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SYSTEMATIC REVIEW OF THE USE OF FLY ASH IN GEOPOLYMER CONCRETE: IMPACT ON ITS PHYSICAL, MECHANICAL, AND MICROSTRUCTURAL PROPERTIES

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ABSTRACT

The environmental impact of Portland cement has driven the adoption of alternative binders such as geopolymer concrete (GC) based on fly ash (FA). This review analyzes 69 studies published between 2021 and 2025 that examine how FA influences the physical, mechanical, and microstructural performance of GC. Workability is strongly affected by the spherical morphology of FA and by the concentration of NaOH, with reported slump values ranging from 62 to 220 mm. Alkaline solutions between 12 M and 18 M accelerate the reaction, reducing initial setting times to 30–150 minutes. Mechanically, mixtures incorporating 50–70% FA and supplementary materials such as slag or microsilica can surpass 60 MPa in compressive strength while also improving tensile and flexural behavior. Microstructural analyses using XRD, SEM, and FTIR confirm the formation of N–A–S–H and C–A–S–H gels that refine and densify the matrix. Overall, FA emerges as a sustainable, high-performance alternative for producing GC, with potential for future construction applications.

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I. INTRODUCTION

In recent years, environmental protection and sustainable development have become one of the most pressing issues for human society[1], In this regard [2] argues that the rapid growth of infrastructure, urbanization, and industry, and similarly in developing countries, around 95% of construction and demolition waste produced is disposed of in landfills or illegally dumped in unoccupied areas [3], This occurs because concrete is a relatively inexpensive and accessible material [4], On the other hand [5] argue that this condition has driven increased demand for concrete over the last few decades, causing a continuous increase in the need for natural aggregates. Therefore, there is concern about the environmental impact of concrete production in terms of the depletion of natural resources [6]. The environmental impact of the construction industry has become increasingly alarming[7], In particular, the cement industry is characterized by its high energy intensity and the presence of multiple hazardous air pollutants, especially during the production of cement clinker[8],

In fact, it is estimated that cement manufacturing contributes to 5-7% of total CO_2 emissions worldwide into the atmosphere[9], because the production of one ton of Portland cement clinker releases between 800 and 1100 kg of carbon dioxide into the atmosphere[10], It is particularly critical that, according to [11], China, the world's largest cement producer, accounted for approximately half of global cement production in 2023, reaching 2 billion tons. The development of green cementitious materials to replace Portland cement (PC) is crucial for sustainable development [12], people have begun to explore the use of alternative cementitious materials [13], In this regard, geopolymers are cementitious materials characterized by a network structure, obtained through the inorganic polymerization of silicoaluminate compounds, which react under alkaline activators [14], Furthermore [15] argue that geopolymers can be produced without calcination, and various industrial solid wastes can be used as precursors.

Geopolymer concrete (GPC) is a substitute for Portland cement (PC) due to its improved mechanical qualities, lower carbon footprint, and ability to use industrial waste as raw materials[16], It also exceptionally withstands freeze-thaw cycles and high temperatures [17]. According to [18] fly ash (FA) generated from coal and biomass combustion represents one of the main industrial by-products worldwide, with FA from municipal solid waste incinerators [19], entering the context of FA. an X-ray diffraction (XRD) analysis has identified relevant crystalline phases such as quartz (SiO_2), mullite ($Al_6Si_2O_{13}$), hematite (Fe_2O_3), and belite (Ca_2SiO_4), which confer pozzolanic and cementitious properties that make them suitable for applications in construction materials[20], However, there is a growing disparity between the supply and demand for FA, driven by its increasing use in the development of sustainable building materials [21], Therefore, it is necessary to move towards a circular economic model that encourages the comprehensive recovery of this waste by promoting its efficient and sustainable reuse within the construction sector [22].

II. METHODOLOGY

This research was based on a review of 69 scientific articles published in high-impact journals indexed in databases such as Scopus and ScienceDirect. The following specific keywords were used: Geopolymer concrete + fly ash, between 2021 and 2025, as shown in Table 01, with the following results: 4 articles in 2021, 9 articles in 2022, 9 articles in 2023, 23 articles in 2024, and 24 articles in 2025, as shown in Table 02. Likewise, the flow of the elicitation process and the parameters established for the search for publications are represented schematically in Figure 01.

Table 1: Research results with filters.

Database	Year of search	Keywords	Document. without filter	Search filter	Document. with Filter	Selected Documents	Total
Scopus	2021-2025	Geopolymer concrete + fly ash	2227	Engineering+ Materials Science+ Article	1185	43	69
ScienceDirect	2021-2025	Geopolymer concrete + fly ash	7707	Engineering+ Materials Science+ Article	1350	26	

Source: Authors, (2026).

Table 2**:** Distribution of articles by database and year of publication.

Database.	Year Articles Published					Total
	2021	2022	2023	2024	2025	
Scopus	2	9	7	7	18	43
ScienceDirect	2	0	2	16	6	26
Total	4	9	9	23	24	69

Source: Authors, (2026).

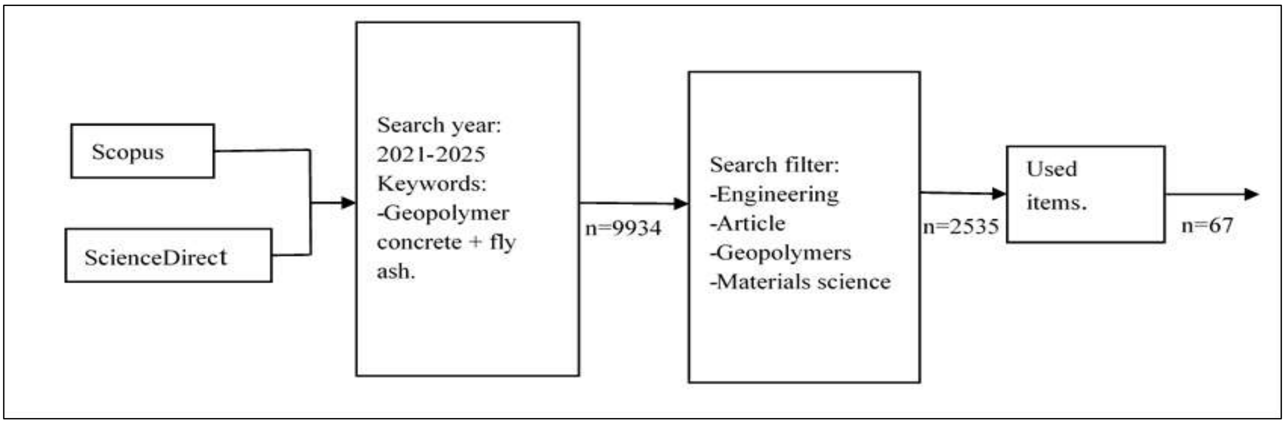

Figure 1: Information Gathering Process Flow and Search Parameters for Publications.
Source: Authors (2026).

II.1 ANALISIS BIBLIOMETRICO

In addition, a bibliometric analysis was performed on the information obtained from the Scopus database, using the following search equation: (TITLE-ABS-KEY (Geopolymer concrete) AND TITLE-ABS-KEY (FLY ASH)) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "MATE")) AND (LIMIT-TO (DOCTYPE , "AR")) AND (LIMIT-TO (EXACTKEYWORD , "FLY ASH") OR LIMIT-TO (EXACTKEYWORD , "GEOPOLYMER CONCRETE")) AND (LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2024) OR LIMIT-TO (PUBYEAR, 2025) OR LIMIT-TO (PUBYEAR, 2026)). This search yielded a total of 1,185 documents, which were analyzed and processed using VOSviewer to generate a keyword co-occurrence map showing the thematic interrelationships within the field of fly ash use in geopolymer concrete, as shown in Figure 2. The interpretation of the keyword co-occurrence map generated with VOSviewer, based on data extracted from Scopus, allows us to identify the main trends and emerging areas in research on geopolymer concrete.

The results show that the terms “geopolymer concrete” and “fly ash” have greater frequency and centrality, which highlights the dominant role of fly ash as the main precursor due to its abundance and reactivity under alkaline activation. Likewise, lines of study related to sustainability, the use of industrial waste, mechanical and durability properties, as well as the incorporation of artificial intelligence tools for mixture optimization and predictive modeling are identified. Overall, the bibliometric analysis reveals an interdisciplinary evolution linking materials engineering, sustainability, and technology, although gaps remain regarding field-scale application, durability under variable environmental conditions, and the exploration of alternative precursors. Thus, the current trend is toward the development of more efficient, sustainable, and adaptable geopolymer concretes for various construction contexts.

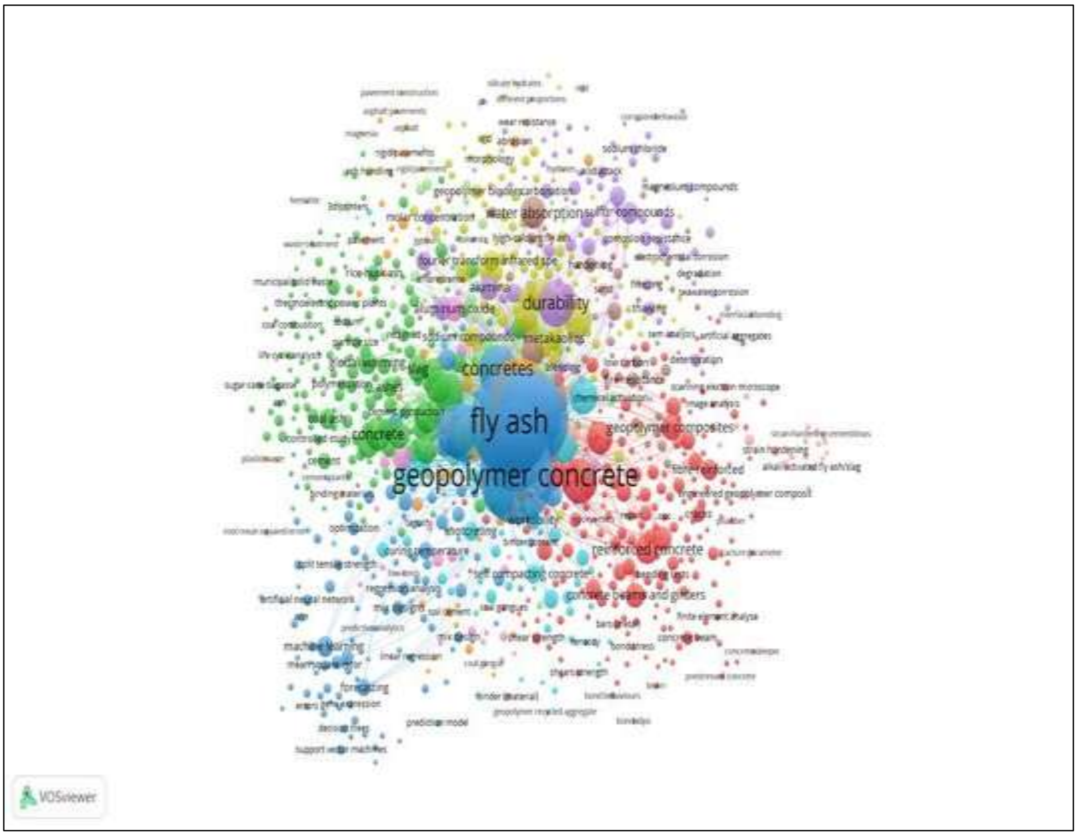

Figure 2: Keyword Co-Occurrence Network Map.
Source: Authors, (2026).

III. RESULTS AND DISCUSSIONS

III.1 PHYSICAL PROPERTIES

III.1.1 Slump

The slump value is tested to determine the workability level of the mixture (GPC), since a higher slump value indicates that the mixture has good workability. In fact, a high slump value is not always accompanied by high compressive strength [23]; In context, the slump of the 0G/100F composition on the (FA) binder is 53.3% lower than that of the 100G/0F composition. By increasing the proportion of (FA) in the combined binder, the slump of the mixtures decreases [24], Likewise [25] highlight that, for (FA)-based RAGPC with a high AAC/B ratio of (0.8) (self-compacting concrete and binder), it was not necessary to use a superplasticizer (SP) to achieve the desired slump. Furthermore, the slump value of the (GPC) increased with increasing molarity of the NaOH solution, with slump values for 6 M, 9 M, 12 M, and 14 M were 62 mm, 78 mm, 87 mm, and 94 mm, respectively [26]. Overall, in mixtures incorporating (FA), workability can be maintained or even improved due to the spherical morphology of its particles, which favors the flow of the paste. Thus, the interaction between the NaOH concentration and the fly ash content defines the balance between the fluidity and cohesion of the material.

In turn [27], There is a slight decrease in the slump of the mixture with sand type M compared to the natural sand mixture, due to the angular shape of the fine aggregates. In another study, the CL1 mixture containing 60% GGBS and 40% pulverized fly ash (PFA) recorded the lowest slump value (185 mm), while the highest value (220 mm) was recorded for the CL3 mixture consisting of 80% GGBS and 20% (PFA). The data indicate that consistency generally improves by keeping the A/P ratio constant and varying the content of granulated blast furnace slag (GGBS) and (PFA) [28], complementing [29] It is argued that the slump test results for GPC with NaOH molarities of GPC12M, GPC14M, and GPC16M are 185 mm, 180 mm, and 175 mm, respectively, indicating that an increase in NaOH molarity leads to a decrease in the workability of fresh GPC. Overall, the studies analyzed show that the workability of GPC is influenced by the physical and chemical factors of its components. All this information is summarized in Table 3, based on a review of one article published in 2022, two in 2024, and four in 2025.

Table 3: Results obtained for the Slump.

Construction material	Activating solution	Percentage of substitution	Settlement (cm)	References
Concrete + (FA)+ Ground coffee	$NaOH + Na_2SiO_3$	90(FA)%+10% ground coffee	128 mm	[23]
Concrete + (FA) + (GGBS)	NaOH	80(GGBS) %20(FA)%	75mm	[24]
Concrete + (FA)+Recycled Aggregates (AR)	NaOH (SH) + Na_2SiO_3 (SS)	Self-Washing and Bonding Aerated Concrete (ACC/B) =0.8	100mm	[25]
Concrete + (FA)	$NaOH + Na_2SiO_3$	(CPC)-14M	94mm	[26]
Concrete +(FA) class F + (GGBS)	$NaOH + Na_2SiO_3$	80%(GGBS)+ 20% (PFA)	220mm	[27]
Concrete + (FA) + (GGBS)	$NaOH + Na_2SiO_3$	50%(GGBS)+ 50% (FA)	650mm	[28]
Concrete + (FA)	NaOH-12M	(GPC)-12M	185 mm	[29]

Source: Authors, (2026).

III.1.2 Air Content

Geopolymer concrete (GC) was prepared with different silica fume (SF) contents (15%, 22.5%, and 30% by volume). In addition, three Portland cement (PC) concretes with a composition and mechanical properties suitable for comparative purposes were prepared, where the air content of (GC) was lower than that of (PC) and decreased as the (FA) content increased. The air content range of (PC) was maintained between 0 and 0.4% [30], on the other hand [31] It maintains that the minimum air content value observed in the M1R0 concrete mix was 1.50 (±0.5); likewise, the air content for the M1R0, M2R25, M3R50, M4R75, and M5R100 concrete mixes was 1.5%, 1.62%, 1.69%, 1.7%, and 1.74%, respectively. In addition, the angular size of the WMA significantly influences the mixture, as it requires a greater amount of water, which generates more voids; on the other hand, due to the high CaO content in marble, concrete samples are prone to cracking. In summary, the air content in concrete depends on the nature and form of the materials used. The increase in fly ash reduces the occluded air, while marble waste increases it due to its angularity and high calcium oxide content.

III.1.3 Setting Time

By [32] As the silica fume (SF) content increased, the setting times decreased, reflecting the pozzolanic reactivity of SF, which accelerates the geopolymerization process. At a curing temperature of 60°C, the initial and final setting times of the paste (GP) were 53 and 159 minutes, respectively, for an 18M NaOH solution. [33]. On the other hand [34] They used the penetration resistance method and found that the GPC mixtures, with the exception of mixture FA0 containing 0% FA, 60% slag (S), and 40% waste clay brick dust (WCB), reached initial setting between 4 and 5 hours and final setting between 12 and 24 hours. (FA), 60% slag (S), and 40% waste clay brick dust (WCB), achieved initial setting between 4 and 5 hours and final setting between 10 and 10.5 hours; The WCB-based GPC developed in this study showed a high hardening rate and a penetration resistance of 28 MPa in approximately 15 hours or less. In this context, when the A/CE ratio was 0.38 and the (FC) content was 50%, the initial (final) setting times of the geopolymers with alkaline contents of 8%, 10%, and 12% were 30 (115), 90.5 (170), and 204 (295) min, respectively. [35]. This suggests that variations in the A/CE ratio, alkaline activator content, and temperature have a significant impact on the setting and hardening properties of geopolymers. All this information is summarized in Table 4, based on a review of one article published in 2023, two in 2024, and one in 2025.

Table 4: Results obtained for the setting time.

Variable modified	Solución activadora	Activating solution	Initial setting time (min)	Final Setting Time (min)	References
Concrete + (FA)+ (SF)	$NaOH + Na_2SiO_3$	30%(SF)+ 70%(FA)	150mim	340min	[32]
Concrete + (FA)+ Escoria	Na2SiO3	Relation a/a 0.45	240 min	630 min	[33]
Concrete + (FA) class C+ (FA) class F	$NaOH + Na_2SiO_3$	50%(CF) A/C=0.38	30mim	115min	[34]
Concrete + (FA)	$NaOH + Na_2SiO_3$	NaOH-18M Temperature: 60°	53min	159min	[35]

Source: Authors, (2026).

III.2 MECHANICAL PROPERTIES

III.2.1 Compressive Strength

In turn [36] The decrease in compressive strength was more pronounced when only recycled concrete aggregate (RFA) was used instead of natural aggregate (NFA). The rate of increase in strength is significantly higher under hot curing conditions than under room temperature curing conditions. Among the mixtures (GPC) cured at room temperature (25°C), the mixture (8M GC-25) in proportions of (FA) at 95% and slag at 5%, cured at a temperature of 25° and molarity 8M, presented the highest strength at 28 days (63 MPa), while the mixture (2M GC-25) in proportions of (FA) 95% and slag 5%, cured at a temperature of 25° and molarity 2 M, showed the lowest strength (33 MPa). [37], on the other hand [38] It mentions that compressive strength reaches its maximum value of 69.65 at 100 °C, then decreases with increasing temperature.

As the recycled coarse aggregate (RCA) content increases, the residual compressive strength decreases. Similarly [39] argues that partial replacement (FA) with recycled binder generally decreased compressive strength, mortars with up to 60% recycled geopolymer cement (RGPC) exhibited strength values greater than 50 MPa, sufficiently high for structural applications. It has been shown that the use of recycled aggregates and recycled binders tends to reduce the compressive strength of GPC compared to the use of natural materials. However, curing at high temperatures significantly improves mechanical properties, partially offsetting this decrease. By [40], studied the positive impact of class F (FA) on the increase in compressive strength, On the other hand [41] They maintain that the compressive strength at 28 days of the specimens without ultrafine slag (UFS) was 38 MPa, and increased to 65 MPa with a 50% substitution, observing a notable increase in mechanical properties due to the high unit weight and density.

Similarly, the increase in the proportion of geopolymer binder replacement increased the compressive strength values, reaching 65.5 MPa, 68.7 MPa, and 72.5 MPa for the Geo25, Geo50, and Geo75 mixtures, replacing 25%, 50%, and 75% of (OPC) with geopolymer binders, respectively [42]. In addition, the highest compressive strength was achieved by hot air oven curing, with 33.3 MPa, followed closely by accelerated curing (32.1 MPa) and outdoor curing (31.5 MPa). The optimal dosage of (GPC) was determined to be a ratio of 70% (FA) and 30% (GGBS) [43]. Overall, the studies reviewed confirm that increasing the proportion of supplementary cementitious materials, such as fly ash and slag, significantly improves the compressive strength of GPC All this information is summarized in Table 5, based on a review of two articles published in 2024 and six in 2025.

Table 5: Results obtained for compressive strength.

Construction material	**Activating solution**	**Optimal percentage of substitution**	**Compressive strength at 28 days (MPa)**	**References**
Concrete + (FA)+GGBFS	NaOH + Na_2SiO_3	0% (NCA) + 30% (RFA)	41.4Mpa	[36]
Concrete+ (FA)	NaOH-8M	95% de(FA)	63 MPa	[37]
Concrete + (FA) + Recycled Aggregates (AR)	NaOH + Na_2SiO_3	50% (RCA) y 50%de(NCA)	67.45Mpa	[38]
Concrete + (FA)+ (RGPC)	NaOH + Na_2SiO_3	60%(RGPC)	50 MPa	[39]
Concrete + (FA) + (FA) Bituminous Coal (BCFA)	NaOH + Na_2SiO_3	40%(BCFA) 60%(FA)	38.97MPa	[40]
Concrete +(FA) + (UFS)	NaOH + Na_2SiO_3	50%(UFC) y 50%(FA)	65MPa	[41]
Concrete + (FA) + Steel Slag (SS)	NaOH(L)-12	(SS): 52.5 %, (FA): 22.5 %	75MPa	[42]
Concrete + FA+ (GGBS)	NaOH + Na_2SiO_3	70% de (FA)	33.3MPa	[43]

Source: Authors, (2026).

III.2.2 Tensile Strength

Accordind to [44], They pointed out that GPC consistently exhibits higher tensile strength values, and although it offers a significant advantage in terms of tensile strength during the early stages of curing, this characteristic highlights its superior mechanical performance compared to ordinary Portland cement (OPC). Likewise [45] They mentioned that the proportion of (GGBS) in the mixture reached a maximum of 20%, since above this level, a decrease in tensile strength was observed. On the other hand, the greatest reduction in tensile strength was observed in the mixture with 100% RCA. Adding carbon fiber (CF) increases tensile strength because the load on the first crack does not exceed the fiber's tensile strength. [46].

Finally, the studies revealed that geopolymer concrete (GPCS) manufactured with different percentages of (SF) and (MK) with additional materials showed greater tensile strength in comparison with the reference mixture of (GPFA); In this regard, favorable results were obtained with the incorporation of 20% metakaolin (MK) and 10% SF, which increased the concrete's flexural strength at 28 days by up to 23% and 20%, respectively [47]. The optimal combination of fly ash (FA) with other cementitious materials and complementary reinforcements generates a significant improvement in the tensile strength of geopolymer concrete. All this information is summarized in Table 6, based on a review of one article published in 2021, one in 2022, and two in 2025.

Table 6: Results obtained for tensile strength.

Construction material	**Activating solution**	**Optimal percentage of substitution**	**Tensile strength at 28 days (MPa)**	**References**
Concrete+ (FA) +(GGBFS)	NaOH + Na_2SiO_3	1:2,5:3,5 (Binder: fine aggregate: coarse aggregate)	4.3 MPa	[44]
Concrete +(FA) +(GGBFS)	NaOH + Na_2SiO_3	80FA%+20GGBFS%	4.35MPa	[45]
Concrete +(FA)+ carbon fibres (FC)+RCA	NaOH-10M y Na_2SiO_3	Precursor concrete + 0.2% de (FC)	3.5MPa	[46]
Concrete + (MK)+(SF)	NaOH + Na_2SiO_3	(GC)+20%(MK) (GC)+10%(SF)	4.83MPa 4.81MPa	[47]

Source: Authors, (2026).

III.2.3 Flexural Strength

The flexural strength evaluation was performed on 28-day specimens, and the results and comparisons with the control mixture (CC) showed that the GPC mixture exhibited a 17.38% increase in flexural strength. [48], In a similar way [49] reported that the highest flexural strength among the modified samples was obtained with the samples containing 60% foamed geopolymer aggregates plus expanded clay (FGA/ECA/P 60), reaching 4,386 MPa, while the lowest was recorded in the FGA 75 sample, with 2,994 MPa. Likewise, the mixture with the best performance in terms of mechanical properties (flexural strength) was composed of 20% microsilica (SF) and 80% fly ash (FA), which significantly improved its mechanical properties [50]. Finally, another study observed an upward trend in flexural strength values as the ordinary Portland cement (OPC) content increased, reaching maximum values of 12.1, 13.12, and 15.21 MPa at 7, 14, and 28 days, respectively, for the 30% OPC and 70% FA mixture; however, a decrease in (FS) was observed after this maximum [51]. In summary, the flexural strength of geopolymer concrete improves with the increase and appropriate combination of supplementary cementitious materials. The presence of fly ash, microsilica, and OPC promotes matrix densification and strength development.

In turn [52] argues that combining recovered fly ash (RFA) with calcium-rich precursor materials such as ground granulated blast furnace slag (GGBFS) to produce geopolymers is a better alternative to geopolymers that incorporate only RFA. In a complementary manner [53] demonstrated by activating the hydration rate and improving the early strength qualities of class C (FA) concrete, an alkaline solution composed of sodium hydroxide and sodium silicate with an optimal molarity of 12M was added. Similarly, the control sample (C-GS) containing fly ash, slag, alkaline activator, coarse and fine aggregates, water, and a superplasticizer achieved the highest flexural strength, 5.1 MPa, while the sample with the highest plastic content (1.5-GS) obtained a reduced strength of 3.7 MPa, representing a decrease of 26.7% [54]. Finally, the results of the experimental flexural capacity of beams reinforced with longitudinal and transverse steel (GPC) are comparable to those of conventional concrete beams (CCB). The difference between the experimental and theoretical flexural capacities was 7.53% and 6.67%, respectively [55] Overall, the studies reviewed demonstrate that the incorporation of calcium-rich precursor materials and the use of alkaline solutions with optimal molarity significantly improve the strength and flexural behavior of (GPC). All this information is summarized in Table 7, based on a review of one article published in 2024 and seven in 2025.

Table 7: Resultados obtenidos para la resistencia a la flexión.

Construction material	Activating solution	Optimal percentage of substitution	Flexural strength at 28 days (MPa)	References
Concrete +(FA) + (GGBS)	NaOH+ Na2SiO3	40% de (FA)	4.8 MPa	[48].
Concrete +(FA) + light aggregates	NaOH+ Na2SiO3	17.90% de (FA)	4.386MPa	[49]
Concrete +(FA) + (SF)	NaOH+ Na2SiO3	80(FA)%+20%(SF)	7.80MPa	[50]
Concrete +(FA)+(OPC)	NaOH+ Na2SiO3	80(FA)%+20(OPC)%	15.21MPa	[51]
Concrete +(FA) + (GGBS)	NaOH+ Na2SiO3	20%(FA)+80%(GGBFS)	9.4MPa	[52]
Concrete +(FA) high calcium content	NaOH+ Na2SiO3	Na_2SiO_3+NaOH/ (FA): 0.37	7.31MPa	[53]
Concrete +(FA) + GGBS+ Recycled Plastic (PR)	Na2SiO3 ·5H2O	Precursor concrete + 0.5% de (PR)	4.7MPa	[54]
Concrete +(FA) +(GGBS)+ longitudinal and transverse reinforcements	NaOH+ Na2SiO3	Precursor concrete +2-8Ɵ+3-10Ɵ	19.84MPA	[55]

Source: Authors, (2026).

III.3 MICROSTRUCTURAL PROPERTIES

III.3.1 Scanning Electron Microscopy (SEM)

By [56], [57] show how the characteristics of aggregates influence the microstructure and properties of materials. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis showed that the use of 2% lime content in steam-cured lime-fly ash geopolymer concrete (L-FGPC) improves the geopolymerization process, resulting in a homogeneous, compact, and finer microstructure and produces a dense gel that reduces the proportion of voids. Therefore, it is believed that lime acted as a catalyst in the L-FGPC mixture when 2% lime content was used. [58]; Furthermore, XRD patterns indicate the formation of well-crystallized materials, with higher peaks of quartz (Q) and mullite (M) noted at 2θ values of 27–32° for all samples. In general, these peaks indicated the formation of the main compound (aluminosilicate hydrate (NASH)) produced by the geopolymerization process [59].

On the other hand [60], XRD analysis allows us to evaluate the effect of municipal solid waste (MFA) replacement rates on (GPC), observing small peak clusters between 18° and 36°, associated with amorphous aluminosilicate gels. These clusters progressively decrease as (MFA) replacement increases, reflecting less hydration product formation. This is due to the lower aluminum and silicon content of MFA compared to MK, which reduces the amount of amorphous gels generated in MFA-GPC. Finally, the XRD results of the geopolymer pastes based on fly ash reinforced with GFRP/FA glass fiber at 3, 7, and 28 days revealed that the crystalline phases of the hardened pastes at different curing ages are mainly quartz (SiO_2), calcite ($CaCO_3$), mullite ($Al_6Si_2O_{13}$), larnite, and portlandite ($Ca(OH)_2$).

Furthermore, the progressive decrease in the quartz peak with curing age indicates the dissolution of Si ions in the alkaline medium during geopolymerization [61]. In summary, XRD analyses show that geopolymerization is strongly influenced by the presence and evolution of amorphous and crystalline phases, demonstrating that the formation of NASH, the variation in quartz and mullite peaks, and the decrease in amorphous gels depending on the type and replacement of the precursor determine both the degree of reaction and the structural stability of the geopolymer. All this information is summarized in Table 8, based on a review of four articles published in 2022.

Table 8: Scanning electron microscopy results.

Condition assessed	Morphology/microstructure observed	Implications	References
Geopolymers of (FA) class F+ Cured with lime and steam.	He observed a dense gel, and the ratio of voids and microcracks decreased.	…..	[58]
Geopolymers of (FA) + nanoclay + nanotitanium	Formation of silicate compound, higher density, decrease in ITZ thickness	Improved ZIT and greater mechanical strength	[59]
Geopolymers of (FA) + (MFA)	Replacement of 10% of MFA continues to appear composed of silicate-aluminate gel, appearance of small cracks.	Decreased structural strength and GPC becomes more porous	[60]
Geopolymers of (FA) class F+ fiberglass (GFRP) + steel slag (SS)	Increase in the amount of gels grouped in the matrix, indicating a high degree of geopolymerization.	Increased mechanical strength	[61]

Source: Authors, (2026).

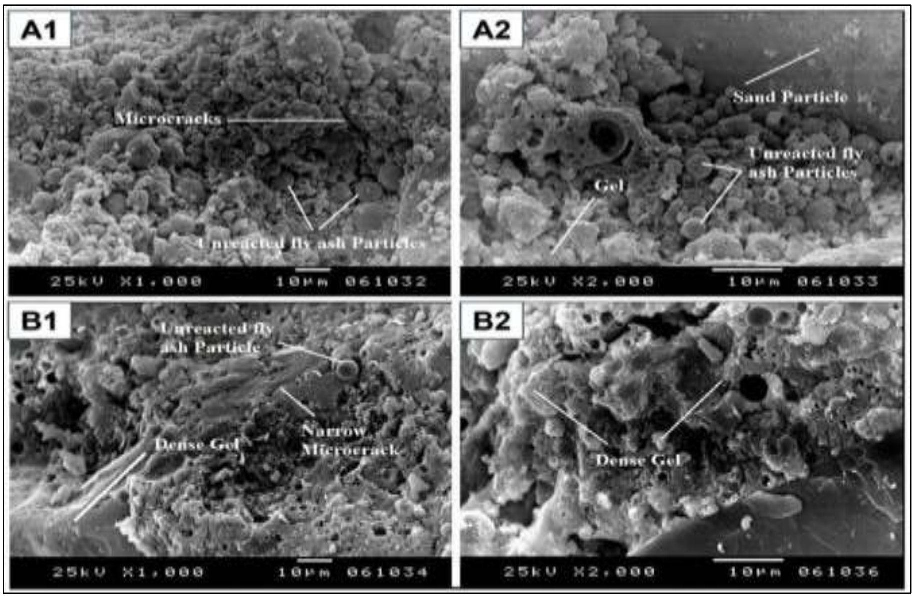

Figure 3: Improvement of the performance of class F geopolymer concrete (FA) through curing with lime and steam.
Source: [60].

III.3.2 X-Ray Diffraction (XRD)

CaO promotes the formation of C(N)–A–S–H gel products, forming a dense microstructure and increasing the compressive strength of self-compacting geopolymer concrete (SCGC) [62]In another study, mixtures A0*, A4, and A8 containing 0%, 4%, and 8% OPC of the total binder at 3 and 28 days, in the early stage, it was found that activation reaction products formed on the surface of the FA particles. This is generally considered to be the precipitation of the sodium aluminosilicate gel produced by the reaction. In contrast, greater precipitation than that mentioned above was observed in sample A8 with 8% OPC [63]. Likewise [64] reported that samples of (GC) 15M2.0NA (natural coarse aggregate, with an NS/NH ratio of 2 and 15 mol) and 15M2.0CM (crushed ceramic waste as coarse aggregate, with an NS/NH ratio of 2 and 15 mol) showed a large crack width and larger pore size in the interfacial transition zone (ITZ) of 15M2.0NA compared to 15M2.0CM.

These results confirmed that the use of waste ceramic aggregate (CM) improved the bonding and homogeneity between the geopolymer paste and the aggregates. Finally [65] They demonstrated that, when comparing the (ITZ) of RS-GP (natural sand and binder) and RFA-GP (recycled fine aggregate and binder), recycled coarse aggregate (RFA) can result in a more compact ITZ than natural sand, which is one of the reasons why compressive strength does not decrease significantly even when the replacement rate of RFA reaches 100%. Overall, studies show that both the presence of CaO and (OPC) and the appropriate selection of aggregates have a decisive influence on gel density, (ITZ) compactness, and, therefore, (GPC) strength. All this information is summarized in Table 9, based on a review of four articles published in 2023.

Table 9: Results obtained for X-ray diffraction.

Condition evaluated	Morphology/microstructure observed	Implications	References
Geopolymers of (FA) + blast furnace slag + (MK)	Reduction in porosity, abundant formation of C–A–S–H gels	Dense microstructure and mechanical strength	[62]
Geopolymers of (FA)+(OPC)	Formation of calcium aluminosilicate hydrate (CASH)	Compressive strength and transverse deformation capacity	[63]
Geopolymers of (FA) + natural fine aggregate (NA) and recycled aggregate (CM)	Greater porosity and water absorption	Lower mechanical properties with (CM)	[64]
Geopolymers of (FA) + natural coarse aggregate (RS) + (RFA)	Lower porosity and water absorption	Lower mechanical properties with (RS)	[65]

Source: Authors, (2026).

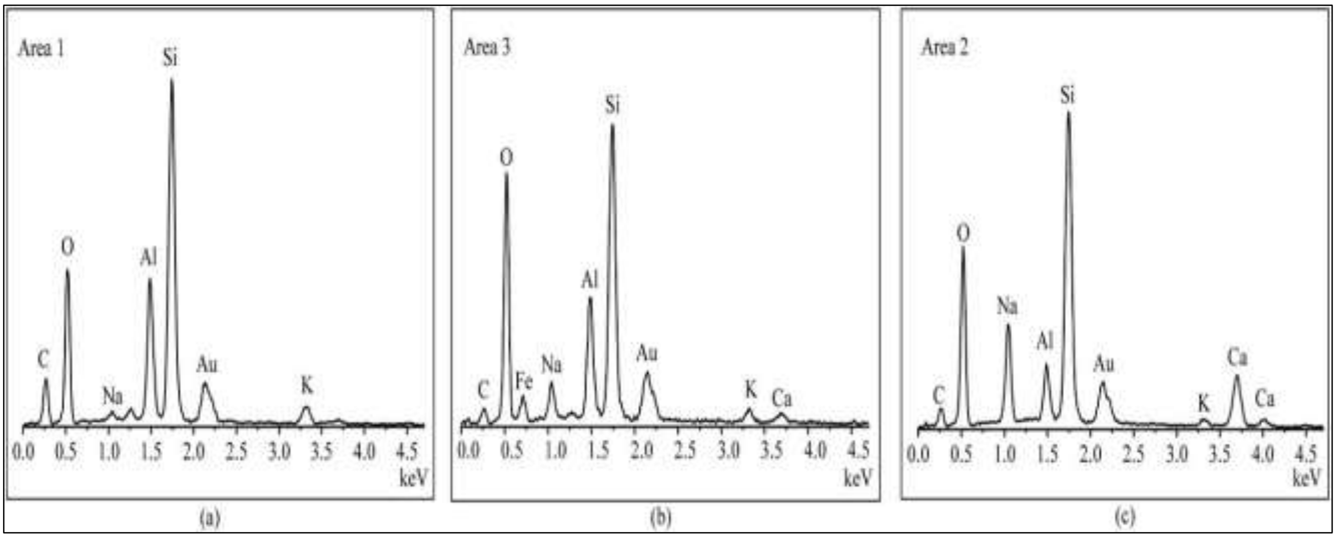

Figure 4: EDS patterns of the FGC matrix at standard curing age. (a): sample A0*; (b): sample A0; (c): sample A8.
Source: [63].

III.3.3 Fourier Transform Infrared Spectroscopy (FTIR)

In GPCs, the optimal CaO/SiO_2 and SiO_2/Al_2O_3 ratios are directly associated with the formation of the C_1S_2H, $C_1(A)_1S_2H$, and $N_1A_1S_2H$ phases, which in turn have a direct influence on microstructure transformation. [66]; according to [67], The FTIR spectra of all specimens consisting of two types of fly ash – high calcium fly ash (HCF) and low calcium fly ash (LCF) – with a weight ratio of HCF to LCF of 1, showed bands at 3700 – 3400 cm^{-1} and 1700–1600 cm^{-1} associated with O–H stretching and H–O–H bending, evidencing the presence of water molecules, while around 1400 cm^{-1} O–C–O stretching was identified in all geopolymers. Likewise, a higher Si–O–Si/Si–O–Al stretching peak was observed in the mixtures with carbon microfiber (CF) compared to the control; however, the mixture with 0.1% (CF) showed a smaller increase in the 1200–950 cm^{-1} band compared to mixtures with higher contents.

Complementarily [68] reported that the FTIR spectra of the CCSW and GCSW groups show similar bands at approximately 3450, 1650, 1450, 1080, 995, and 875 cm^{-1} evidencing a comparable product composition; Furthermore, the absorptions at 1450 and 875 cm^{-1} are mainly associated with carbonates, originating from the calcium carbonate in the concrete slurry (CSW) and a small fraction of carbonized hydrated products. Likewise, the progressive intensification of the CASH band is directly related to the improvement in the mechanical properties of the GCSW samples. Finally, the FTIR spectra of the geopolymers studied in samples Si337, Si325, Si350, and GS15 show that aluminum binds with silicon to form a geopolymer gel, suggesting relatively high compressive strength. in contrast, the peak centered around 972 cm^{-1} in samples GS8, GS4, and Si375 shows that geopolymerization did not generate a solid network and that some slag remained unreacted, especially in GS8 and GS4.

The FTIR results were consistent with the compressive strength of the samples [69]. Together, the FTIR spectra allow the formation and quality of the geopolymer gel to be identified, showing that compositions with a higher degree of polymerization, supported by the intensification of the Si–O–Si/Si–O –Al and CASH bands, develop better microstructures and mechanical properties, while mixtures with lower reactivity show peaks linked to unreacted carbonates or slag, which explains their poor performanceAll this information is summarized in Table 10, based on a review of three articles published in 2021 and one in 2023.

Table 10: Results obtained for Fourier transform infrared microscopy.

Condition evaluated	Identified FTIR bands	Interpretation / Observations	References
Optimal blends: 75%(FA)+25% (UPOFA) 75%(GBFS)+25% (FA)	The shift of (O–Si–O or Si–O–Si) is within 730.95–777 cm^(−1), and the AlO_2 functional group is within 650.12 cm^(−1)–695 cm^(−1).	Formation of gels (C–(A)–S–H) and C–S–H, N–A–S–H	[66]
Geopolymers of (FA) + carbon microfiber (CF)	They showed wave numbers of 3700–3400 cm^(−1) and 1700–1600 cm^(−1) for O–H stretching and H–O–H bending, and O–C–O stretching was detected at a wave number of 1400 cm^(−1).	A noticeable difference was the larger peak elongation of Si–O–Si or Si–O–Al in the CF mixtures compared to the control mixture.	[67]
Geopolymers of (FA) + blast furnace slag (BFS) + concrete slurry (CSW)	The main bands are detected at approximately 3450, 1650, 1450, 1080, 995, and 875 cm^(−1), such as stretching of the –OH group, bending of water (H–OH), carbonate (CO_3^{2-}), silicates or sulfates, and stretching of Si–O.	Gradual improvement of the CASH absorption band leads directly to a significant improvement in the mechanical properties of GCSW samples.	[68]
Geopolymers of (FA)+ (GGBFS)	The bands in the range 900–1200 cm−1 were attributed to Si-OT (T = Si or tetrahedral Al).	A relatively high compressive strength was observed for these samples.	[69]

Source: Authors, (2026).

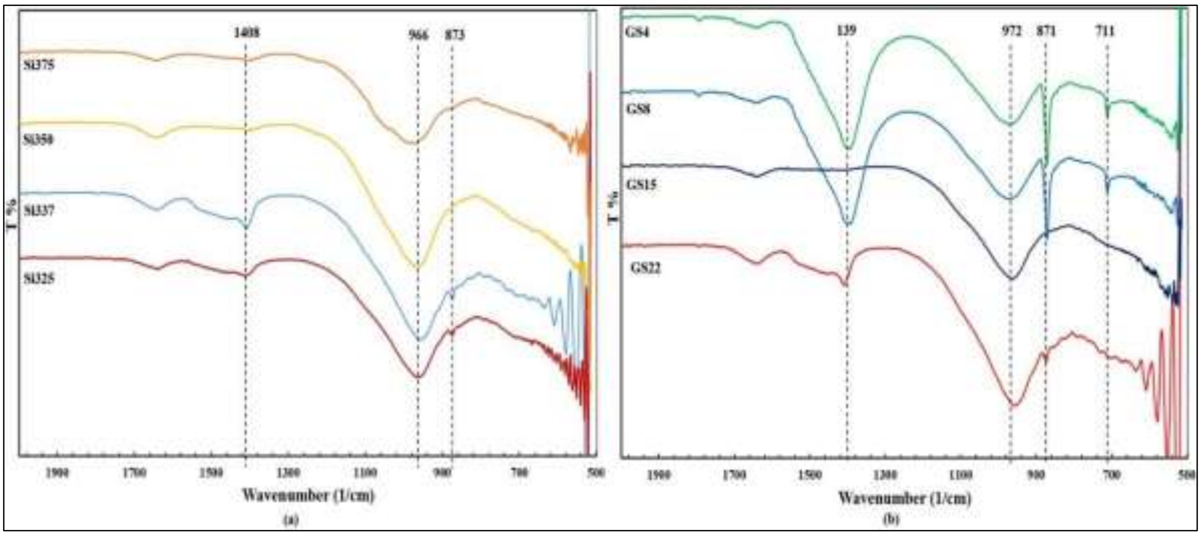

Figure 5: FTIR spectra of geopolymers.
Source: [69].

IV. CONCLUSIONS

Fly ash has established itself as an efficient substitute for Portland cement, reducing the carbon footprint and promoting the circular economy through waste recovery. Its performance in geopolymer concretes depends on proper dosing and the use of alkaline activators such as NaOH and Na_2SiO_3, which generate N–A–S–H and C–A–S–H gels responsible for mechanical and microstructural properties. Factors such as activator molarity, activator-precursor ratio, aggregate type, and curing influence workability and strength development. With the incorporation of supplementary materials such as slag, microsilica, or metakaolin, these concretes can match or exceed conventional concrete in compression, tensile, and flexural strength. Microstructural analyses show dense and stable matrices, confirming that geopolymer concrete with fly ash is a viable and durable alternative for structural and sustainable applications.

V. AUTHOR'S CONTRIBUTION

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Discussion of results: Cristian Chuquipul Angulo, Socrates Pedro Muñoz Perez, Victor M. Valdivieso Sir
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Writing: review and editing: Cristian Chuquipul Angulo, Socrates Pedro Muñoz Perez
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