Review Article

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Review on geopolymer concrete incorporating Alccofine-1203

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Abstract: The emergence of geopolymer concrete (GPC) has occurred as a sustainable substitute for conventional cement-based concrete, offering enhanced mechanical characteristics and reduced environmental impact. In the quest to further optimize GPC, incorporating supplementary cementitious materials has gained attention. For the research, Alccofine-1203 was considered as the material for incorporation into the geo-polymer concrete. This review study specifically examines the utilization of Alccofine-1203 as a material in GPC within the domain of structural engineering. Alccofine-1203, a high-performance mineral additive, exhibits pozzolanic and reactive properties, making it a promising candidate for enhancing GPC performance. This paper provides a comprehensive analysis of the chemical compositions and physical properties of Alccofine 1203, highlighting its potential benefits in GPC. Furthermore, it explores the influence of Alccofine-1203 on various aspects of GPC, including workability, compressive strength, flexural strength, durability, microstructure, and thermal properties. The review encompasses an analysis of relevant tests conducted to evaluate these properties. In summary, this review article is a great resource for researchers, engineers, and practitioners who are interested in the development and application of GPC containing Alccofine-1203.

Keywords: geopolymer, geopolymer concrete, Alccofine-1203, workability, compressive strength and FS

1 Introduction

The amount of development and advancement of a country can be assessed by the extent of its built environment expansion, which is further underscored by the manufacturing of concrete. Concrete is widely recognized as an essential material for meeting the increasing infrastructure needs of today's world. Concrete is widely utilized across the globe because of its flexible mechanical characteristics, this material is widely employed in construction, therefore being among the least often utilized building materials worldwide [1]. Internationally, experts are expressing significant concern over the need to decrease CO_2 emissions, which is widely recognized as a major contributor to global warming. The global demand for concrete as a construction material is incredibly high, second only to water. This has led to a significant increase in cement production. According to a study, each ton of cement production requires approximately 94.76 × 106 J of energy [1]. This energy consumption contributes to about 5–7% of the total CO_2 emissions from cement production. Thus, it is crucial to explore the development of cement-free concrete as an environmentally friendly alternative for construction, possessing the desired properties.

In today's world, there has been a substantial rise in the production of waste materials as a result of rapid industrialization and urbanization worldwide. According to research, the amount of solid waste generated worldwide is projected to be enhanced by 73% from 2.24 billion tons in 2020 to 3.88 billion tons per year by 2050 [2]. In India, the annual production of solid waste amounts to around 1 billion tons, resulting from a range of activities including municipal, manufacturing or related to industry, farming, mining, and other sectors [3]. However, the global demand for construction materials is incredibly high, reaching approximately 10 billion tons per year. This demand is leading to the exhaustion of renewable assets as well as the excessive energy consumption requisite to the manufacturing and transportation of natural resources. The natural environment is being altered as a consequence [4].

By incorporating supplementary cementitious materials (SCMs) into the manufacturing process, it is possible to significantly reduce the amount of cement needed for concrete production. The use of SCMs has brought about a significant transformation in the realm of civil engineering [5]. Thanks to the unique properties of SCMs, when

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combined with cement, they can create a wide range of strong and long-lasting concretes. Therefore, we can reduce environmental pollution by using SCMs as a substitute or partial substitute for cement in concrete production. Several forms of SCMs are available, such as limestone fines, FA, silica fume, rice husk ash, metakaolin ground granulated blast furnace slag (GGBS), pond ash, and more [6]. The SCMs are derived from the treatment of garbage generated by manufacturing and industry. In addition, improper disposal of these waste materials can contribute to environmental issues and disease transmission [7]. The construction industry can repurpose waste materials after modifications, transforming them into valuable SCMs. Utilizing recyclables from enterprises and factories through recycling provides several economic, technological, and sustainability advantages. Globally, the use of SCM-based concretes is increasing due to their eco-friendly attributes, outstanding behavior, and energy-conserving advantages.

Ambuja Cements Pvt. Ltd., a major cement manufacturing plant in India, has developed a new micro-mineral SCM called Alccofine [8]. There are three commercially available types of Alccofine on the market, each with a different calcium content. These types are Alccofine-1101, Alccofine-1203 (AF-1203), and Alccofine-1206. Table 1 provides the composition and use of each type.

Out of these three options, Alccofine-1101 stands out as a material with a high calcium silicate content. It is mainly utilized for grouting and soil stabilization purposes, as highlighted by Gautham Kishore and Ramadoss [9]. AF-1203, a material with a low calcium silicate content, commonly serves as a SCM. High-strength concrete (HSC) as well as high-performance concrete (HPC) often use provides a substitute for silica fume. Additionally, Alccofine-1206 is a material with a low calcium silicate content that is utilized in the production of different types of concrete [7]. Table 2 displays the physical and chemical properties of AF-1203, which adhere to ASTM C 989–99 standards.

The chemical compositions of cement, AF-1203, and various SCMs are compared in Table 3, as reported by refs. [10–13]. The use of CaO (Lime) in AF-1203 enhances its performance, surpassing that of all other mineral admixtures [9].

AF-1203 is a sustainable and environmentally friendly microfine material made from low calcium silicate. It contains a significant amount of glass content and has a high reactivity. AF-1203 is a refined substance derived from GGBS, which is the byproduct of India's iron ore industries. AF-1203 is a powder that consists of extremely small particles, known for its high fineness. It has a distinct chemical composition, as mentioned in various studies [5,10,14–17].

Geopolymer concrete (GPC) can increase environmental sustainability in industrial and building industries by recycling waste and reducing carbon emissions [2]. General purpose concrete (GPC) is made from aluminate (AlO_2) and silicate (SiO_3) with caustic activators like fly ash (FA) from Fe (iron) and metal manufacture. GPC may be the best ordinary Portland cement (OPC) substitute [3]. FA, silica fume, rice husk ash, pond ash, GGBS, limestone fines, metakaolin, *etc.*, can be used in the GPC [4]. Curing the heat of low calcium of any material-based geopolymer increases strength. Geopolymer was weaker than other materials in many studies [5]. Alccofine can be strong and workable at ambient and oven-curing temperatures.

The extensive industrial adoption of GPC can positively effect environmental sustainability promoted in the industrial or building industries through the practice of reusing garbage also its binding solutions it helps in the reduction of carbon emissions [2]. Generally, GPC is one of the types of concrete prepared by aluminate (AlO_2) chemical elements as well as silicate (SiO_3) relevant materials with caustic activators like FA from Fe (iron) and metal

Table 1: The composition and use of all three types of Alccofine [8]

Name	Composition	Use
Alccofine-1101	High calcium silicate	Grouting and soil stabilisation
AF-1203	Low calcium silicate	To substitute silica fume in the production of HSC and HPC
Alccofine-1206	Low calcium silicate	Manufacturing of various types of concrete

Table 2: Investigation of the physical as well as chemical properties of AF-1203 [8]

Physical properties					Chemical properties			
D10	D50	D90	Specific gravity	Density ($kg \cdot m^{-3}$)	Glass content	SiO_2	Al_2O_3	CaO
1–2	4–5	8–9	2.9	600–700	>90%	33–35%	23–25%	31–33%

Table 3: The chemical compositions of cement, AF-1203, and other SCMs have been studied [10–13]

Oxide constituents	FA	GGBS	Silica fume	Cement	AF-1203	Rice husk ash
Aluminium oxide (Al_2O_3)	28.15	14.53	0.043	4.72	24.57	0.14
Silicon dioxide (SiO_2)	61.55	32.99	99.88	22.53	37.53	92.96
Magnesium oxide (MgO)	1.02	7.73	—	1.46	5.23	—
Calcium oxide (CaO)	2.35	40.91	0.001	63.68	29.46	0.45
Ferric oxide (Fe_2O_3)	4.22	0.18	0.04	3.38	0.92	0.05
Potassium oxide (K_2O)	1.75	0.33	0.001	0.71	0.61	—
Sodium oxide (Na_2O)	0.2	0.25	0.003	0.37	0.032	0.29
Sulphur trioxide (SO_3)	0.25	1.84	—	1.32	0.18	1.32
Loss of ignition (LOI)	0.3	1.32	2.7	0.75	0.58	3.2

production. GPC can be considered the best replacement in place of OPC [3]. There are some important waste materials like FA, silica fume, rice husk ash, pond ash, GGBS, limestone fines, metakaolin, *etc.*, which could be incorporated into the GPC [4]. However, to increase substantial strength, the heat of low calcium of any material-based geopolymer should be cured. Many researchers have analyzed other different materials but the outcome was that geopolymer did not show good strength characteristics [5]. Various studies have explored the impact of incorporating different SCMs into GPC. Notably, The use of granite waste powder as pozzolanic materials in geopolymer composites improves geopolymer mechanical characteristics by achieving a greater degree of geopolymerization due to their exceptionally high reactivity [18]. This study evaluates the mechanical properties and workability of FA-slag-based GPC, indicating that the incorporation of slag improves mechanical characteristics while maintaining medium workability. It specifically examines various slag contents and their effects on performance, including a similar *A*/*B* ratio [19].

However, the material named Alccofine has the potential to attain strength and workability at ambient and oven-curing temperatures. Incorporating Alccofine-1203 in GPC offers significant sustainability benefits. It reduces the carbon footprint and energy consumption in concrete production. This slag-based material promotes waste utilization from the steel industry, contributing to circular economy principles. These advantages make Alccofine-1203 a promising component for creating more environmentally friendly construction materials. The utilization of AF-1203 has increased in the construction of several types of concrete, such as GPC, because of its efficient organization of ultrafine particles and unique chemical composition. This study aims to conduct a comprehensive analysis of the influence of AF-1203 on the workability, strength characteristics, and durability properties of GPC. AF-1203 serves as a replacement for FA or other supplemental cementitious materials (SCMs). Furthermore, this study seeks to determine the ideal proportion of AF-1203 that will yield the best mechanical and durability attributes for future applications in GPC.

The environment and humans will be in danger when cement production results in the emission of greenhouse gases (GHG). So, there is a purpose to identify other binding materials that pose less danger and are environmentally friendly [20]. The widespread use of GPC in various industries and construction sectors can contribute to environmental sustainability through the utilization of recycled waste materials and binding solutions, as well as the reduction of carbon emissions [21]. Generally, GPC is one of the types of concrete prepared by aluminate (AlO_2) chemical elements as well as silicate (SiO_3) relevant materials with caustic activators like FA from Fe (iron) and metal production. GPC can be considered the best replacement for ordinary Portland concrete (OPC) [22]. Significant waste materials include FA, limestone fines, GGBS, pond ash, rice husk ash, silica fume, metakaolin, *etc.*, which could be incorporated into the GPC [23]. However, to increase substantial strength, the heat of low calcium in any material-based geopolymer should be cured. Many researchers have analyzed other different materials, but the outcome was that geopolymer did not show good strength characteristics [24]. Alccofine, a substance, has the capability to achieve both strength and workability at normal temperatures and during the process of heat curing.

The material Alccofine has unique attributes that enhance the performance of the GPC in the new phase as well as in the solidified stage because the material has a developed particle size distribution [25,26]. Alccofine-1203 and Alccofine-1101 are two variants of Alccofine that differ in their calcium silicate content, with Alccofine-1203 having a lower calcium silicate content and Alccofine-1101 having a higher calcium silicate content. However, this research has focused on incorporating one type of Alccofine (Alccofine-1203) into geo-polymer concrete and the Flow chart of the process

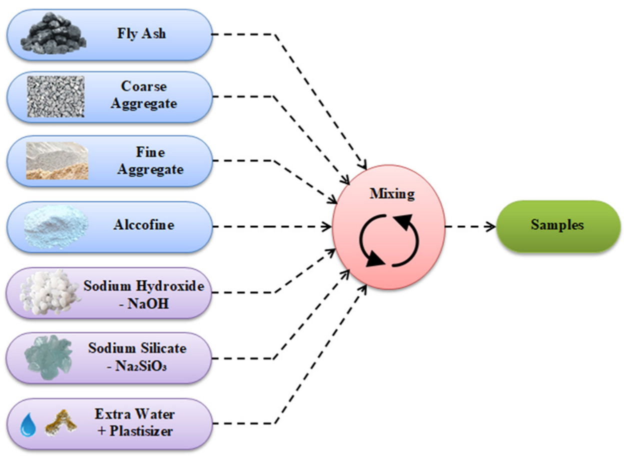

Figure 1: Process flow diagram for the production of Alccofine-incorporated GPC.

for Alccofine-based GPC has been explained in Figure 1. There are some of the advantages of the AF-1203 material incorporating GPC [27,28]:

- Durability parameters and pump ability of the concrete could be upgraded with decreasing permeability.
- Resistance of the concrete will be increased to assertive environmental agents.
- For safeguarding the steel reinforcement, the pH (power of hydrogen) of the concrete mix will be well-conserved.
- Shuttering and rotation of forms will be more rapid in the industry.
- Upon analyzing the obtained concrete mixtures, the strength rate will be enhanced. Alccofine-1203 has a crucial role in reducing the heat generated during hydration and enhancing strength during all stages [29]. Nevertheless, the issue arose when substituting concrete with AF-1203 in quantities exceeding 10%, resulting in adverse impacts on many metrics [30].

To identify relevant articles for this review, a comprehensive literature search was conducted using the Web of Science database. Two search strings were employed to capture a broad range of articles related to GPC and its incorporation of Alccofine:

TS = ((“GPC” OR “Geopolymer binder” OR “Geopolymers” OR “Alkali-activated concrete” OR “Alkali-activated binder”) AND (“Alccofine” OR “GGBS” OR “GGBFS” OR “ultra-fine slag” OR “SCMs”) AND (“Mechanical Properties” OR “Compressive strength” OR “Stress-strain relationship” OR “Dynamic compressive strength” OR “Energy absorption” OR “workability” OR “setting time” OR “microstructure”) AND (“DURABILITY” OR “CARBONATION” OR “PERFORMANCE” OR “BEHAVIOR”)).

TS = ((“Geopolymer*” OR “Alkali-activated*” OR “Inorganic polymer*”) AND (“concrete” OR “mortar” OR “paste” OR “binder” OR “composite” OR “material” OR “cement” OR “construction” OR “building” OR “infrastructure” OR “application” OR “production” OR “properties” OR “performance” OR “durability” OR “sustainability” OR “environmental impact” OR “waste management” OR “circular economy”)).

The first search string focused specifically on GPC incorporating Alccofine, while the second search string aimed to capture a wider range of articles discussing GPC and its various applications, properties, and sustainability aspects.

Figure 2 shows the bibliometric (keyword) analysis of GPC with different types of binders. A total of 1,000 papers’ data have been collected from Web of Science and analyzed on VOSviewer. The lines between the geopolymer and different binders show the no. of research papers on geopolymer with that particular binder.

Figure 3 shows the bibliometric (keyword) analysis of Alccofine with different materials and GPC types. A total of 45 papers’ data are collected from Web of Science and analyzed on VOSviewer. The lines between the Alccofine and GPC show the no. of paper on geopolymer with Alccofine.

2 Literature review

Before incorporating recently created cementitious substance into the building of concrete construction, it is essential to conduct a comprehensive assessment of the mechanical and durability properties of the resulting concrete. It is essential to conduct a comprehensive investigation into the mechanical characteristics and durability characteristics of AF-1203-based concretes before using it in the construction of concrete structures, as AF-1203 is a newly developed SCM for the construction sector. The mechanical characteristics of concrete have a significant influence on the analysis and design of concrete structures. Furthermore, the durability and longevity of these structures depend on the concrete’s ability to withstand chemical attacks. To conduct a comprehensive evaluation, recent studies have been chosen to provide an in-depth investigation of the mechanical and durability properties of different types of concretes utilizing AF-1203 as a basis material. The workability and reduction in water demand had been refined by the Alccofine. Because of the ultra-fine particle size, the strength properties of GPC were further refined. To refine the concrete footpaths in a new difficult phase and chemical composition, Alccofine-1203 was utilized. So, in this article, Section 2.1 defines the geo polymer concrete, Section 2.2 illustrates the Alccofine 1203, and Section 2.3 describes the analysis of the test for GPC incorporating Alccofine 1203.

2.1 GPC

GPC is a unique type of concrete that gains its strength through a chemical reaction between certain waste materials and alkaline activating solutions, instead of relying on a cement binder [31,32]. The contact between the base materials facilitates the geo-polymerization process, resulting in the creation of a strongly interconnected polymer network [33].

The study conducted, the hybrid life cycle assessment of GHG emissions from cement, concrete, and GPC in Australia [34]. The important aim was to create a process-based and hybrid life cycle assessment (hLCA)comparison by utilizing Australian cement and concrete production. From findings, it was identified that OPC outcomes were also higher in hLCA when compared with other LCA-based studies and reported the carbon footprint of OPC production in Australia ranges from 0.7 to 0.9 kg CO_2-eq kg^{-1}. There were many effect categories but only GHG was considered. In a study, a rubberized glass fiber-reinforced polymer composite (GPC) was developed and investigated for its strength and durability properties [35]. The results indicated that the pull-off strength of GPC reduced from 13.46 to 21.1% by increasing rubber fiber content in OPC concrete by 10 and 20% on the pull-off strength. Results indicated a reduction in pull-off strength that varied from 2.38 to 21.42% as the rubber fiber content was enhanced. Due to the better bonding, GPC obtained extremely higher tensile strength when compared with OPC. Their study investigated the potential of geopolymer concrete as a viable solution for reducing GHG emissions [36]. The analysis focused on the examination of GPC mix designs, the determination of equivalent OPC, and the evaluation of curing energy. The analysis revealed that when examining 817 scenarios involving various types of allocation, it was observed that the production of geo polymer 818 concretes generally resulted in lower CO_2-eq emissions compared to OPC 819 concretes. However, it is important to note that this trend was not consistently observed and was dependent on factors such as the absence of allocation and minimal transportation distances.

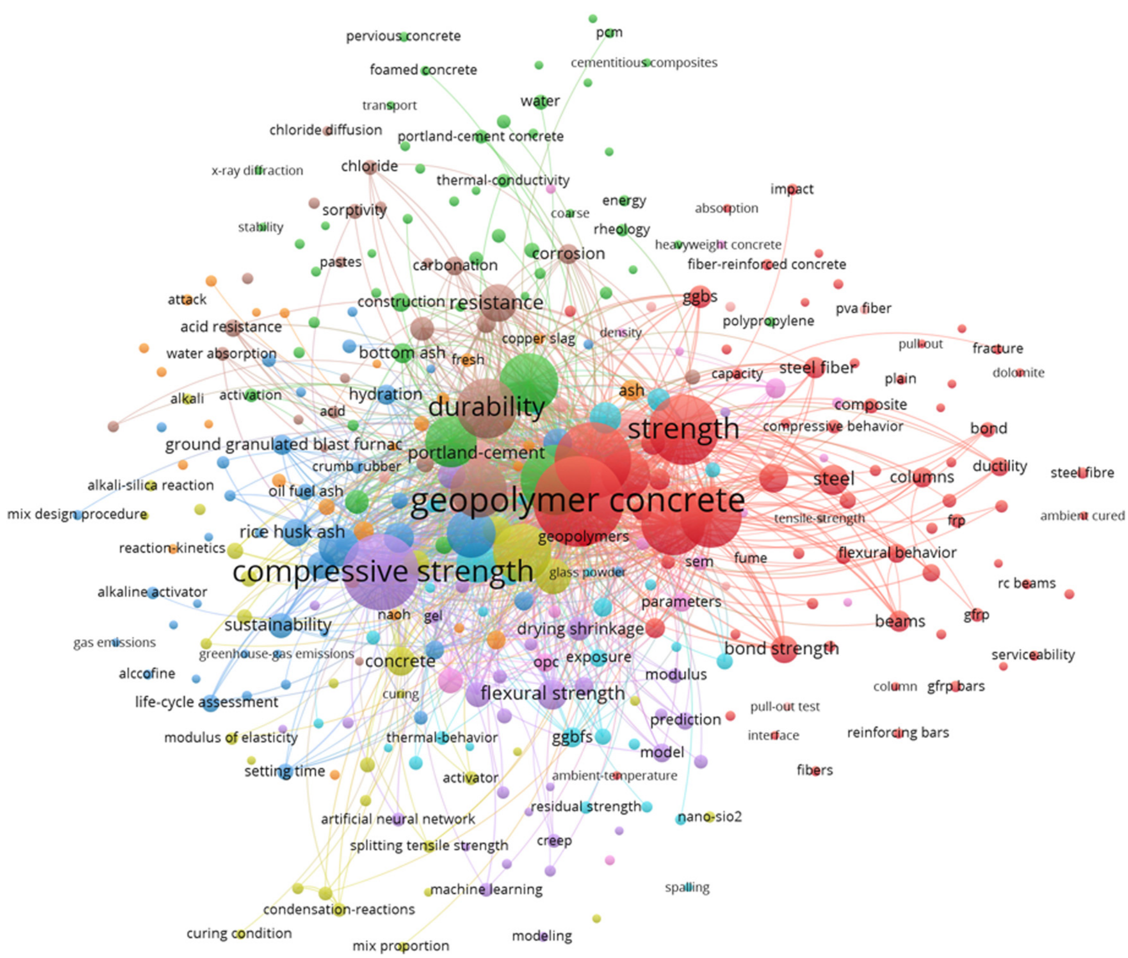

Figure 2: Keyword co-occurrence network of GPC and various binders based on bibliometric data.

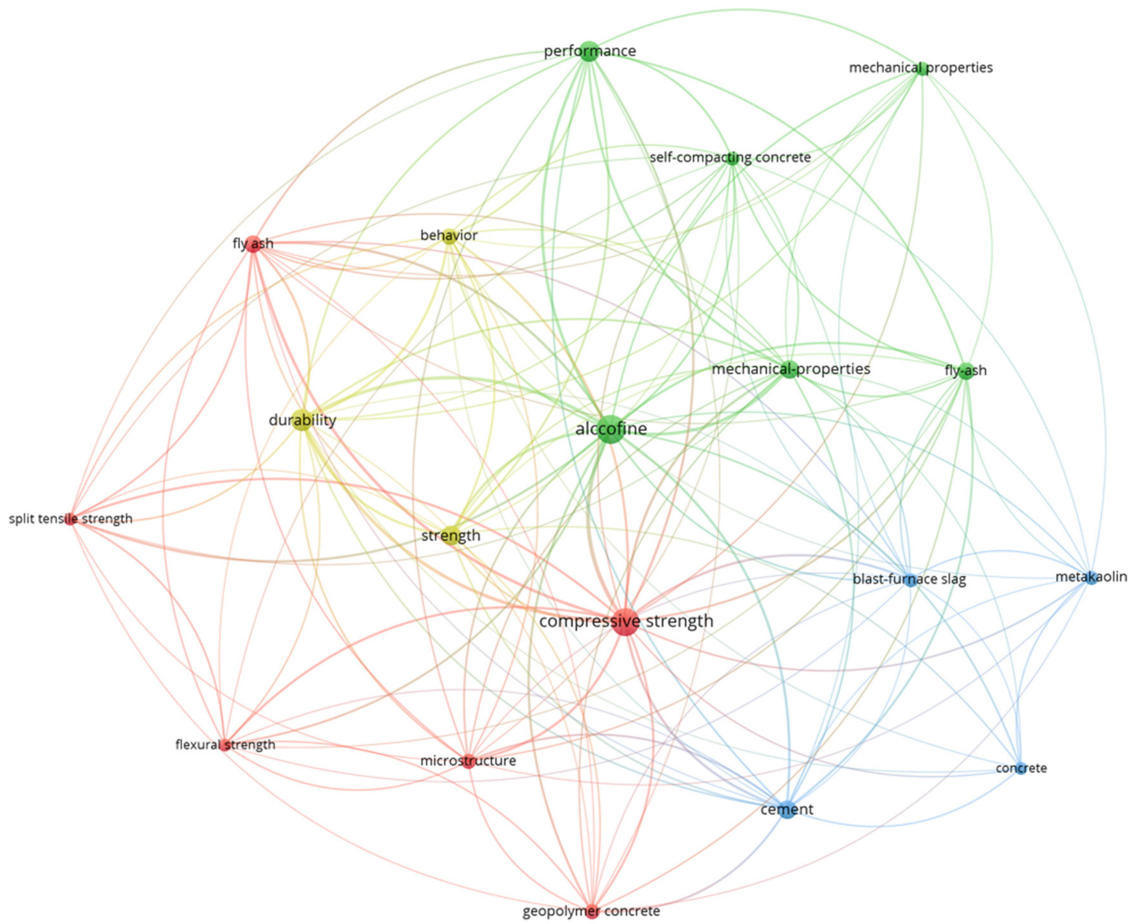

Figure 3: Bibliometric keyword analysis of Alccofine with different materials.

The ecological sustainability of one-part geopolymer binder concrete is studied [37]. For better handling and mixing with standard OPC, GPC was developed from a one-part geo polymer binder. It consists of powdered source ingredients and activators. The analysis revealed that the geopolymer and OPC binders are the main components that contribute to the overall carbon footprint of the concrete mix, accounting for approximately 86 and 52% of the total, respectively in their description of geo-polymer concrete's behavior at high temperatures [38]. Based on their material qualities, FA and GGBS were considered potential substitute materials. After undergoing high-temperature heating to compare its thermal performance with other specimens cured at 70°C, the compressive strength (CS) analysis of GPC heat cured at 60°C for 24 h showed superior results based on resistance.

2.1.1 Materials for GPC production

Geopolymer cement concrete is a type of construction material that is produced by incorporating various waste materials, such as Alccofine 1203, FA, GGBS, metakaolin, rice husk, and silica fume. Among these, a thermal power plant's byproduct is FA, while a steel mill's byproduct is powdered granulate blast furnace slag [39]. FA and GGBS are two commonly used SCMs in the production of concrete. These materials are manufactured using suitable technologies and are utilized in the form of binders in geopolymer concrete for various construction applications [40]. Table 4 explains the works of the list of materials used for GPC production with its attained outcomes and limitations.

The durability of geo-polymer concrete based on FA in the presence of silica fume was studied [41]. Weights and percentage losses in CS were used to evaluate the specimens' resistance to chemical attack at different time intervals. The results showed that at 90 days, the control (M40) and GPC3 in 2% H_2SO_4 experienced 36 and 8% decreases in CSs, respectively. In description of GGBFS-based geo-polymer concrete, covered a variety of materials and their overall characteristics. A variety of GPC mixtures were tested for their compressive, flexural, and tensile strengths. Different concentrations of GPC were used to make the mixtures. A 30, 20, and

25% improvement in GPC's compressive, flexural, and tensile strengths may be achieved by replacing GGBFS with SF at a 30 wt% substitution, according to the analysis [42]. There was no discernible effect of NaOH concentration on tensile strength. The effect of recycled aggregate on the characteristics of FA geo-polymer concrete was studied. The concrete samples were created using two kinds of coarse aggregate, a sodium silicate solution, a sodium hydroxide solution, and high calcium FA. In GPCs with a calcium FA content ranging from 30.6 to 38.4 MPa, the test results demonstrated that recycled concrete aggregate could be used as a coarse aggregate [43].

2.2 Alccofine 1203

Generally, Alccofine can be used either as an additive or a cement replacement to upgrade both fresh and hardened state concrete properties [44]. Alccofine-1203 is recognized as a novel micro-fine material with a particle size significantly smaller than other materials such as cement and FA [45]. According to previous research, the product known as Alccofine-1203 has been identified as a potential SCM. It is a suitable substitute for silica fume, which is commonly used in the production of HPC [46].

The effectiveness of concrete was studied when Alccofine-1203 was partially substituted [47]. A total of 33 mixes were made for the reason of the grade of concrete. All these mixes of concrete were evaluated for the different tests of fresh concrete with 3 days, 7 days, and 28 days. From findings, it had been found that cement cubes were tested for 3-, 7-, and 28-day strengths and partially replaced cement with 10% Alccofine, and a strength of 19.26 MPa was attained in 28 days. Hybrid fiber-reinforced concrete's characteristics were studied about the effect of the mineral additive accofine-1203 [48]. The concrete compositions used components of OPC 53 grade, while another substance called AF-1203 was imported from India. The results showed that the best concrete CS was achieved by using 7.5% AF-1203 in place of cement and 1.5% hybrid fibers (80% steel fiber and 20% polypropylene fiber), according to the trials conducted using M60 grade concrete. The application of Alccofine-1203 to concrete roadways was detailed by [49]. This article evaluates the efficacy of using SCM like Alccofine in concrete. According to the results, the compressive and flexural

Table 4: Works of materials used for the GPC production with its attained outcomes and limitations

Sources	Materials used	Findings	Limitations
[50]	FA and silica fume	According to the research, the minimum critical transport distances for the raw ingredients of geopolymer mixes were determined to be 3219.27 km for FA, 3704.58 km for silica fume, 905.92 km for NaOH, 922.74 km for Na_2SiO_3, and 420.60 km for fine and coarse aggregates	The assumption was made that the quality of pavement and other transportation factors would remain constant throughout the study. However, it is important to note that any changes in these variables could potentially impact the results and findings of the research
[51]	OPC	The findings of the study demonstrate that GPC exhibits advantageous characteristics in both water and air-cooling scenarios when subjected to thermal shock conditions. Consequently, this suggests that GPC could be effectively utilized in environments with an elevated fire hazard, necessitating prompt extinguishing using water	Measuring temperatures would pose a formidable challenge so the outcomes obtained will be less accurate
[52]	Alccofine 1203	Through analysis, it was determined that a significant increase in strength was achieved by adding 10% Alccofine to the mix design, resulting in a high-strength GPC of 73 MPa	During analysis, the consumption rate sometimes will be high
[53]	Catalytic liquid system	The findings indicated that the greatest degree of strength was observed at a CLS ratio of 2.5:1. It is advised that a CLS ratio of 2.5:1, with a maximum replacement level of 40% CCA and 60% GGBFS, can be employed in typical construction as structural concrete	The analysis of the CLS ratio before any design or construction should have been conducted, but it was ignored
[54]	Fine aggregate	The study found that the mechanical characteristics were enhanced when the fine aggregate blending ratio was 60:40, but a decline in these capabilities was detected when the blending ratio was 40:60	The range of the specific strength should be mentioned but it was neglecte

Table 5: Works on the list of chemical composition in Alccofine-1203 with its results attained and limitations

Ref.	Compounds	Compositions (%)	Findings
[55]	Calcium oxide (CaO)	43.92	Research showed that early on, the concrete's strength increased significantly, reaching a maximum bond stress of 22,000 $N \cdot mm^{-2}$ for a 16% Alccofine substitution at 7 days of age
[56]	Silicon dioxide (SiO_2)	27.53	The results showed that compared to concrete made with river sand, GPC with 80% pond ash as fine aggregate had 26% higher CS, 29% higher FS, and 31% higher STS
[57]	Alumina (Al_2O_3)	16.26	The STS of concrete at 28, 56, and 90 days was 3.78, 4.11, and 4.42 $N \cdot mm^{-2}$, respectively, when 16% Alccofine and 6% Sawdust were used with cement and fine aggregate
[58]	Magnesium oxide (MgO)	5.82	When compared to ACI-318 and IS 456, the results demonstrated that applied empirical relations had the lowest integral absolute error at 3.29 and 3.32% for flexural and STS amounts, respectively

strengths (FSs) of materials that were 5, 10, and 15% Alccofine replaced showed very little variation. During analysis, there was no considerable increase in final 28th-day test results but there was a swift gain in initial strength. [59] conducted a study on the utilization of GGBS in combination with AF-1203 for the production of HPC. The experiment was carried out to evaluate properties such as FS, CS, and split tensile strength (STS). The findings showed that by maintaining a consistent water–cement ratio of 0.30 for M70 concrete, Alccofine was substituted with different proportions of cement by weight, ranging from 10 to 15%. This substitution led to the production of both standard and HSC.

2.2.1 Chemical compositions of Alccofine-1203

Due to its distinctive chemical composition and excellent particle packing of ultrafine particles, AF-1203 has recently seen an increase in its usage in the production of various types of concrete [60,61]. Table 5 explains the works on the list of chemical composition in Alccofine-1203 with its results attained and limitations.

Using the AF-1203 chemical compositions, [62] studied geopolymer masonry. The chemical constituents utilized in the Alccofines were SiO_2, Al_2O_3, Fe_2O_3, CaO, SO_3, and MgO with percentages of about 35.4, 21.6, 1.2, 34.0, 0.12, and 6.5. From the findings, at a 30% substitution of Alccofine for FA, the maximum bulk density value reached was 2145.18 $kg \cdot m^{-3}$. For managing the manufacturing process of the geo polymer brick process, the geo polymer idea should be upgraded. The experimental investigation on an Alccofine-based GPC deep beam was studied, A variety of parameters were examined, including load-bearing capability, deflection, energy absorption, and failure modes [63]. Results showed that compared to the average value of GDBM10b specimens, CDB1b had a 1.5-fold larger final deflection at the mid-span. It was bigger than regular concrete because geo-polymer has a modulus of elasticity that is around 15–20% greater.

The X-ray diffraction (XRD) analysis of Alccofine, as depicted in Figure 4, reveals the presence of calcite as

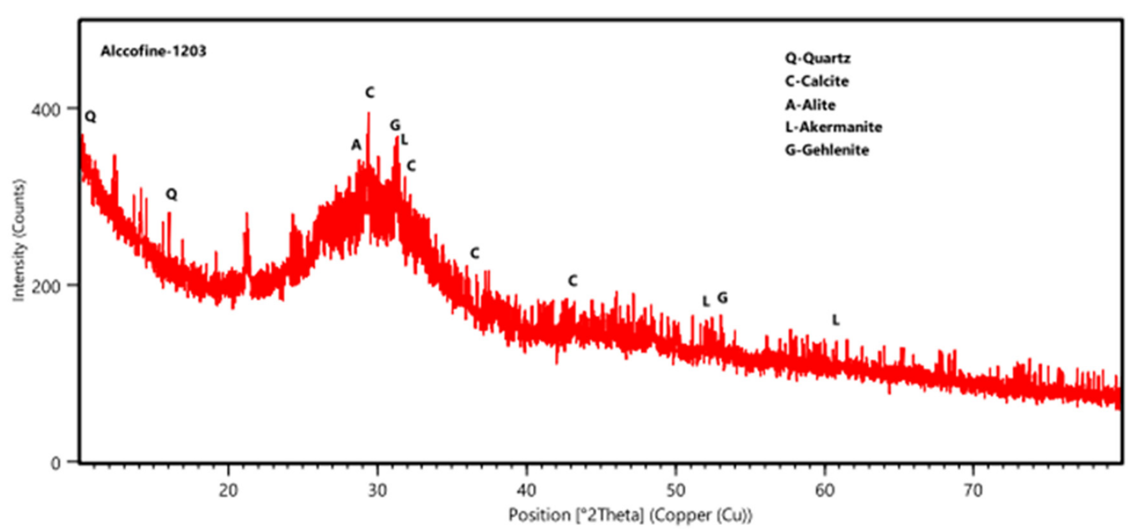

Figure 4: XRD Alccofine [13].

the predominant phase compound. Additionally, there are small quantities of quartz, gehlenite, and akermanite detected as trace components [13].

Figure 5 displays the constituent compositions of Alccofine, determined using energy-dispersive X-ray analysis (EDAX), as part of microstructural research [64].

2.2.2 Physical properties of Alccofine-1203

Generally, physical properties are utilized for the reason to observe and describe matter. Not only AF-1203, However, extensive and intense qualities are commonly used to describe the physical characteristics of many materials and systems as well [65,66]. A system or object can be categorized in this way according to the features that depend on its size distribution or extent [8]. The mix design approach for GPC with AF-1203 was studied, Physical properties of AF-1203 like particle size distribution, bulk density, specific gravity, and Specific surface were considered. From the results, it was found that the applied mix design method perfectly achieved the properties and targeted the strength [67]. It was guaranteed that GPC production with AF-1203 could be done successfully at room temp. of 27°C. The physical properties of geo-polymer concrete based on low calcium FA were studied by Singh and Sandhu [68] about Alccofine and curing conditions. Factors like as water absorption, fitness modulus, and specific gravity were taken into account. Adding Alccofine to the matrix improves the strength, even at room temperature, according to GPC10AF, which is sufficient for most building applications (up to 43 MPa). We neglected to take into account the significance of the strength value enhancement. The performance of GPC including the materials with AF-1203 and its physical properties. The important physical properties of AF-1203 like Specific gravity, the search encompassed the inclusion of specific surface area ($m^2 \cdot kg^{-1}$), bulk density ($kg \cdot m^{-3}$), and particle size in microns as key parameters [69]. Based on the results obtained, it was observed that the resistivity of GPC exhibited an increase when Alccofine and FA were added to the mixture. This increase in resistivity can be attributed to the homogeneity achieved by incorporating up to 8% of Alccofine into the composite. However, it was noted that the resistivity decreased when the dosage of Alccofine was further increased beyond this threshold. In a study, the properties of Alccofine-based GPC were thoroughly examined and documented [63]. AF-1203 exhibits a specific gravity property of 2.72, a bulk density of 680 $kg \cdot m^{-3}$, and a specific surface area of 1,200 $m^2 \cdot kg^{-1}$. The findings from the GPC study incorporating Alccofine indicate that it not only enhances the strength of concrete but also presents a viable alternative to conventional concrete materials. An important effect was observed in the polymerization process of GPC when Alccofine-1203 was introduced, resulting in an enhanced strength.

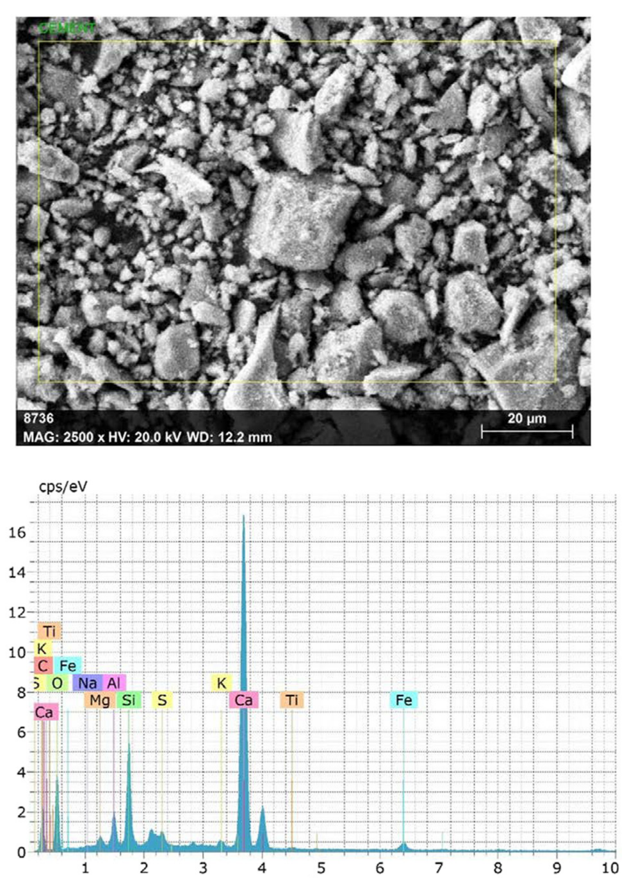

Figure 5: Imaging and composition of alccofine through EDAX [64].

Figure 6 displays the partial size distribution of Alccofine. The particle size distribution of Alccofine particles spans from 1 to 75 µm, with a predominant portion falling within the 20–50 µm range. In Figure 7, the scanning electron microscopy (SEM) image depicts the morphology of Alccofine particles. The analysis indicates that the particles exhibit an irregular shape, characterized by sharp edges [13].

2.3 Analysis of tests for GPC incorporating Alccofine-1203

For the analysis, there were different kinds of tests like workability tests: CS testing, FS, durability assessments, and microstructural analysis were carried out [13,69]. The 1-day strength of GPC is about 60% of 28 days' strength [70]. In many research works, the addition of AF-1203 showed

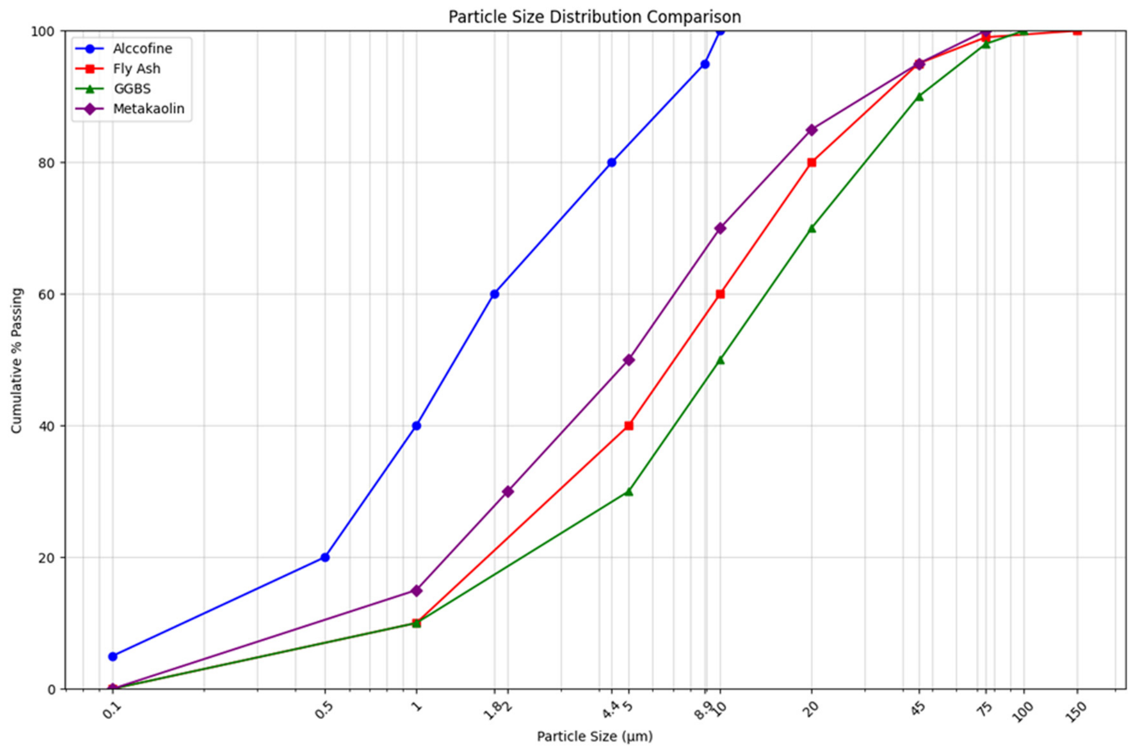

Figure 6: Particle size distribution of Alccofine [13,71–73].

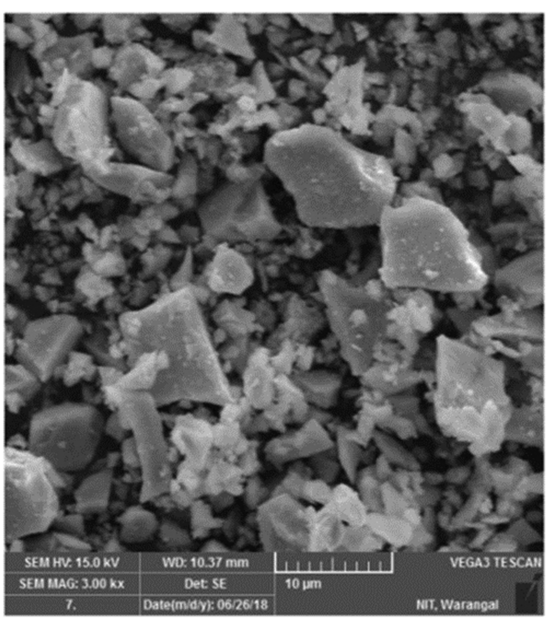

Figure 7: SEM image of Alccofine [13].

satisfactory results [74,75]. Table 6 explains the works on the analysis of tests for concrete incorporating AF-1203 with its attained results and limitations.

In a study conducted, the researchers delve into the workability and strength characteristics of self-compacting GPC that are based on FA and GGBS [76]. Their experimental investigation sheds light on this subject. Experiments were conducted on newly produced samples of self-compacting GPC to evaluate its workability characteristics. The tests conducted comprised the V-funnel test, slump flow test, J-ring test, and L-box test. The analysis revealed that the ease of working with fresh concrete was somewhat reduced as the concentration of sodium hydroxide solution increased. The addition of Alccofine-1203 generally improves the workability of fresh GPC mixtures. According to Figure 8 [12], as the percentage of Alccofine-1203 increases from 0 to 10%, the slump value increases from about 130 to 165 mm, indicating improved workability. This is due to the ultra-fine particles of Alccofine-1203 which reduce water demand and increase flowability. However, beyond 10%, there is a slight decrease in slump, suggesting an optimal dosage for workability improvement. The impact of Alccofine inclusion on the mechanical characteristics of ultra-high performance geo-polymer concrete was studied, Cube specimens were subjected to a compression test using a compression testing machine with a force of 2,000 kN [77]. We evaluated three samples of each combination at 7, 28, and 90 days. The findings revealed that GPC had remarkable early-age strength, with over 80% of the typical strength being achieved after only 7 days. The issue, though, was that no discernible trend toward a longer cure period emerged. Here

Table 6: Works on analysis of tests for concrete incorporating AF-1203 with its attained results and limitations

Ref.	Tests	Attained results	Limitations
[75]	Water permeability test, seawater attack, rapid chloride permeability, and chloride resistance	Analysis indicated that the mentioned tests showed extremely higher values (0.25, 0.5, 0.75, and 1%) for the substitution of ZnO and performance when compared with the control mix	In the mentioned tests for the analysis, the water permeability test needs more time
[78]	Split tensile and FS	Results revealed that the percentage of STS for AF-1203-based GPC showed a 36.18 value for 7 days and for FS, the value and days remain similar	Outcomes for CS tests will take more time
[79]	The tests include water permeability, acid attack, seawater, and sulfate attack	The analysis revealed that the concrete exhibited optimal performance when the produced sand constituted 50% of its composition. However, above this threshold, the strength values of the concrete decreased	Sometimes due to carelessness, these tests have the potential to result in concrete expansion, cracking, decreased strength, and disintegration
[80]	Slump flow test, concrete cube test, and CS	Analysis indicated that the Workability of concrete of matrix-2 was enhanced and after that, the standard concrete increased up to 13.61%	The tests did not yield conclusive results about the disparity in workability between stiff mixes, which exhibit zero slumps, and wet mixes which result in a collapsing slump
[69]	CS test	Out of the twenty possible combinations, the highest CS of cement mortar cubes was achieved by employing Alccofine10% (OPC AF ES) in a volume equivalent to 10% of the cement. The maximum strength obtained was 53.12 $N \cdot mm^{-2}$	Difficulty in obtaining homogeneous and representative samples
[80]	Chloride attack test, acid resistant test, and CS	The investigation indicated that the optimal dosage range for AF-1203 was found to be between 8 and 12%. In addition, AF-1203 greatly improved the ease of use, structural integrity, and long-lasting quality of the concrete when used at the highest recommended amount	The data relating to the incorporation of AF-1203 were very few
[81]	CS test and SEM	Analysis revealed that as the Na_2SiO_3-to-NaOH ratio grew, there was an initial rise in weight loss up to a ratio of 1.5, followed by a subsequent decline down to a ratio of 2.5	In the bands, the important information regarding the AF-1203 remains nil
[82]	Slump flow, L-box, and V-funnel.	Results showed that Alccofine with 30% replacement showed the optimum results and Alccofine with 60% of replacement showed the least result, but, in all the series, Alccofine-based SCC mixes showed higher values when comparing to conventional	The strength did not meet the entire expectation
[63]	CS tests	Analysis indicated that the strength characteristics of the AF-1203 showed better outcomes in substituting cement with a higher % of values	The absence of a subsequent reaction only caused by cement will result in a deficiency in geo-polymer concrete

is Figure 9 summarizing the research available on Alccofine with GPC, including the percentage of Alccofine, and its effect on concrete. The specific chemical composition of Alccofine-1203 significantly influences the geopolymerization process in GPC through multiple mechanisms. Its high silica (35.3% SiO_2) and alumina (21.4% Al_2O_3) content contribute to the formation of the essential aluminosilicate network in geopolymers, promoting the development of Si–O–Al bonds that are fundamental to the geopolymer structure [3,8]. The relatively high calcium content (32.2% CaO) leads to the formation of additional C–S–H (calcium silicate hydrate) gel alongside the typical N–A–S–H (sodium aluminosilicate hydrate) gel found in geopolymers, enhancing strength and densifying the microstructure [15]. Alccofine-1203's high glass content (>90%) increases its reactivity in the alkaline environment of GPC, promoting faster and more complete geopolymerization, which contributes to improved early strength development [4]. The fine particle size (d50 = 4.4 μm) of Alccofine-1203

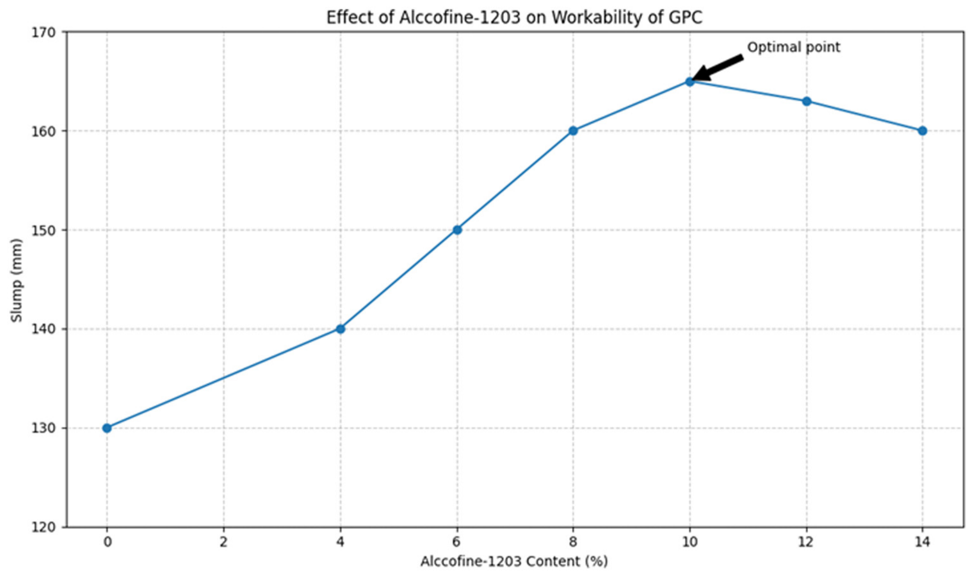

Figure 8: Slump result of GPC at different Alccofine content [12].

facilitates pozzolanic reactions, consuming $Ca(OH)_2$ and forming additional C–S–H gel, further improving strength and durability [12]. Moreover, the ultra-fine nature of Alccofine-1203 particles helps in filling voids between larger particles, leading to a denser microstructure, as evidenced by SEM analysis showing reduced voids and cracks in Alccofine-incorporated GPC [15,83]. These factors collectively contribute to enhanced mechanical properties, improved workability, and increased durability observed in Alccofine-1203 incorporated GPC. Alccofine-1203 significantly prolongs the setting time of GPC, allowing for an extended working period. Replacing FA with increasing percentages of Alccofine-1203 (5, 10, and 15%) increases the setting time due to its high glass content and low calcium content, enhancing workability [11]. Substituting GGBFS with Alccofine-1203 further increases the setting time compared to replacing FA, as a result of the increased FA content in these mixes [11]. However, to achieve the desired setting time while maintaining strength and workability, mix design adjustments may be

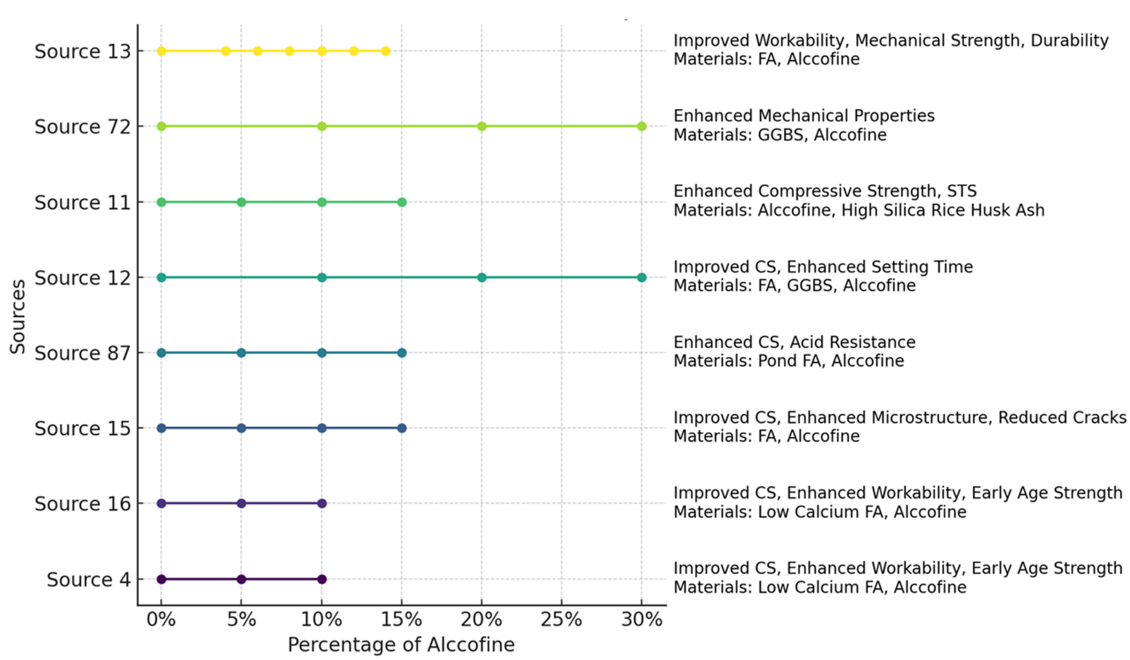

Figure 9: Effect of AF-1203 on GPC at different compositions of AF-1203.

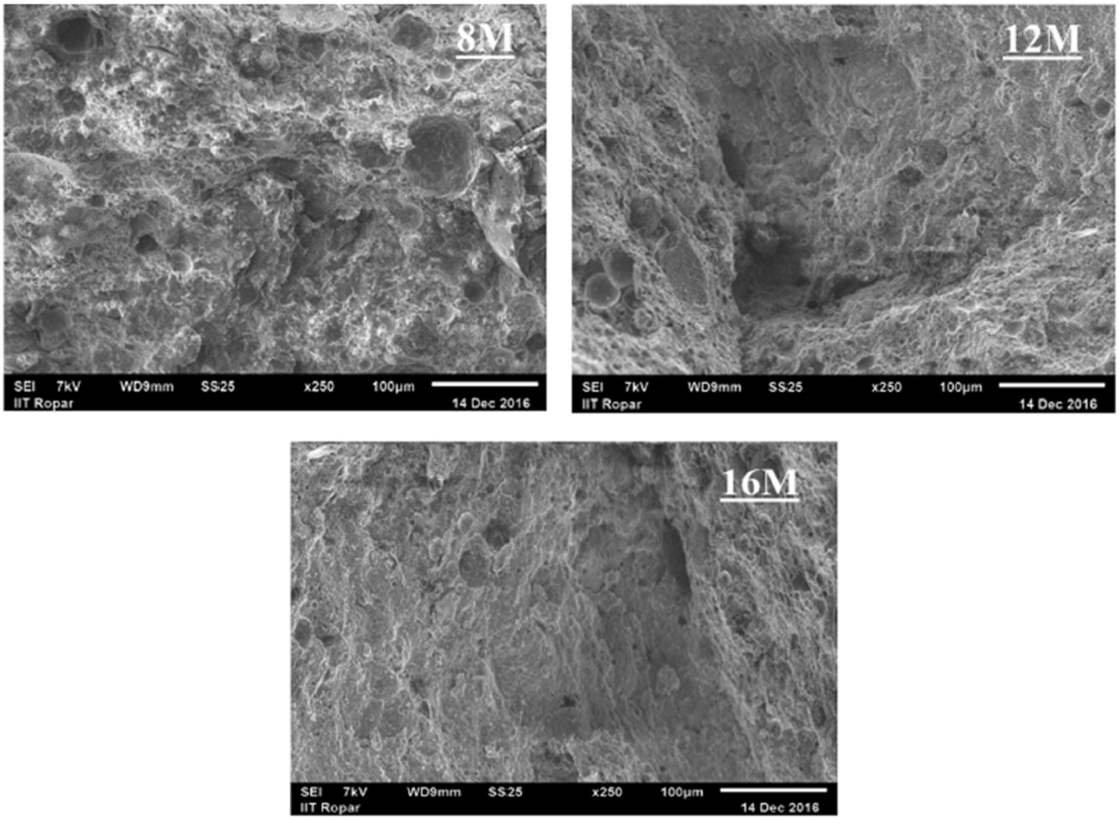

Figure 10: SEM images of GPC with Alccofine at 8, 12, and 16 M [15].

necessary, such as optimizing the proportions of Alccofine-1203, FA, GGBFS, and the alkaline activator solution [11]. Alccofine generally provides better early strength and superior microstructural properties compared to GGBS in GPC. This is because Alccofine, being a micro-fine material with a high calcium content and glassy phase, promotes rapid hydration and polymerization, which accelerates the formation of calcium silicate hydrate (C–S–H) and alumino-silicate gels. These gels contribute to the densification of the matrix, resulting in higher early strength and reduced porosity. Alccofine's fine particle size also enhances the geopolymerization process, creating a denser and more compact microstructure at an earlier stage [11,81]. On the other hand, GGBS, although effective in increasing the overall strength of GPC, does not provide the same early strength as Alccofine. This is because GGBS undergoes a slower hydration process, which results in delayed strength gain, particularly at early curing ages. GGBS requires a more extended period for the calcium–silicate–hydrate (C–S–H) gel formation, which develops the microstructure over time but is less effective for immediate strength development [15,81].

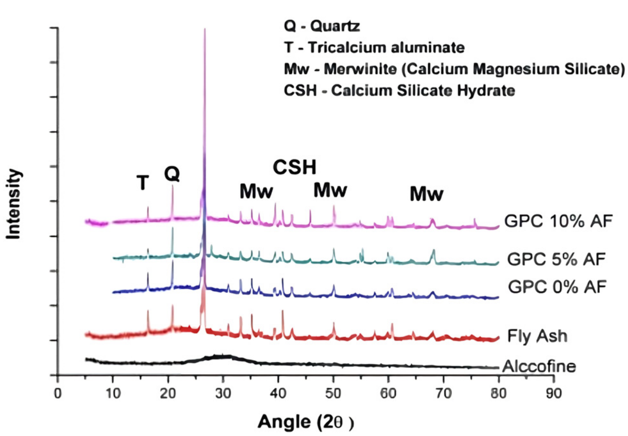

Figure 11: XRD images of GPC incorporating alccofine [4].

Curing of GPC containing Alccofine-1203 at elevated temperatures like 90°C significantly enhances the early age and long-term compressive, flexural, and tensile strengths of GPC with Alccofine-1203, Heat curing activates the geopolymerization process more rapidly, leading to denser microstructure and improved mechanical properties [4,68]. GPC with 10% Alccofine-1203 cured at 90°C for 28 days can achieve very high CSs up to 73 MPa, making it suitable for precast concrete components [4]. GPC containing

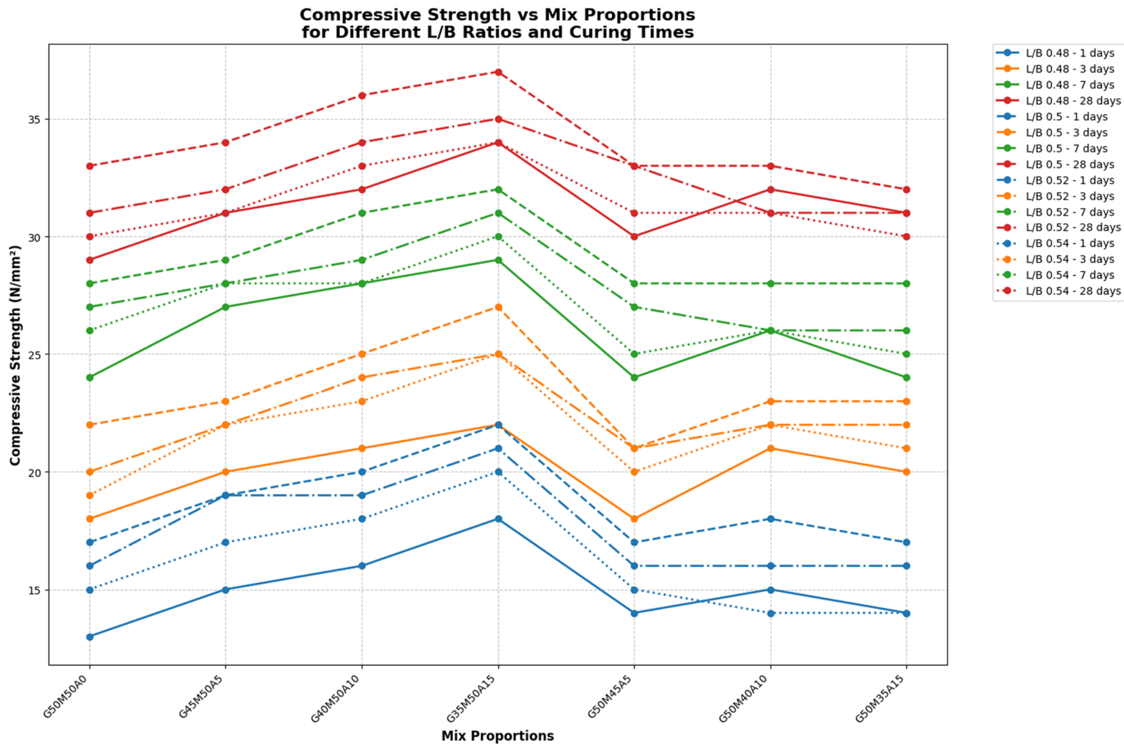

Figure 12: CS of GPC incorporating Alccofine: A comparative study at different *l*/*b* ratios [84].

Alccofine-1203 can also achieve the required CSs for general construction purposes (up to 43 MPa) when cured at ambient temperatures around 27°C [4,68]. Ambient curing is more practical for cast-in-situ applications compared to heat curing [4].

The research consistently shows that adding Alccofine to GPC enhances several attributes, including CS, early age strength, workability, microstructural features, and durability. Alccofine, being a finer particle, improves the packing density, leading to a denser and more durable matrix. Incorporating nanoparticles into construction materials significantly enhances their mechanical properties, durability, and environmental sustainability as compare to

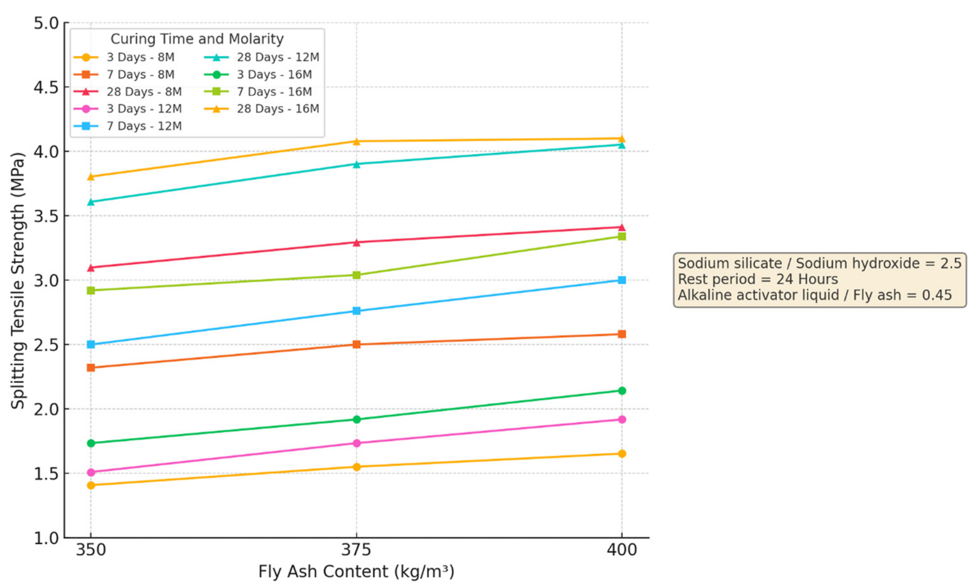

Figure 13: Splitting tensile strength response of GPC incorporating Alccofine to different FA dosages [15].

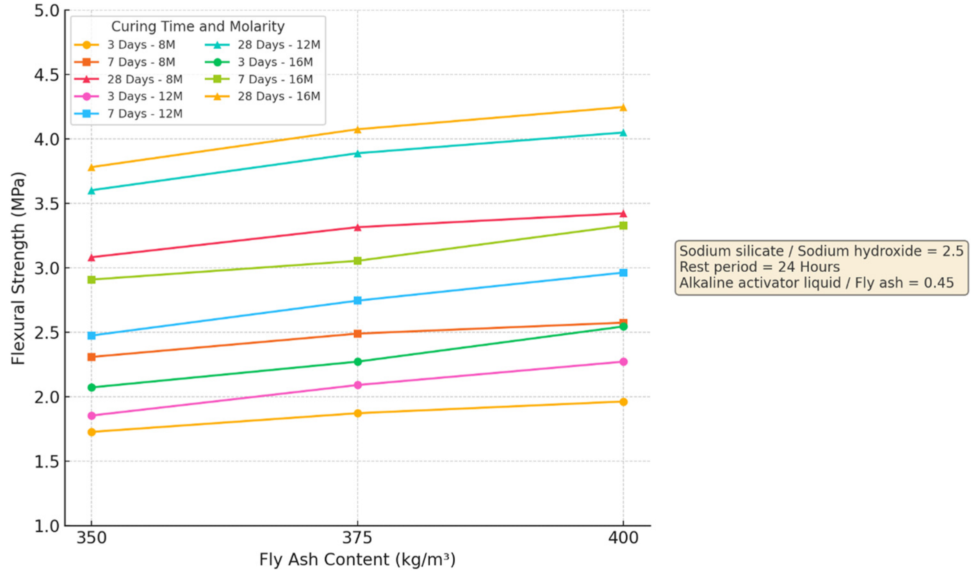

Figure 14: Variation of FS at different FA content [15].

other SCM like flyash, GGBFS, metakeoline, *etc.* [85]. The optimal dosage of Alccofine varies across studies but generally falls within the range of 5–15%. When Alccofine is used in conjunction with materials such as FA, GGBS, and rice husk ash, it has been found to significantly improve the performance of GPC.

An investigation was conducted to study the mechanical characteristics of GPC, which was developed by partially replacing FA with Alccofine 1203. The properties were examined at 3, 7, and 28 days, using different molarities of NaOH [15]. The microstructural changes in GPC with varying percentages of Alccofine-1203 have been studied using

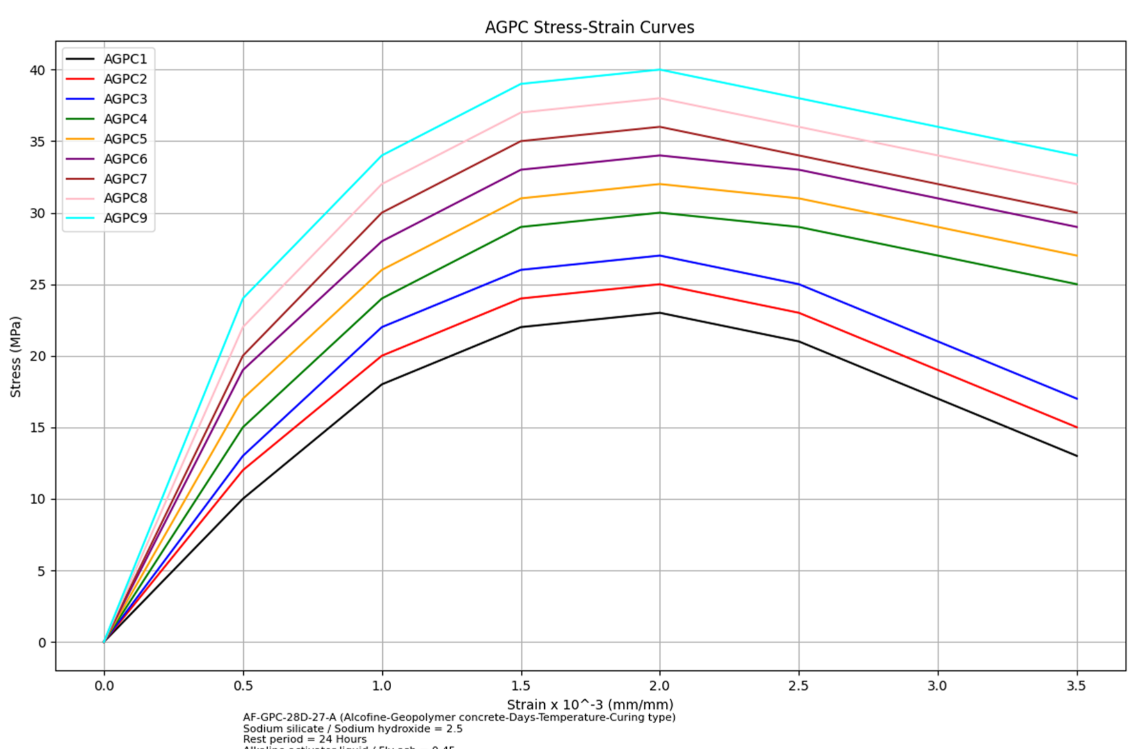

Figure 15: Variation of stress–strain at different FA content [15].

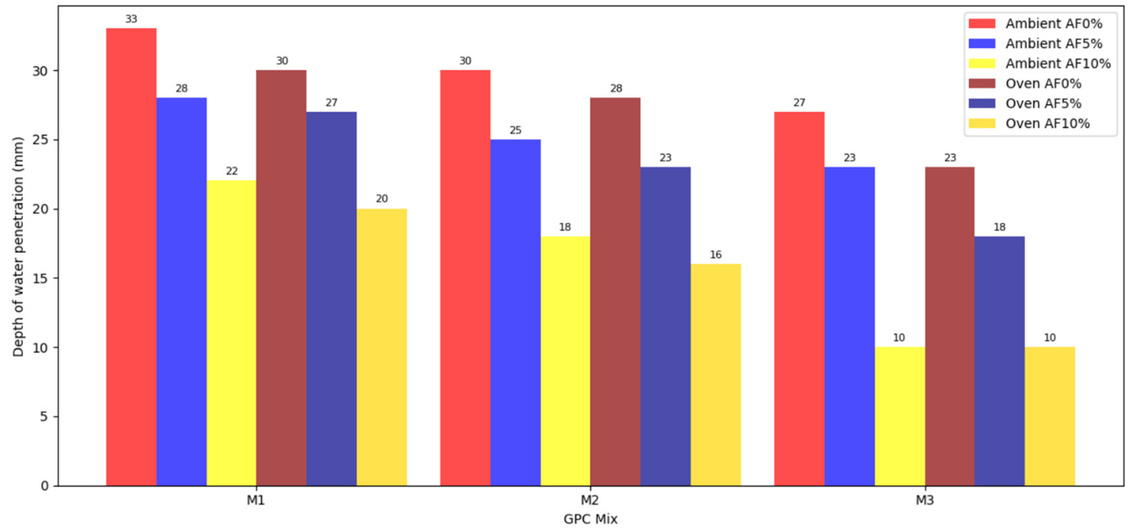

Figure 16: Permeability of GPC at different Alccofine contents [65].

advanced characterization techniques like XRD and SEM. In the SEM analysis (Figure 10), the GPC mix with 16 M NaOH showed a significant reduction in the presence of voids and cracks. This suggests that the geopolymer matrix with 16 M NaOH was effective in minimizing these imperfections. It is expected that the permeability of GPC with 8 M and 12 M will be lower. XRD analysis reveals that increasing Alccofine-1203 content leads to higher crystallinity and the formation of additional phases like calcium silicate hydrate (C–S–H) and stratlingite (Figure 11), the intensity of unreacted FA peaks decreases, indicating more complete geopolymerization [16]. The ultra-fine particles of Alccofine-1203 fill voids and enhance the formation of geopolymer gel products. EDAX indicates an increased Ca/Si ratio in the binder matrix and more uniform element distribution [84]. These microstructural changes explain the improved mechanical and durability properties of Alccofine-1203 incorporated GPC. The finer particles contribute to a more compact matrix, enhancing strength and reducing permeability [15]. Overall, the addition of Alccofine-1203 leads to a more refined and denser microstructure in GPC, which is consistent with the observed improvements in its performance characteristics. In addition, it suggests that using GPC with Alccofine and curing it at high temperatures will result in a denser matrix. However, this may also lead to a higher number of cracks, similar to what was observed in the ambient cured GPC matrix.

In the study by [84], Figure 12 illustrates the CS of geopolymer mortar incorporating varying proportions of GGBS, metakaolin, and Alccofine-1203 at different liquid/binder ratios. The results indicate that the optimal mix proportion, G50M35A15, achieved the highest CS at an *l*/*b* ratio of 0.50. The addition of Alccofine-1203 significantly enhanced the CS up to an optimum level, beyond which a decrease in strength was observed. Figure 13 illustrates the differences in splitting tensile strength when using various FA content under ambient curing conditions. Figure 14 illustrates the fluctuation in FS when different amounts of FA are used under ambient curing conditions. GPC with Alccofine-1203 exhibits higher FS compared to conventional concrete, incorporating 10% Alccofine-1203 as a partial replacement of FA (by weight) provides the best results in terms of FS and higher Alccofine contents beyond 10% may not yield proportional benefits in FS [11]. Gaining a comprehensive understanding of the stress–strain behavior of construction materials is essential to develop

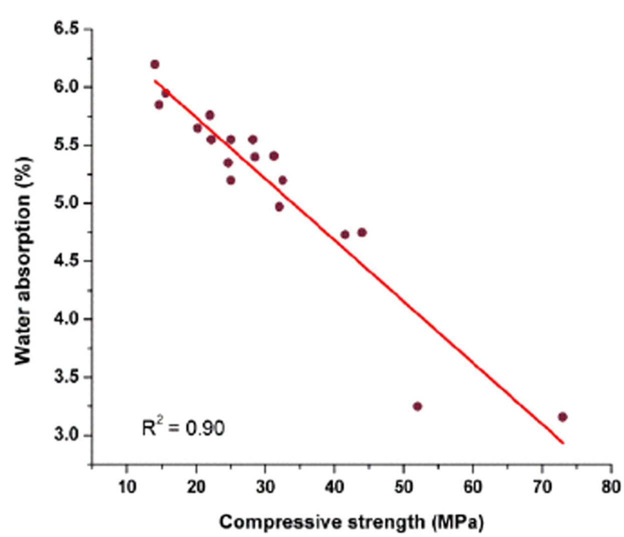

Figure 17: Water absorption and CS relationship [65].

accurate constitutive models. Tests were carried out on a range of concrete samples with varying levels of concentration and under normal environmental conditions. The findings from these tests are illustrated in Figure 15. Load and strain measurements were recorded until the point of failure. Figure 15 illustrates the stress–strain behavior of the geopolymer specimens, showcasing the effects of different NaOH molarity and FA content during ambient curing conditions [15].

A study reveals that increasing FA content and adding Alccofine significantly reduces water penetration depth in GPC under both ambient and heat curing conditions (Figure 16) according to the water permeability test on GPC. This improvement is attributed to the densification of the concrete microstructure due to increased binder content and pore-filling effect of Alccofine's ultrafine particles [65]. Heat curing further enhances this effect by accelerating geopolymerization. Figure 17 demonstrates an inverse relationship between water absorption and CS, indicating that stronger concrete exhibits lower permeability. These trends are explained by the formation of additional cementitious products from the reaction between Alccofine's calcium oxide and FA's silica and alumina, resulting in a more refined pore structure and improved concrete properties [65].

One study through RCPT found that mixes containing 20% ultra-fine slag (Alccofine) showed a 12.60% reduction in chloride ion penetration compared to control mixes without ultra-fine slag (Alccofine). This reduction is attributed to the densification of the concrete's microstructure due to the pozzolanic reaction of Alccofine, which reduces pore sizes and connectivity, thereby limiting the pathways for chloride ions to infiltrate the concrete matrix [86]. The addition of Alccofine improves the density and reduces the porosity of the concrete matrix, leading to lower permeability and mitigating the ingress of sulfate ions that can lead to expansion and deterioration of concrete [87]. The CS of GPC containing Alccofine remains relatively stable when subjected to sulfate solutions over extended periods; this stability is attributed to the effective binding of sulfate ions within the geopolymer matrix, preventing destructive reactions [87].

GPC, by nature, contains a highly alkaline pore solution due to the presence of alkali activators such as sodium hydroxide and sodium silicate. This alkaline environment can potentially react with reactive silica present in certain aggregates, resulting in the formation of an expansive gel. However, the lower calcium content in GPC compared to traditional OPC concrete may limit the extent of expansion typically associated with AAR [88].

The incorporation of Alccofine-1203, a micro-fine SCM, into GPC has been shown to enhance its mechanical properties and improve its microstructure. The refined pore structure and reduced permeability achieved through the addition of Alccofine-1203 can help mitigate the potential for AAR. By reducing the available pore space and limiting the mobility of reactive species, Alccofine-1203 can hinder the formation and expansion of AAR gel [16,11]. To further mitigate the risk of AAR in GPC incorporating Alccofine-1203, several strategies can be employed. Regular testing and monitoring of GPC incorporating Alccofine-1203 using standardized methods such as the concrete prism test can provide valuable insights into its long-term performance and susceptibility to AAR [89].

2.4 Cost analysis

The cost implications of incorporating Alccofine-1203 in GPC are not directly addressed. However, the study shows that GPC (which includes Alccofine) costs 4501.59 Rs m^{-3}, slightly higher than traditional IS M40 concrete (4,086 Rs m^{-3}) but lower than ACI M40 (5379.6 Rs m^{-3}) and DOE M40 (5117.42 Rs m^{-3}) mixes [87].

3 Scope for future research on AF-1203 in GPC

1) Microstructural investigations: More in-depth microstructural studies employing advanced characterization techniques like X-ray computed tomography, nanoindentation, *etc.*, can provide better insights into the role of AF-1203 in the geopolymerization process and the resulting microstructure of AF-1203-based GPCs.
2) Durability studies: While some studies have reported on durability aspects like acid resistance, chloride penetration, *etc.*, comprehensive investigations on various durability parameters like carbonation, sulfate attack, freeze-thaw resistance, *etc.*, are required for AF-1203 GPCs.
3) High-temperature performance: The effect of elevated temperatures on the mechanical and durability properties of AF-1203-based GPCs needs exploration for their potential use in high-temperature applications, also in terms of spalling resistance and residual strength.
4) Structural applications: Research on the flexural, shear, and bond behavior of AF-1203 GPC members is essential for their implementation in structural applications.
5) Fiber reinforcement: The synergistic effects of AF-1203 and different types of fibers (steel, synthetic, natural) on the properties of GPC can be studied.

6) Mixture proportioning: Development of mixture proportioning methodologies specific to AF-1203-based GPCs can enable their optimized design and production.
7) Life cycle analysis: Comprehensive life cycle assessments factoring in the environmental impacts of AF-1203 production and its use in GPC are required to establish their sustainability credentials.
8) Large-scale studies: Most investigations so far have been limited to laboratory studies. Pilot and full-scale studies are needed to address practical aspects related to the mixing, transportation, placement, and field performance of AF-1203 GPCs. Application in mass concreting and problems related to heat of hydration need to be studied. Fatigue damage and brittle fracture need to be determined under long-term cyclic loading conditions.
9) Shrinkage and creep analysis: The shrinkage and creep characteristics of GPC incorporating AF-1203 require investigation. Understanding these time-dependent deformation properties is crucial for predicting the long-term performance and serviceability of AF-1203-based GPC structures. Experimental studies and modeling efforts in this area can provide valuable insights for design and practical applications.
10) Optimization techniques: Taguchi method, response surface methodology, central composite design, Box–Behnken design, analysis of variance, *etc.*, used for optimization of GPC incorporating Alccofine 1203.
11) Thermal conductivity: Thermal conductivity and heat capacity of GPC with Alccofine need to be determined.

The future scope should aim to address the existing knowledge gaps and facilitate the transition of AF-1203-based GPCs from laboratory to field applications while ensuring their performance, sustainability, and economic viability.

4 Conclusions

The innovative construction material known as GPC is produced through a chemical reaction involving inorganic molecules. In addition, it is worth noting that the production of cement results in the emission of approximately one ton of carbon dioxide per ton of cement produced. This emission poses a significant environmental concern. Furthermore, it is worth noting that the production of cement necessitates a substantial amount of energy. Therefore, it is imperative to identify a substitute adhesive. The utilization of FA, slag, and rice husk as a binder in geopolymer concrete (GPC) has gained significant attention in recent research. These materials serve as substitutes for the conventional concrete binder, offering potential benefits in terms of sustainability and performance. By incorporating FA, slag, and rice husk into the GPC mixture, researchers aim to explore their impact on various properties and characteristics of the resulting concrete. This approach aligns with the ongoing efforts to develop alternative construction materials that minimize the environmental impact associated with traditional concrete production. In this review article, for the substitution as a binder, AF-1203 material was utilized. This review also examines the advantages as well as limitations when adding AF-1203 with GPC. Solving the identified limitations, such as less quality control, allowable stress design discourages the use of HSC, *etc.*, can pave the way for further advancements in the addition of AF-1203 with GPC.

1) AF-1203, a micro-fine material with a unique chemical composition and particle size distribution, has shown promising results as an SCM in GPC.
2) The incorporation of AF-1203 in GPC has been found to enhance various properties, including workability, CS, FS, and durability.
3) The optimal dosage of AF-1203 in GPC varies across studies but generally falls within the range of 5–15% replacement of the binder material.
4) The combination of AF-1203 with other materials like FA, GGBS, and rice husk ash has demonstrated synergistic effects in improving the performance of GPC.
5) Microstructural studies using SEM analysis have revealed that AF-1203 contributes to the formation of a denser geopolymer matrix with reduced voids and cracks, especially at higher NaOH molarities.
6) The CS, splitting tensile strength, and FS of GPC incorporating AF-1203 have shown significant improvements compared to control mixes, particularly at ambient curing conditions.
7) The stress–strain behavior of AF-1203-based GPC has been investigated, providing valuable insights for the development of constitutive models.
8) Durability parameters, such as water permeability and water absorption, have been positively influenced by the addition of AF-1203 in GPC.
9) The reviewed literature highlights the potential of AF-1203 as a sustainable and effective SCM for the production of high-performance GPC.
10) However, further research is needed to address aspects such as long-term durability, high-temperature performance, structural applications, and the development of standardized mixture proportioning methods for AF-1203-based GPC.

In conclusion, the literature review demonstrates that AF-1203 is a promising material for enhancing the properties and performance of GPC. Its incorporation has the potential to contribute to the development of sustainable and high-performance construction materials. Continued research and practical implementation will pave the way for the wider adoption of AF-1203-based GPC in the construction industry.

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