi.org/10.11159/icceia25.155
Begaye, M. L., Aboubakr, S. H., Kim, J. J., & Reda Taha, M. M. (n.d.). *NANO-CREEP OF SYNTHETIC CSH PRODUCED USING 1.5 AND 0.7 CAO/SIO 2 MIXTURE RATIOS.*
Canpolat, F., Yurdusev, M. A., Targan, S., & Yilmaz, K. (2007). *Sulfate resistance of mortars with and without silica fume and natural pozzolan.* Sustainable Construction Materials and Technologies - International Conference on Sustainable Construction Materials and Technologies, 325–332.
Cao, M., & Zhang, H. (2023). *Fractal characteristics of particle groups and mechanochemical effects of Yellow River sediment after mechanical grinding.* Journal of Sustainable Cement-Based Materials, 12(10), 1322 – 1333. https://doi.org/10.1080/21650373.2023.2218841
Cao, Y., Chen, L., Xie, G., Zhang, L., & Fan, Z. (2025). *Simulation the Hydration Process and Products Evolution of Low-Heat Cement Blended with Fly Ash*. In G. Feng, B. Zhang, W. X.-Y.,

J. Zhao, & A. Almerich-Chulia (Eds.), *Sustainable Civil Infrastructures* (pp. 393–401). Springer Science and Business Media B.V. https://doi.org/10.1007/978-3-031-87959-3_34

Cascone, S., Fazio, M., & Saeli, M. (2025). *Building Sustainability with Volcanic Ash: A Green Roof System Innovation.* Lecture Notes in Civil Engineering, 611 LNCE, 134–149. https://doi.org/10.1007/978-3-031-71863-2_9

Cavalieri, M., Ferrara, P. L., Finocchiaro, C., & Martorana, M. F. (2024). *An Economic Analysis of the Use of Local Natural Waste: Volcanic Ash of Mt. Etna Volcano (Italy) for Geopolymer Production.* Sustainability (Switzerland), 16(2). https://doi.org/10.3390/su16020740

Dahiru, D., Ibrahim, M., & Gado, A. A. (2019). *Evaluation of the Effect of Volcanic Ash on the Properties of Concrete 1 2 3*. In ATBU Journal of Environmental Technology (Vol. 12).

Darwis, F., Banggu, I., & Sultan, M. A. (2018). *The Effects Of Volcanic Ash On The Strength And Permeability Mortar*. https://doi.org/10.2991/icst-18.2018.78

Das Gupta, S., Zayed, A., Ferraro, C., & Riding, K. (2025). *Sulfate Durability of Type IL-Slag Blended Cement under Different Curing Exposures.* Journal of Materials in Civil Engineering, 37(12). https://doi.org/10.1061/JMCEE7.MTENG-20938

de Siqueira, A. A., & Cordeiro, G. C. (2022). *Sustainable Cements Containing Sugarcane Bagasse Ash and Limestone: Effects on Compressive Strength and Acid Attack of Mortar*. Sustainability (Switzerland), 14(9). https://doi.org/10.3390/su14095683

Demirel, B., & Keleştemur, O. (2010). *Effect of elevated temperature on the mechanical properties of concrete produced with finely ground pumice and silica fume*. Fire Safety Journal, 45(6–8), 385–391. https://doi.org/10.1016/j.firesaf.2010.08.002

Díaz, J. E., Izquierdo, S. R., de Gutiérrez, R. M., & Gordillo S., M. (2013). *Ternary mixture of portland cement, blast furnace slag and limestone: Mechanical strength and durability; [Mezcla ternaria de cemento portland, escoria de alto horno y piedra caliza: Resistencia mecánica y durabilidad].* Revista de la Construccion, 12(3), 53 – 60.

Djon Li Ndjock, B. I., Elimbi, A., & Cyr, M. (2017). *Rational utilization of volcanic ashes based on factors affecting their alkaline activation.* Journal of Non-Crystalline Solids, 463, 31–39. https://doi.org/10.1016/j.jnoncrysol.2017.02.024

Edris, W. F., Abdelkader, S., Salama, A. H. E., & Al Sayed, A. A. K. A. (2021*). Concrete behaviour with volcanic tuff inclusion.* Civil Engineering and Architecture, 9(5), 1434–1441. https://doi.org/10.13189/CEA.2021.090516

Elshinawy, A., Yousry Elshikh, M. M., Kaloop, M. R., El-Demerdash, W. E., & Elemam, W. E. (2025). *An experimental investigation on mechanical characteristics of steel-fiber-reinforced volcanic concrete*. Next Materials, 6. https://doi.org/10.1016/j.nxmate.2024.100308

Fernandes, I. V, Gonçalves da Silva, A. G. A., Santos, M. D., Nascimento, C. F. G., Lima, V. M. E., Holanda, R. M., & Melo Neto, A. A. (2025). *Physicochemical and microstructural interactions between cement and textile sludge ash for application in dry concrete.* Journal of Building Engineering, 112, 113919. https://doi.org/https://doi.org/10.1016/j.jobe.2025.113919

Fernández-Jiménez, A., Garcia-Lodeiro, I., Maltseva, O., & Palomo, A. (2023). *Sustainable Cements: Hybrid Alkaline Cements Overview.* In RILEM Bookseries (Vol. 40, pp. 626–639). Springer Science and Business Media B.V. https://doi.org/10.1007/978-3-031-21735-7_68

Flores Medina, N., Barluenga, G., & Hernández-Olivares, F. (2015). *Combined effect of Polypropylene fibers and Silica Fume to improve the durability of concrete with natural Pozzolans blended cement.* Construction and Building Materials, 96, 556–566. https://doi.org/10.1016/j.conbuildmat.2015.08.050

Gao, R., Zhao, S., Li, Q., & Chen, J. (2010). *Experimental study of the deterioration mechanism of concrete under sulfate attack in wet-dry cycles.* Tumu Gongcheng Xuebao/China Civil Engineering Journal, 43(2), 48–54.

Garces-Vargas, J. F., Díaz-Cardenas, Y., & Martirena Hernandez, J. F. (2024). *Evaluation of the Durability of Concrete with the Use of Calcined Clays and Limestone in Salinas, Ecuador.* Minerals, 14(5). https://doi.org/10.3390/min14050460

Gil-Martín, L. M., Oliveira, M. J., Fernández-Ruiz, M. A., Branco, F. G., & Hernández-Montes, E. (2025). *Sustainable Use of Volcanic Ash in Mortars as a Replacement for Cement or Sand: Shrinkage and Physical and Mechanical Properties.* Materials, 18(15). https://doi.org/10.3390/ma18153694

Hasan, M. S., Karmokar, J., & Mahmood, S. M. F. (2024). *Strength and Workability of Concrete Incorporating Volcanic Ash as a Partial Replacement for Cement.* Lecture Notes in Civil Engineering, 512 LNCE, 251–258. https://doi.org/10.1007/978-3-031-63280-8_26

Hazarika, A., Huang, L., Erlingsson, S., de Weerdt, K., Löfgren, I., Iftikhar, S., & Babaahmadi, A. (2025). *Characterization, activation and reactivity – A case study of Nordic volcanic materials for application as Supplementary Cementitious Materials*. Case Studies in Construction Materials, 22. https://doi.org/10.1016/j.cscm.2024.e04096

Ho, L. S., Ngo, H. T. T., Vu, H. T., Nguyen, S. T., Chau, V. N., & Dang, V. Q. (2023). *Durability of mortar and concrete containing pozzolans as a partial cement replacement in the marine environment: a review.* Journal of Science and Transport Technology, 3(3), 13 – 25. https://doi.org/10.58845/jstt.utt.2023.en.3.3.13-25

Hossain, A. (n.d.). *Lightweight structural concrete incorporating volcanic materials for sustainable construction.*

Hossain, A., Khandaker, M. A., & Lachemi, M. (2006). *Development of volcanic ash concrete: Strength, durability, and microstructural investigations.* ACI Materials Journal.

Hossain, K. M. A. (2003). *Blended cement using volcanic ash and pumice.* Cement and Concrete Research, 33(10), 1601–1605. https://doi.org/10.1016/S0008-8846(03)00127-3

Hossain, K. M. A., & Lachemi, M. (2004). *Corrosion resistance and chloride diffusivity of volcanic ash blended cement mortar.* Cement and Concrete Research, 34(4), 695–702. https://doi.org/10.1016/j.cemconres.2003.10.021

Hossain, K. M. A., & Lachemi, M. (2007). *Strength, durability and micro-structural aspects of high performance volcanic ash concrete.* Cement and Concrete Research, 37(5), 759–766. https://doi.org/10.1016/j.cemconres.2007.02.014

Hossain, M. U., Dong, Y., & Ng, S. T. (2021). *Influence of supplementary cementitious materials in sustainability performance of concrete industry: A case study in Hong Kong.* Case Studies in Construction Materials, 15. https://doi.org/10.1016/j.cscm.2021.e00659

Hu, Y. J., & Du, Y. L. (2013). *Effect of pore structure on the chloride permeability of concrete with mineral admixture.* Advanced Materials Research, 690 693, 835–838. https://doi.org/10.4028/www.scientific.net/AMR.690-693.835

Ibrahim, M., Bahraq, A. A., Salami, B. A., Alhems, L. M., Hussaini, S. R., Nasir, M., & Adewumi, A. A. (2025). *Pore Structure Characterization and Environmental Assessment of Ground Volcanic Pumice-Based Alkali-Activated Concrete.* International Journal of Concrete Structures and Materials, 19(1). https://doi.org/10.1186/s40069-025-00791-3

Jackson, M. D., Mulcahy, S. R., Chen, H., Li, Y., Li, Q., Cappelletti, P., & Wenk, H. R. (2017). *Phillipsite and Al-tobermorite mineral cements produced through low-temperature water-rock reactions in Roman marine concrete.* American Mineralogist, 102(7), 1435–1450. https://doi.org/10.2138/am-2017-5993CCBY

Játiva, A., Corominas, A., & Etxeberria, M. (2025). *Durable Mortar Mixes Using 50% of Activated Volcanic Ash as A Binder.* Materials, 18(8). https://doi.org/10.3390/ma18081777

Jaturapitakkul, C., Kiattikomol, K., Tangchirapat, W., & Saeting, T. (2007). *Evaluation of the sulfate resistance of concrete containing palm oil fuel ash.* Construction and Building Materials, 21(7), 1399–1405. https://doi.org/10.1016/j.conbuildmat.2006.07.005

Jubera-Pérez, F. J., Jaizme-Vega, E., Rosa-Orihuela, R., Damas-Montesdeoca, R., Hernández-Díaz, C., Rodríguez-Díaz, J., & González-Díaz, E. (2024). *Pozzolanic activity of volcanic ashes produced by the eruption of the Tajogaite Volcano in La Palma, Canary Islands.* Construction and Building Materials, 419. https://doi.org/10.1016/j.conbuildmat.2024.135498

Keshta, M. M., Elshikh, M. M. Y., Abd Elrahman, M., & Youssf, O. (2022). *Utilizing of Magnetized Water in Enhancing of Volcanic Concrete Characteristics.* Journal of Composites Science, 6(10). https://doi.org/10.3390/jcs6100320

Khan, K., & Amin, M. N. (2017). *Influence of fineness of volcanic ash and its blends with quarry dust and slag on compressive strength of mortar under different curing temperatures.* Construction and Building Materials, 154, 514–528. https://doi.org/10.1016/j.conbuildmat.2017.07.214

Khan, K., Amin, M. N., Saleem, M. U., Qureshi, H. J., Al-Faiad, M. A., & Qadir, M. G. (2019). *Effect of fineness of basaltic volcanic ash on pozzolanic reactivity, ASR expansion and drying shrinkage of blended cement mortars.* Materials, 12(16). https://doi.org/10.3390/ma12162603

Khan, K., Amin, M. N., Usman, M., Imran, M., Al-Faiad, M. A., & Shalabi, F. I. (2022). *Effect of Fineness and Heat Treatment on the Pozzolanic Activity of Natural Volcanic Ash for Its Utilization as Supplementary Cementitious Materials*. Crystals, 12(2). https://doi.org/10.3390/cryst12020302

Kiran Kumar, V., Seshadri Sekhar, T., & Srinivasa Rao, P. (2024). *EXPERIMENTAL STUDIES ON QUATERNARY BLENDED CONCRETE UNDER ACID RESISTANCE, SULPHATE RESISTANCE,WATER PERMEABILITY, AND CHLORIDE PERMEABILITY*. Indian Concrete Journal, 98(9), 51–58.

Klausen, A. B. E., Menga, A., & Kanstad, T. (2025). *Compressive strength development of concretes with volcanic ash exposed to realistic temperature conditions*. In M. Briffaut & J. M. Torrenti (Eds.), fib Symposium (pp. 825–833). fib. The International Federation for Structural Concrete.

Kupwade-Patil, K., Al-Aibani, A. F., Abdulsalam, M. F., Mao, C., Bumajdad, A., Palkovic, S. D., & Büyüköztürk, O. (2016). *Microstructure of cement paste with natural pozzolanic volcanic ash and Portland cement at different stages of curing.* Construction and Building Materials, 113, 423–441. https://doi.org/10.1016/j.conbuildmat.2016.03.084

Kupwade-Patil, K., Chin, S., Ilavsky, J., Andrews, R. N., Bumajdad, A., & Büyüköztürk, O. (2018). *Hydration kinetics and morphology of cement pastes with pozzolanic volcanic ash studied via synchrotron-based techniques.* Journal of Materials Science, 53(3), 1743–1757. https://doi.org/10.1007/s10853-017-1659-4

Kupwade-Patil, K., De Wolf, C., Chin, S., Ochsendorf, J., Hajiah, A. E., Al-Mumin, A., & Büyüköztürk, O. (2018). *Impact of Embodied Energy on materials/buildings with partial replacement of ordinary Portland Cement (OPC) by natural Pozzolanic Volcanic Ash.* Journal of Cleaner Production, 177, 547–554. https://doi.org/10.1016/j.jclepro.2017.12.234

Kupwade-Patil, K., Palkovic, S. D., Bumajdad, A., Soriano, C., & Büyüköztürk, O. (2018). *Use of silica fume and natural volcanic ash as a replacement to Portland cement: Micro and pore structural investigation using NMR, XRD, FTIR and X-ray microtomography.* Construction and Building Materials, 158, 574–590. https://doi.org/10.1016/j.conbuildmat.2017.09.165

Kupwade-Patil, K., Tyagi, M., Brown, C. M., & Büyüköztürk, O. (2016). *Water dynamics in cement paste at early age prepared with pozzolanic volcanic ash and Ordinary Portland Cement using quasielastic neutron scattering.* Cement and Concrete Research, 86, 55–62. https://doi.org/10.1016/j.cemconres.2016.04.011

Lammertijn, S., & De Belie, N. (2008). *Porosity, gas permeability, carbonation and their interaction in high-volume fly ash concrete.* Magazine of Concrete Research, 60(7), 535–545. https://doi.org/10.1680/macr.2008.60.7.535

Letelier, V., Ortega, J. M., Tarela, E., Muñoz, P., Henríquez-Jara, B. I., & Moriconi, G. (2018). *Mechanical performance of eco-friendly concretes with volcanic powder and recycled concrete aggregates.* Sustainability (Switzerland), 10(9). https://doi.org/10.3390/su10093036

Liu, J. C., Hossain, M. U., Xuan, D., Ali, H. A., Ng, S. T., & Ye, H. (2023). *Mechanical and durability performance of sustainable concretes containing conventional and emerging supplementary cementitious materials.* Developments in the Built Environment, 15. https://doi.org/10.1016/j.dibe.2023.100197

Liu, J., Wu, K., Wang, Y., & Yang, Y. (2017). *Effects of fly ash/diatomite admixture with variable particle sizes on the mechanical properties and porosity of concrete.* Journal Wuhan University of Technology, Materials Science Edition, 32(5), 1072–1079. https://doi.org/10.1007/s11595-017-1713-8

Lo, T. Y., Nadeem, A., Tang, W. C. P., & Yu, P. C. (2009). *The effect of high temperature curing on the strength and carbonation of pozzolanic structural lightweight concretes.* Construction and Building Materials, 23(3), 1306–1310. https://doi.org/10.1016/j.conbuildmat.2008.07.026

Martín-Rodríguez, P., Fernández-Jiménez, A., Alonso, M. del M., Palomo, A., & García-Lodeiro, I. (2024). *Valorisation of "La Palma" Volcanic Ash for Making Portland-Blended, Alkaline and Hybrid Portland–Alkaline Cements.* Materials, 17(1). https://doi.org/10.3390/ma17010242

Masmoudi, R., Kupwade-Patil, K., Bumajdad, A., & Büyüköztürk, O. (2017). *In situ Raman studies on cement paste prepared with natural pozzolanic volcanic ash and Ordinary Portland Cement.* Construction and Building Materials, 148, 444–454. https://doi.org/10.1016/j.conbuildmat.2017.05.016

Mitrović, A. A. (2011). *Pozzolan obtained by mechanochemical treatment of kaolinite clay.* AIP Conference Proceedings, 1400, 82–86. https://doi.org/10.1063/1.3663090

Mohamad, S. A., Al-Hamd, R. K. S., & Khaled, T. T. (2020). *Investigating the effect of elevated temperatures on the properties of mortar produced with volcanic ash.* Innovative Infrastructure Solutions, 5(1). https://doi.org/10.1007/s41062-020-0274-4

Nair, N. A., & Viswanathan, T. S. (2023). *β-CaSiO3 and colloidal n-SiO2 based blended cement composites- their properties, regression analysis and micro-characterization studies.* Materiales de Construccion, 73(350). https://doi.org/10.3989/mc.2023.304722

Nováková, I., Jhatial, A. A., Kekez, S., Gjerløw, E., Gulik, V., Kannathasan, K. R., Vaišnoras, M., & Krasnikovs, A. (2024). *Investigating the Influence of Oil Shale Ash and Basalt Composite Fibres on the Interfacial Transition Zone in Concrete.* Buildings, 14(7). https://doi.org/10.3390/buildings14071952

Ogunbode, E. B., & Hassan, I. O. (2011). *Effect of addition of calcium nitrate on selected properties of concrete containing volcanic ash.* Leonardo Electronic Journal of Practices and Technologies, 10(19), 29–38.

Omikrine Metalssi, O., Quiertant, M., Jabbour, M., & Baroghel-Bouny, V. (2024). *Effect of Exposure Conditions on Mortar Subjected to an External Sulfate Attack.* Materials, 17(13). https://doi.org/10.3390/ma17133198

Özen, S., & Uzal, B. (2021). *Effect of mineralogical composition of clinoptilolite-bearing tuffs on their performance as a natural pozzolan in cementitious systems.* Advances in Concrete Construction, 12(1), 25–31. https://doi.org/10.12989/acc.2021.12.1.025

Peng, G., Zhang, G., Zuo, X., Ding, H., Chen, X., Wang, H., & Liu, X. (2024). *Mechanism for the Influence of Added Hydrated Lime on Mechanical Properties of Ultra-high Strength Concrete.* Cailiao Daobao/Materials Reports, 38(3). https://doi.org/10.11896/cldb.22060068

Petroche, D. M., & Ramirez, A. D. (2022). *The Environmental Profile of Clinker, Cement, and Concrete: A Life Cycle Perspective Study Based on Ecuadorian Data.* Buildings, 12(3). https://doi.org/10.3390/buildings12030311

Pinos-Velez, V. P., Araujo, G. S., Echeverria-Paredes, P., Abril, M., Acosta, S., Cipriani-Ávila, I., Moulatlet, G. M., & Capparelli, M. V. (2024). *Acute and Chronic Ecotoxicity of Daphnia magna Exposed to Ash Leachate from the Cotopaxi Volcano, Ecuador*. Bulletin of Environmental Contamination and Toxicology, 113(3). https://doi.org/10.1007/s00128-024-03946-2

Pinto-Almeida, C., Abril-Camino, A., & Abril-Camino, D. (2025). *Mechanical Performance of Volcanic Ash Concrete Showing Modulus Reduction with Strength Retention.* Civil Engineering Journal, 11(10), 4422–4435. https://doi.org/10.28991/CEJ-2025-011-10-024

Rajesh, A., Gowdhaman, D., & Sumathi, A. (2023). *Utilization of industrial and agricultural waste as supplementary cementitious addition in bacteria concrete—a review.* In Valorization of Wastes for Sustainable Development: Waste to Wealth. Elsevier. https://doi.org/10.1016/B978-0-323-95417-4.00016-0

Rajesh, J., & Kandasamy, S. (2025). *Particle size reduction effects on fly ash pozzolanic performance in cement.* Construction and Building Materials, 494, 143458. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2025.143458

Rodrigues, A. L. M. V., Mendes, Á. Á. F., Gomes, V., Battagin, A. F., Saade, M. R. M., & Da Silva, M. G. (2022). *Environmental and Mechanical Evaluation of Blended Cements With High Mineral Admixture Content.* Frontiers in Materials, 9. https://doi.org/10.3389/fmats.2022.880986

Rols, S., Ambroise, J., Péra, J., & Chabannet, M. (2000). *Calcined paper sludge-pozzolanic admixture to improve sulfate resistance of concrete.* In V. M. Malhotra (Ed.), American Concrete Institute, ACI Special Publication: SP-192 (pp. 353–367). American Concrete Institute.

Rovnaník, P., Teplý, B., & Rovnaníková, P. (2007). *Concrete mix and environmental load in the context of durability and reliability.* CESB 2007 PRAGUE International Conference - Central Europe Towards Sustainable Building, 2.

Shahjalal, M., Sabrin, R., Bachu, H. A. E., Habib, M. M. L., Mobasharah, N., & Billah, A. H. M. M. (2025). *Repurposing waste pozzolans for cleaner mortar production: mechanical and durability properties with microstructural behavior.* Canadian Journal of Civil Engineering, 52(9), 1698–1717. https://doi.org/10.1139/cjce-2025-0014

Sharfuddin Ahmed, M., Kayali, O., & Anderson, W. (n.d.). *Evaluation of Binary and Ternary Blends of Pozzolanic Materials Using the Rapid Chloride Permeability Test.* https://doi.org/10.1061/ASCE0899-1561200921:9446

Sharma, M., Bishnoi, S., Martirena, F., & Scrivener, K. (2021). *Limestone calcined clay cement and concrete: A state-of-the-art review.* Cement and Concrete Research, 149. https://doi.org/10.1016/j.cemconres.2021.106564

Siddique, R. (2012). *Properties of concrete made with volcanic ash.*

Sideris, K. K., & Savva, A. E. (2001). *Resistance of Fly Ash and Natural Pozzolans Blended Cement Mortars and concrete to carbonation, sulfate attack and chloride lon penetration.* American Concrete Institute, ACI Special Publication, SP-199, 275–293. https://doi.org/10.14359/10499

Singh, L. P., Zhu, W., Howind, T., & Sharma, U. (2017). *Quantification and characterization of C-S-H in silica nanoparticles incorporated cementitious system.* Cement and Concrete Composites, 79, 106–116. https://doi.org/10.1016/j.cemconcomp.2017.02.004

Singh, N., Sharma, R. L., & Yadav, K. (2023). *Sustainable development by carbon emission reduction and its quantification: an overview of current methods and best practices.* In Asian Journal of Civil Engineering (Vol. 24, Number 8, pp. 3797–3822). Institute for Ionics. https://doi.org/10.1007/s42107-023-00732-z

Singh, S., Sahu, I., Majmundar, B. P., David, R., Singh, J., Vanitha, S., & Thakur, G. (2026). Multi-*Scale evaluation and predictive modeling of volcanic Ash–Silica fume aggregate concrete for* *sustainable construction. Architecture*, Structures and Construction, 6(1), 6. https://doi.org/10.1007/s44150-026-00187-1

Sokołowska, J. J. (2025). *Utilizing Sakurajima Volcanic Ash as a Sustainable Partial Replacement for Portland Cement in Cementitious Mortars*. Sustainability (Switzerland), 17(17). https://doi.org/10.3390/su17177576

Souza, M. T., Onghero, L., Sakata, R. D., Neto, F. C., de Campos, C. E. M., de Castro Pessôa, J. R., Repette, W. L., & de Oliveira, A. P. N. (2023). *Insights into the acting mechanism of ettringite in expansive Portland cement.* Materials Letters, 345. https://doi.org/10.1016/j.matlet.2023.134496

Suraneni, P., Hajibabaee, A., Ramanathan, S., Wang, Y., & Weiss, J. (2019). *New insights from reactivity testing of supplementary cementitious materials.* Cement and Concrete Composites, 103, 331–338. https://doi.org/10.1016/j.cemconcomp.2019.05.017

Tomoyose, A., Noguchi, T., Sodeyama, K., & Higashi, K. (2020). *Concrete with high-purity volcanic glass fine powder manufactured from pyroclastic deposit.* SN Applied Sciences, 2(5). https://doi.org/10.1007/s42452-020-2614-6

Toulkeridis, T., & Zach, I. (2017). *Wind directions of volcanic ash-charged clouds in Ecuador–implications for the public and flight safety.* Geomatics, Natural Hazards and Risk, 8(2), 242–256. https://doi.org/10.1080/19475705.2016.1199445

Uzbaş, B., & Aydın, A. C. (2019). *Analysis of Fly Ash Concrete With Scanning Electron Microscopy and X-Ray Diffraction.* Advances in Science and Technology Research Journal, 13(4), 100–110. https://doi.org/10.12913/22998624/114178

Vedalakshmi, R., Raj, A. S., Srinivasan, S., & Babu, K. G. (2003). *Quantification of hydrated cement products of blended cements in low and medium strength concrete using TG and DTA technique.* Thermochimica Acta, 407(1–2), 49–60. https://doi.org/10.1016/S0040-6031(03)00286-7

Wahyuni, Abdullah, Mulyati, S., & Hayati, Y. (2025). *Performance analysis of ordinary portland cement and portland pozzolan cement cement in improving sea sand and sea water concrete with zeolite powder.* Journal of Ecological Engineering, 26(4), 264–274. https://doi.org/10.12911/22998993/200278

Wang, Y., Hu, Y., He, X., Su, Y., Strnadel, B., & Miao, W. (2023). *Hydration and compressive strength of supersulfated cement with low-activity high alumina ferronickel slag.* Cement and Concrete Composites, 136. https://doi.org/10.1016/j.cemconcomp.2022.104892

Wang, Y., Liu, H., Nie, Z., Xue, R., Zhu, W., & Sun, X. (2025). *Experimental investigation into the influence of calcium aluminate cement on the micro- and macro-mechanical properties of the interfacial transition zone in geopolymer concrete.* Developments in the Built Environment, 21. https://doi.org/10.1016/j.dibe.2025.100618

Wei, F., Lu, Y., Lan, X., & Xu, Z. (2005). *Hydration products of fly ash cement-based material.* Kuei Suan Jen Hsueh Pao/ Journal of the Chinese Ceramic Society, 33(1), 52-56+62.

Xiong, C., Zhou, Y., Jin, Y., Liu, C., & Feng, P. (2022). *Fabrication, structure, and mechanical properties of a high-order calcium silicate hydrate based on polymer and pH tuning.* Materials Today Communications, 33. https://doi.org/10.1016/j.mtcomm.2022.105020

Yu, L., Zhou, S., & Deng, W. (2015). *Pozzolanic activity of volcanic rocks from Southern Jiangxi Province, China.* Journal of Sustainable Cement-Based Materials, 5(3), 176–198. https://doi.org/10.1080/21650373.2015.1010660

Zeyad, A. M., Shubaili, M., & Abutaleb, A. (2023). *Using volcanic pumice dust to produce high-strength self-curing concrete in hot weather regions.* Case Studies in Construction Materials, 18. https://doi.org/10.1016/j.cscm.2023.e01927

Zhang, J., Yang, Y., Li, X., & Chi, C. (2025). *Alkali activation of industrial waste fly ash to produce high-value-added C-S-H seeds.* Advances in Cement Research. https://doi.org/10.1680/jadcr.24.00141

Zhao, J., Li, D., Liao, S., Wang, D., Wang, H., & Yan, P. (2018). *Influence of mechanical grinding on pozzolanic characteristics of circulating fluidized bed fly ash (CFA) and resulting consequences on hydration and hardening properties of blended cement.* Journal of Thermal Analysis and Calorimetry, 132(3), 1459–1470. https://doi.org/10.1007/s10973-018-7103-4

Zhou, Z., Sofi, M., Sabri, Y., Liu, J., Kang, S., & Mendis, P. (2021). *Microstructural Investigation of High-Volume Fly Ash Composites Containing Nano-Calcium Silicate Hydrate Crystals.* Journal of Materials in Civil Engineering, 33(12). https://doi.org/10.1061/(asce)mt.1943-5533.0003974

Zhuginissov, M. T., Kuldeyev, E. I., Nurlybayev, R. E., Khamza, Y. Y., Orynbekov, Y. S., & Iskakov, A. (2026). *Use of fly ash and ground tuff as pozzolanic additives in lightweight structural.* Kompleksnoe Ispolzovanie Mineralnogo Syra, 339(4), 38–51. https://doi.org/10.31643/2026/6445.39

Zunino, F., & Scrivener, K. (2025). *Hydration and strength development of low-clinker (<50 %) factor limestone calcined clay cements (LC3): A comparative study with natural pozzolans.* Construction and Building Materials, 499, 144075. https://doi.org/10.1016/j.conbuildmat.2025.144075

Zunino, F., & Scrivener, K. L. (2024). *The Key Role of Limestone Calcined Clay Cements on the Roadmap towards Eco-Efficient Cement and Concrete.*