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Review Article

A Comprehensive Review and Future Directions on the Utilization of Agricultural Waste Ash in Geopolymer Concrete

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Abstract - *Agricultural wastes burned for energy production, such as rice husk, wheat straw, rice straw and sugarcane bagasse, produce ash as a byproduct. These residues typically contain silica content of 50% or higher. This ash byproduct holds significant potential for application in the production of zero-cement concrete, offering an eco-friendly alternative to conventional cement concrete, which is known for its substantial carbon dioxide emissions. This study aims to comprehensively review existing research concerning the utilization of agricultural waste ash as a building material while offering recommendations for future investigations. Various aspects of its utilization of agricultural waste ash in construction, including fresh concrete properties, compressive strength, split tensile strength, microstructural analyses, curing effects, and the influences of activator molarity, are thoroughly examined. The study reveals that the incorporation of agricultural waste ash into cement has both advantages and drawbacks. The four primary types of agricultural waste ash investigated are rice husk ash, coconut husk ash, bagasse ash, and banana leaf ash. When utilized as cement substitutes in appropriate proportions, these ashes enhance compressive strength and durability. However, improper mixing can result in reduced compressive strength post-curing. Each type of agricultural waste ash exhibits distinct properties, affecting the concrete's performance in unique ways.*

Keywords - *Agro waste ashes, Eco-friendly concrete, Sustainable concrete materials, Compressive strength, Microstructural analysis.*

1. Introduction

Concrete is the most consumed resource on earth, next to water. In ordinary Portland cement, the primary component is responsible for 9% of CO_2 emissions globally. Over time, this results in significant environmental degradation. [1] Consequently, various types of concrete are currently being researched to address this environmental concern. Researchers are exploring innovative concrete alternatives to replace conventional aggregates. Geopolymer is emerging as a significant type of concrete in development. [2] The construction sector prioritizes the development of green and sustainable concrete, using recycled materials and agricultural waste to mitigate environmental impacts. One of the critical concerns for sustainability in the developing world is the construction industry, where natural resources are depleted due to the massive production of concrete and cement. [3] The current and ongoing research on cementitious materials aims to replace traditional cement, thereby reducing greenhouse gas emissions associated with cement production and usage. [4] The sustainability of a building is evaluated based on the Green Building rating, considering various criteria, with construction material being one of them. In the modern construction industry, challenges such as carbon dioxide emissions, water usage, energy usage, fillers, aggregates, and concrete demolition waste conflict with environmental requirements. [5] Currently, the prevailing idea is that the introduction of new binders is essential to completely replace traditional Portland cement in concrete manufacturing, as concerns grow regarding CO_2 emissions and energy consumption in the cement industry. Current research in scientific communities focuses on creating a novel cement using waste as the raw material, distinct from Portland cement.

In recent decades, agricultural waste and industry byproducts have been introduced into the building industry to replace OPC partially. Significant amounts of aluminum oxides and silicon can be found in this waste material. These chemicals and an alkaline solution react to form a Portland cement-like binder. This new type of binder is referred to as a geopolymer binder. [2] GPC made from agricultural waste ashes, like rice husk ash, sugarcane bagasse ash, palm oil fuel ash, and GGBS, has emerged as an environmentally friendly substitute for OPC. GGBS supplies reactive calcium that improves early strength and promotes ambient curing, whereas agro-waste ashes offer greater silica content that enhances long-term performance. However, a few shortcomings remain, such as insufficient mechanistic insight into agro ash–GGBS interactions, lack of defined reactivity indices and mix design protocols, inadequate long-term durability and structural information, and an absence of thorough life-cycle and techno-economic evaluations. It is crucial to address these problems for the dependable scaling and field implementation of agro-waste–derived geopolymer concretes. GPC, by incorporating agricultural waste ashes such as rice husk ash, sugarcane bagasse ash, or palm oil fuel ash, blended with GGBS, has emerged as a sustainable alternative to OPC. GGBS provides reactive calcium that enhances early strength and enables ambient curing, while agro-waste ashes contribute high silica content, improving long-term performance. However, key gaps remain: limited mechanistic understanding of agro ash–GGBS reactions, absence of standardized reactivity indices and mix design frameworks, scarce long-term durability and structural datasets, and a lack of comprehensive life-cycle and techno-economic assessments. Addressing these challenges is essential for reliable scale-up and field deployment of agro-waste–based geopolymer concretes. Geopolymer materials are considered the future of cement, owing to their promising characteristics, such as efficient use of raw resources and low environmental impact. From an environmental aspect, the major distinction between geopolymers and conventional cement is that geopolymers emit lower amounts of CO_2 than OPC. The manufacturing processes of Portland cement, such as limestone decarbonization and fossil fuel combustion, emit a considerable amount of CO_2 and other greenhouse gases. Conversely, the production of geopolymer raw materials does not require high-temperature calcining, thus reducing energy consumption and CO_2 emission considerably [1, 5].

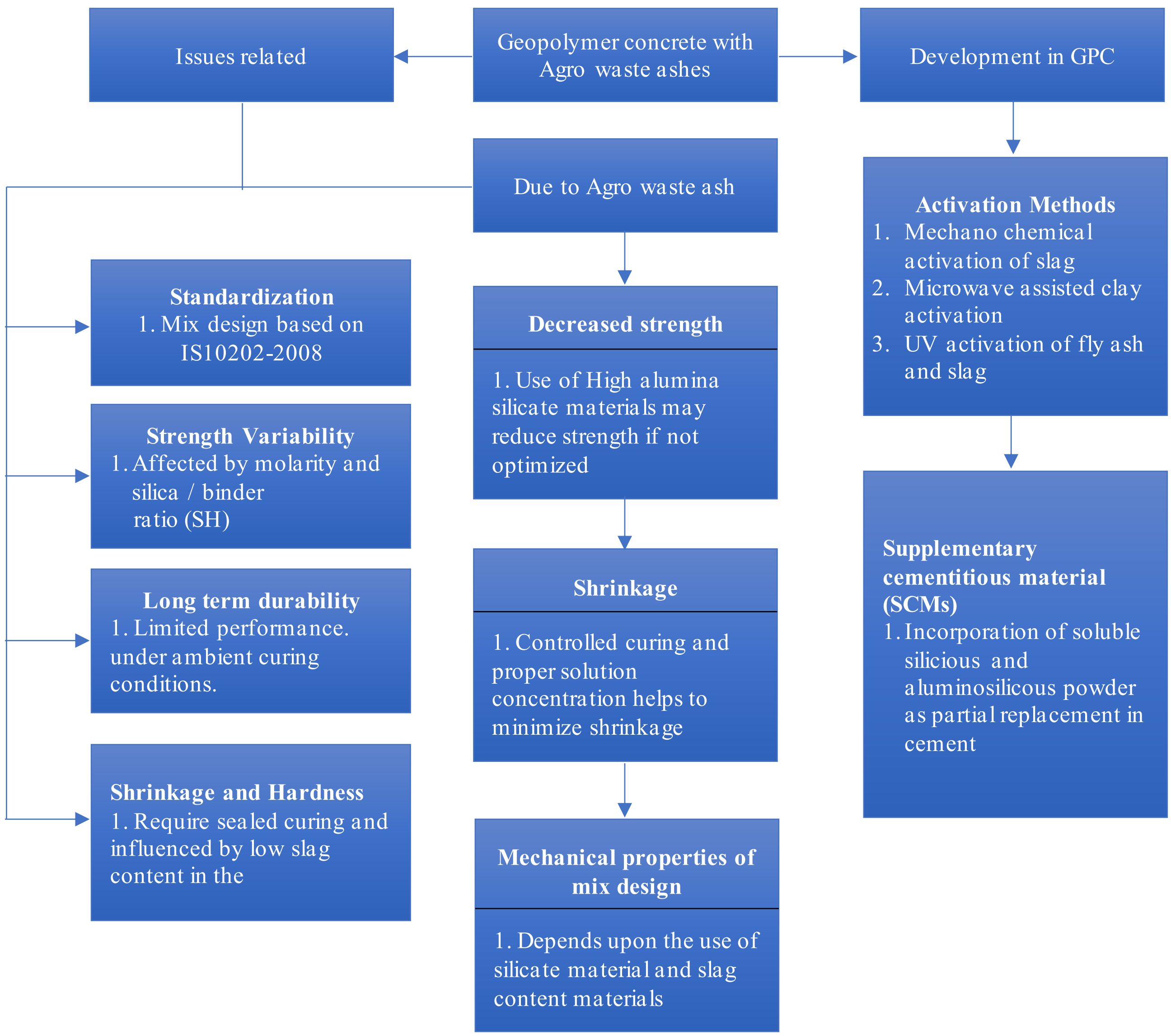


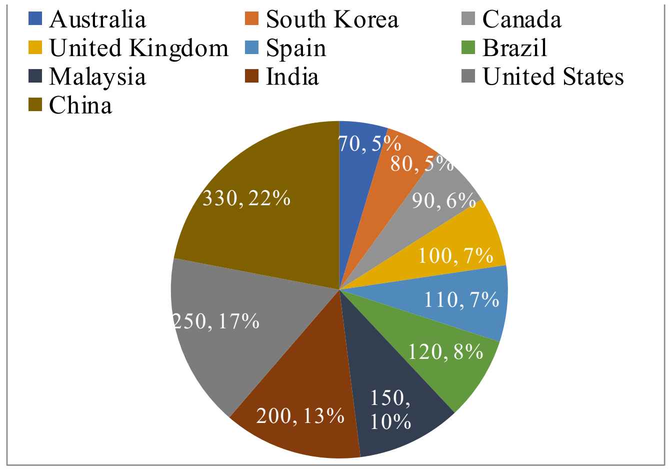
Fig. 1 Flow chart on issues related to GPC and their development

The concept of zero-cement concrete or geopolymer concrete was first proposed by Joseph Davidovits in 1976. When inorganic materials are activated, aluminosilicate is employed as a precursor in dry form. Naturally occurring aluminum and silicon are used as the source materials. An alkali activator solution is used to create a bond [6]. Alkali-activated materials include high calcium materials containing GGBS, and low calcium materials that contain fly ash and raw materials. Studies have explored the roles of activator type and alkali concentration in these two systems, as well as the optimal dosage of raw materials, the effects of curing temperature, the impact of admixtures, thermal strength, mechanical strength, and durability, among other factors [6, 7]. Geopolymer concrete exhibits superior chemical, physical, and mechanical properties compared to traditional cement concrete. The parameters of geopolymer concrete vary slightly from traditional Portland cement concrete, depending on the chosen raw materials and processing method. In terms of rapid hardening, acid resistance, low creep, and drying shrinkage, high as well as early compressive strengths, fire resistance, and geopolymer concretes are renowned for their superior performance, because these distinctive qualities make geopolymer concrete a top contender for replacing traditional Portland cement concrete. Therefore, adopting geopolymer technology lowers the CO_2 emission by cement manufacturers and uses byproducts of aluminosilicate composition and/or industrial wastes to create added-value building materials [7, 8].

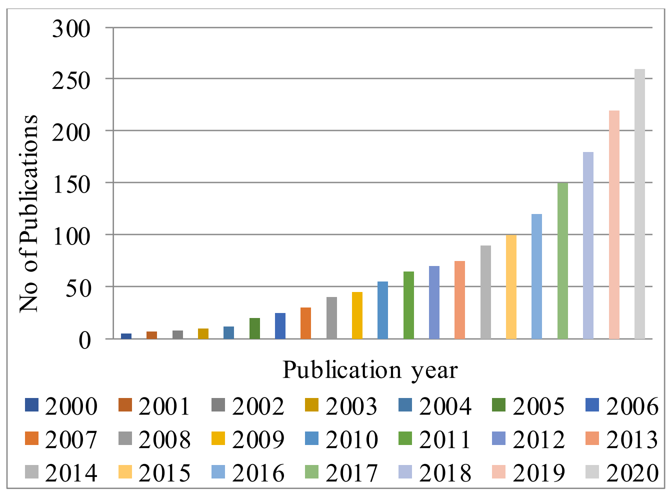
In recent years, the demand for sustainable construction methods has positioned agricultural waste ashes as an alternative for producing zero-cement concrete. This would serve as an eco-friendly substitute for conventional Portland cement, which is known for its significant carbon dioxide emissions. An extensive study is being conducted on the use of agricultural waste ash in building; however, a more systematic examination is needed to identify its advantages and disadvantages. Thus, this study aims to provide a comprehensive summary of current research on the use of agricultural waste ash as a construction material. It concentrates on four primary categories of ashes: rice husk ash, coconut husk ash, bagasse ash, and banana leaf ash. It discusses the differences in physical and chemical characteristics of these ashes and their impact on fresh and hardened concrete properties. The review discusses the advantages of using these ashes, such as enhanced strength parameters when used appropriately, as well as the potential drawbacks of the ashes.

2. Research Approach

This review paper promotes the use of agricultural waste as a secondary source material and supplementary cementitious component. It explores the usage of high alumina silicate material in geopolymer concrete along with its mechanical properties [9]. This comprehensive approach focuses on sustainability and the use of secondary source material in geopolymer concrete. This result approach for investigating the agro-waste ash geopolymer concrete involves a detailed methodology, including a review layout and data collection strategies. The detailed research methodology is illustrated in Figures 2, 3 and 4.



(a)



(b)

Fig. 2 (a) Number of publications over the years, and (b) Publication over countries. [10]

The characteristics of geopolymer concrete will be mentioned in detail, including the impact on mechanical properties. The conclusion will summarise the important findings of the research and provide suggestions for future research in this area, highlighting the importance of the usage of secondary source material in geopolymer concrete and its sustainability. The data collection involved retrieving 100 relevant articles on 'geopolymer concrete' and 'usage of agro-waste ash' from the Web of Science database. The use of the VOS viewer has allowed for the meticulous analysis of co-authorship patterns and term co-occurrence within authors and keywords. Figures 3 and 4 visually summarise thematic concentrations of co-occurrences and collaborative networks of co-authorships, respectively.

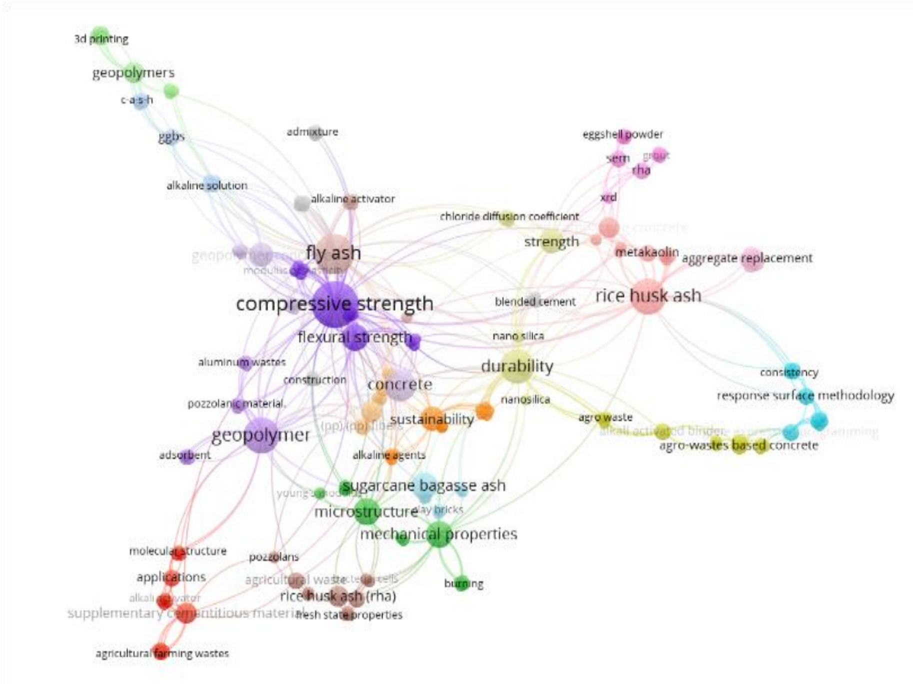


Fig. 3 Analysis of co-occurrence with keywords on Geopolymer concrete with Agro waste ash

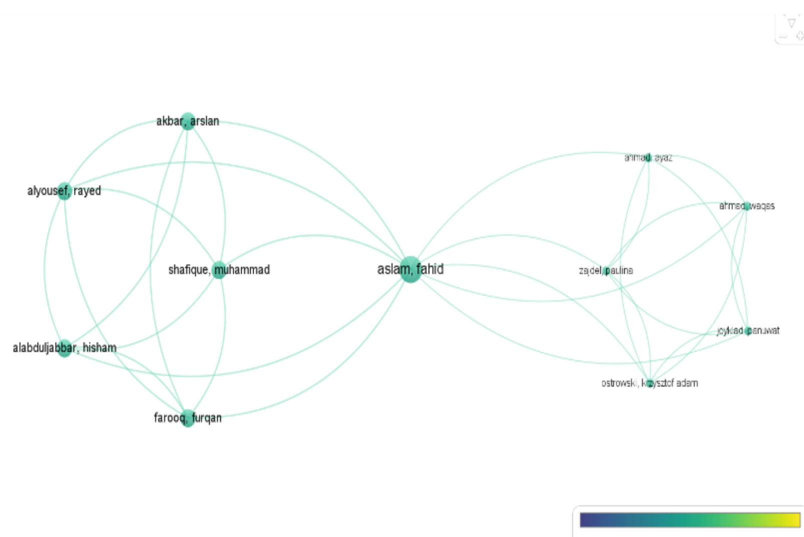


Fig. 4 Analysis of co-occurrence of co-authorship on GPC with agro ash

2.1. Cement Replacement Materials

Cement replacement materials have gained significant attention due to their potential to improve sustainability. Researchers highlight that concrete made from agricultural waste can enhance sustainability due to its good thermal properties. In India, the need to utilize agro-waste is growing to promote environmental sustainability [11]. Replacing cement with alternatives such as fly ash, red mud, silica fume, ground granulated blast furnace slag, rice husk ash, metakaolin, corncob ash, and sugarcane bagasse ash can help reduce global warming. Some of the cement replacement materials are shown in Figure 5. These materials are used in producing geopolymer concrete and offer better thermal resistance, durability, and strength. Extensive research has been conducted on creating geopolymers using various agricultural and industrial wastes [8, 12]. This review paper examines the use of agricultural and industrial waste in producing sustainable geopolymer concrete. Annually, India generates an estimated 0.5 billion tons of agro-waste. Inefficient management of this waste causes air, soil, and water pollution, damaging human health and the environment in the long term [4, 13].

Fig. 5 Supplementary cement replacement materials [7]

This paper extensively reviews recent key references on various agricultural waste supplementary cementitious materials. It focuses on various types of agricultural waste that can be used in concrete for sustainability. This review includes globally published studies on environmental sustainability and zero-cement concrete from the past two decades. The literature was categorized based on the type of agricultural waste used for ash in geopolymer concrete. Waste ashes from agriculture, including SBA and RHA, have been extensively studied and used as ingredients in geopolymer concrete over the past few years. Geopolymer concrete is more environmentally friendly than Portland cement concrete as it emits fewer greenhouse gases and utilizes industrial byproducts and waste as binders [14, 15]. Several research studies have focused on maximizing ash content and investigating the mechanical properties, long-term performance, and durability using various activation techniques. RHA, a highly reactive pozzolan, is frequently utilized in geopolymer concrete, replacing some cementitious material. Studies show that RHA-based geopolymer concrete performs better than conventional Portland cement concrete in terms of sulfate attack resistance, drying shrinkage, and compressive strength [16]. Research on geopolymer concrete has also highlighted that SBA and other agricultural waste ashes perform well as a partial substitute for Portland cement. SBA-based geopolymer concrete exhibits good mechanical strength and helps to reduce CO_2 emissions [14, 17]. Geopolymer concrete containing agricultural waste ashes generally exhibits equal or better mechanical strength than normal concrete. Geopolymer concrete has been found to have early strength, remarkable durability in various environments, and significant resistance to chemical attack. Ongoing research aims to improve the mix design and evaluate the concrete's long-term behavior. Agricultural waste ash is now used in geopolymer concrete for construction, such as building construction, pavements, and other infrastructure components. Therefore, geopolymer has the potential to be extensively used in building due to its feasibility and benefits [16, 18]. The development and adoption of agricultural waste ashes in geopolymer concrete may vary across regions and depending on the local availability of waste materials, technological advancements, and regulatory frameworks. Ongoing research and technological advancements will continue to shape the future of agricultural waste utilization in geopolymer concrete. [19, 20]

The literature screening process was conducted in line with PRISMA guidelines to ensure methodological transparency. A total of 200 records were initially identified through database searching, of which duplicates were removed to yield 170 unique records. After title and abstract screening, 120 full-text articles were assessed for eligibility, and finally, 78 studies were included in the review. This systematic filtering process enhances reproducibility and minimizes bias in the selection of relevant studies.

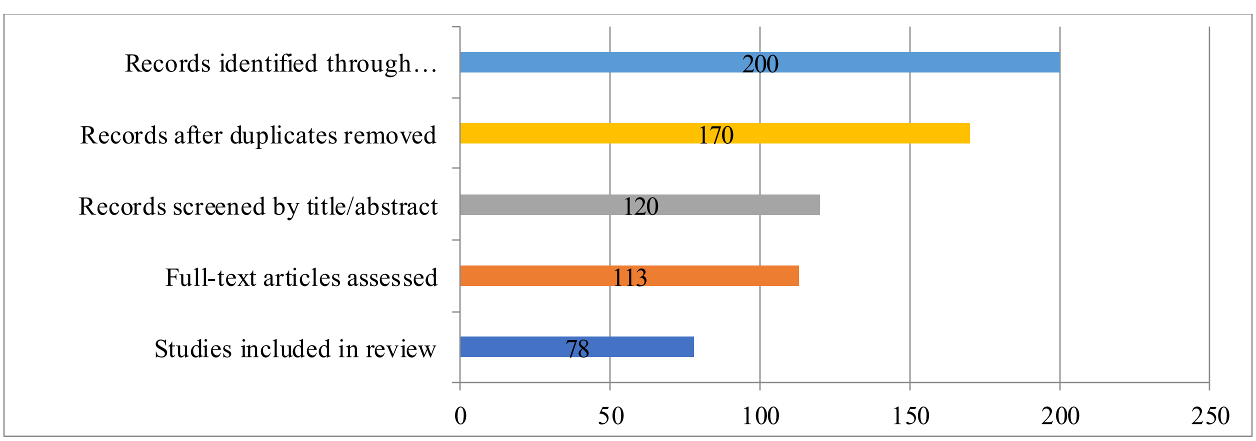


Fig. 6 Data collection for the review article

3. Geopolymerization Mechanism

The chain structure formed by Al & Si ions acts as the basis for the geopolymers, which belong to the inorganic polymer family. The framework of polymeric Si-O-Al forms a geopolymer with SiO_4 and AlO_4 tetrahedrally connected by sharing all the oxygen atoms, as described by Davidovits [21]. The term 'polyciliate' was created to describe the silico-aluminate structure and characterize the molecular structures of geopolymer. Sialate is the acronym for sili-con-oxo-aluminate. Semi-crystalline or amorphous chain and ring polymers, called polysialates, are composed of Si^{4+} and Al^{3+} with oxygen in IV-fold coordination [22]. Based on the chemical combinations of the compound, the terms poly (sialate-disiloxo), poly (sialate) and poly (sialate-siloxo) have been defined. According to Table 1 [12], a geo-polymer can exist in one of the three fundamental forms listed by Davidovits. The schematized structures of these polysialates are shown in Figure 6.

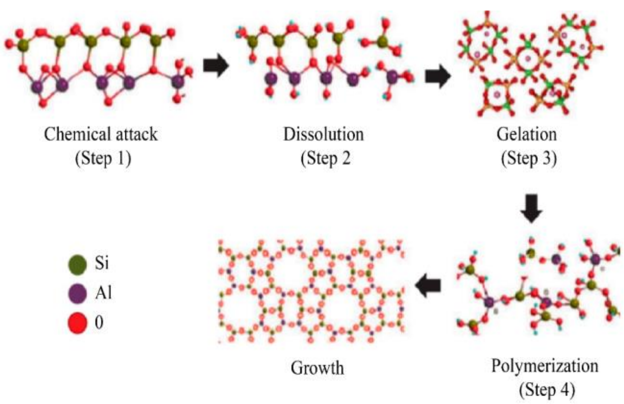


Fig. 7 Polymeric reaction on geopolymer concrete [12]

Geopolymers are distinct from OPC as their materials employ a unique chemical pathway to achieve structural integrity. Unlike OPC, geopolymers do not produce Calcium-Silicate Hydrates (CSH) to strengthen the matrix. Instead, they offer structural strength through a combination of high alkali content and the polycondensation of alumina and silica precursors [23]. The reaction process between regular cement-based concrete and geo-polymer is depicted in Figure 7. Geopolymers are also known as inorganic polymer concretes, geo-cements, and alkali-activated cement. Despite the variety of names used in the literature, all these titles refer to substances created using the same chemistry and derived from alumino-silicate-based raw ingredients, [24-26]. The process of "geopolymerization" is an exothermic polycondensation reaction that involves alkali activation by a cation present in the solution. Several parameters influence the geopolymerization process, including the mineralogical and chemical composition, curing temperature, the molar ratio of Si/Al, alkaline compound concentration and water content [27, 28]. In polymerization, monomers are small molecules that combine to produce polymers, acting as large chains or network-like molecules. Under alkaline conditions, alkali polysilicates and solid alumino-silicate oxides undergo a relatively quick chemical reaction, producing three-dimensional polymeric chain and ring structures that are amorphous to semi-crystalline and contain Si-O-Al bonds. Polysilicates are made up of sodium or potassium silicates [27].

From the alumino-silicate source material, Al and Si convert into monomers by dissolving due to the hydroxide ions in the very alkaline solution. This leads to precursor ion condensation, diffusion, or transportation. Solid inorganic polymeric structures are created through polycondensation, or polymerization of monomers. The many phases involved in the production of geopolymer can overlap and occur almost simultaneously due to the high development rate of the material, making it challenging to isolate and analyze each step independently. [27]

4. Various Agro-Waste Materials

Primarily, geopolymer concrete relies on alkaline solutions and source materials alongside the fine aggregate and typical coarse aggregate found in traditional concrete. These source materials are crucial for alkali activation of geopolymer and must contain aluminosilicates with aluminum in IV-Fold coordination [28]. There is a direct effect between the alkaline activator and the aluminosilicate-based source material on the final product of the geopolymers. Additionally, the properties of the source material play a very significant role in influencing both the subsequent reactions and dissolution process. The alkaline activators dissolve the solid aluminosilicate material and control the recombination, aluminosilicate structure, and polycondensation within the reaction system. [27, 29]

Alkali-activated binders are considered more environmentally friendly alternatives to traditional cement concrete. This research paper provides a comprehensive analysis of the performance of agricultural residue ashes as construction materials and binders in geopolymer concrete, which is essential for the industry's adoption of these materials. This research focuses on an organized and complete review of the alkali activation of ashes derived from banana leaves, bagasse, rice, and coconut husks. Research indicates that among all the agricultural waste ashes, rice husk ash stands out due to its higher silica content, while the other ashes exhibit silica levels comparable to fly ash. Binders based on fly ash and agro-waste ashes show better resistance to acid attacks compared to fly ash-based binders containing slag [30, 31]. Furthermore, the use of agro-waste ashes significantly improves the drying properties of the produced concrete. These agro-waste ashes are manufactured in various forms and colors. The binders based on fly ash and agro-waste ashes have demonstrated greater resistance to acid attacks compared to fly ash-based binders containing slag. Additionally, the use of agro-waste ashes significantly improves the drying properties of the produced concrete. [10, 32]

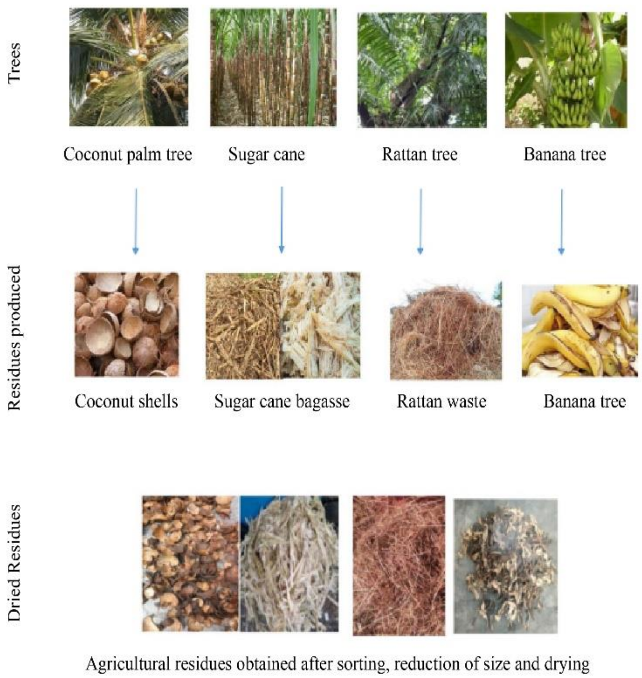


Fig. 8 Agricultural residues from various secondary waste materials [33]

4.1. Chemical Composition of AWA

Research into the composition of Rice Husk Ash (RHA) has found that silica content is approximately 93%, while the Na_2O compound accounts for 0.055 %[1]. The specific surface area of RHA is 615 m2/kg, which is significantly larger than cement's specific surface area of 372 m2/kg. Furthermore, X-ray fluorescence spectrometry analysis revealed a silica concentration of nearly 90% [34]. RHA particles have a highly porous surface with a large specific surface area and a rough texture. Acid-leaching treatment can smooth the outer surface of RHA by removing organic compounds during an acid-induced hydrolysis process. [4, 35]. Silica is the main component of Sugarcane Bagasse Ash (SCBA), which is valued for its pozzolanic properties, benefiting both the economy and the environment. Over the years, SCBA has gained acceptance in the construction industry, particularly for its performance as a supplementary material in concrete [36]. At 50% moisture content, each ton of sugarcane produces about 30% bagasse and 0.7% residual ash. The residue after combustion is dominated by silicon dioxide. The specific gravity of SCBA is 2.17. Silica and aluminum play key roles in providing strength to geopolymer concrete. The minimum criteria for selecting bagasse ash include a combined silica, aluminum, and iron content of above 70%. The physical properties, such as particle packing density, voids, and fineness, tend to increase the material's reactivity [23, 36, 37]. The banana leaves and stems used for this study were obtained from local banana farms. Residual ash is collected from the leaves and stems after combustion. These chemical properties of Banana Leaf Ash (BLA) are obtained by using the leaves instead of the trunk. In 2012, nearly 95 million tons of banana waste were produced. Banana fiber ash is a pozzolanic material that offers several benefits in civil engineering construction, such as reducing costs and environmental impact. A 10% replacement of banana leaf ash in concrete showed pozzolanic activity and increased concrete strength. Banana fiber ash is produced by burning banana leaves at 900°C for 24 hours, then grinding the material in a Marconi ball mill at 351 rpm for 30 minutes. The physical and chemical properties of banana fiber ash were then analyzed in a laboratory [38].

Table 1. Chemical composition of Agro waste ashes [39-42]

S.No	Oxide composition	Percentage of composition				
		Cement	RHA	SBA	BLA	CHA
		(%)				
1	Silicon dioxide	17 - 25	93	72	51	38.02
2	Aluminum oxide	8	0.15	1.5	2.8	25.12
3	Calcium oxide	62 - 67	0.55	3.6	-	5.69
4	Magnesium oxide		0.35	0.5	-	-
5	Sulphur trioxide	3	0.24	-	-	-
7	Iron oxide	-	-	-	16.23	16.23
8	Calcium oxide	-	-	-	5.69	5.69
9	Sodium oxide	-	-	-	0.98	0.98

Table 2. Physical properties of agro waste ashes [39, 41-43]

S. No	Particular	Properties				
		RHA	SBA	BLA	CHA	
1	Colour	Grey	Reddish grey	Grey	Brownish grey	
2	Shape texture	irregular	Spherical	Irregular	Rod-like structure	
3	Bulk Density (Kg/M^3)	996	994	1610	1650	
4	Specific Gravity	2.4	2.88	3.12	2.65	
5	Odour	odourless	odourless	odourless	Odourless	

Coconut Husk Ash (CSH), shell and fiber waste materials produce ashes, with significant alkali activation observation in husk ash and coconut shell ash. Coconut shell powder is known for its low cellulose content and water absorption. Coconut shells are incinerated under controlled conditions at temperatures between 500 °C and 550 °C for nearly two hours to produce ash. [39].

4.2. Second-Order Heading

In the concrete mixes, the inclusion of Rice Husk Ash (RHA) led to a slight increase in water consumption. Higher percentages of RHA negatively impacted several fresh properties, including slump flow, likely due to the increased surface area of RHA particles. Notably, an 8% RHA inclusion significantly decreased slump flow, indicating the substantial effect of RHA. The porous structure and large specific surface area of RHA allow it to absorb considerable amounts of water, reducing the water available for cement hydration and aggregate friction, which results in a significant reduction in slump flow. These findings align with previous research highlighting RHA's significance in Self-Compacting Concrete (SCC) [18, 35, 43, 44]. The use of RHA marginally improved the concrete workability, often achieving results comparable to or better than the control mix. Ternary blends containing RHA and Limestone powder (LS) showed a strong trend toward significantly improved workability. Additionally, high binder concentrations in combination with RHA and superplasticizers were shown to address segregation issues, resulting in a highly workable and cohesive mixture at water-to-cement ratios as low as 0.30 to 0.34 [42]. Superplasticizers counteracted the increased water requirement caused by RHA inclusion. In SCC mixtures, replacing up to 50% by weight with foundry sand waste increased the need for superplasticizer while decreasing fresh density. FDW also extended flow duration in the V-funnel test when combined with RHA-SCC mixtures [34, 42]. No apparent blockage was observed in SCC mixes containing 10 % or 20 % RHA. The workability of RHA concrete was assessed using the slump method. Concrete mixes became stiffer at RHA percentages of 15 % and 20 %, requiring the addition of superplasticizers to maintain the required workability. In some cases, some cement combinations caused segregation and bleeding, which reduced concrete strength [39, 44, 45]. Based on these findings, Gill and Siddique concluded that RHA had a minimal impact on workability and suggested that this effect could be mitigated by increasing the dosage of water-reducing admixtures. [46]

According to [14], an increase in the percentage of SBA in the concrete mix will increase the slump value. This suggests that the addition of SBA reduces the demand for water in the concrete mixture. The compaction factor value of the various mixes with SBA while the Water-to-Cement (w/c) was held constant, showed that other mixtures exhibited higher compaction factor values compared to the control mix (M0), indicating they were easier to work with. Research findings indicate that the addition of NaOH to geopolymer mortar enhances the workability of slump flow mortar [48]. This improvement is attributed to the higher viscosity of NaOH at high concentrations. Fresh SBA concrete workability increases as the percentage of concrete weight increases due to the increased surface area of SBA. It was noticed that the setting time increases as the amount of cement replaced with SBA increases [49]. This is logical, as the increase in SBA content reduces the cement content in the mix and decreases the cement surface area. As a result, the hydration process slows down and the setting time increases [50]. The properties of concrete, such as cohesiveness and stiffness, are increased by adding the fine mineral mixture to the concrete. By adding a minimum amount of mineral admixture, an increase in workability and a reduction in segregation and bleeding are expected. A small percentage of mineral admixture was observed to increase workability and reduce bleeding. The obtained slump value for conventional concrete was 30 mm, while it was 50 mm for concrete containing banana leaf ash [51]. Under the low workability category, the traditional concrete was classified, whereas the concrete containing banana leaf ash was classified as the medium workability category, as per the IS code. Typically, it was observed that the concrete mix's workability increases upon any material with the fineness equivalent to cement. When cement is replaced with banana leaf ash, the workability of the mix improves, i.e., the more banana leaf ash is added, the better the mix performs [52]. As mentioned earlier, the stiffness and cohesiveness are enhanced by adding fine mineral admixture to concrete. An increase in workability and reduction in bleeding and segregation are expected from adding a small amount of mineral admixture to the previous study. The slump value decreases with an increase in the percentage of coconut fiber ash, indicating that as the CFA content increased, concrete became less workable (stiff) [24]. Adding CSA content also decreases the concrete slump. This is due to the high loss on ignition of the CSA compound compared to cement and the high specific surface area of CSA, which impacts workability despite constant water content. [53]

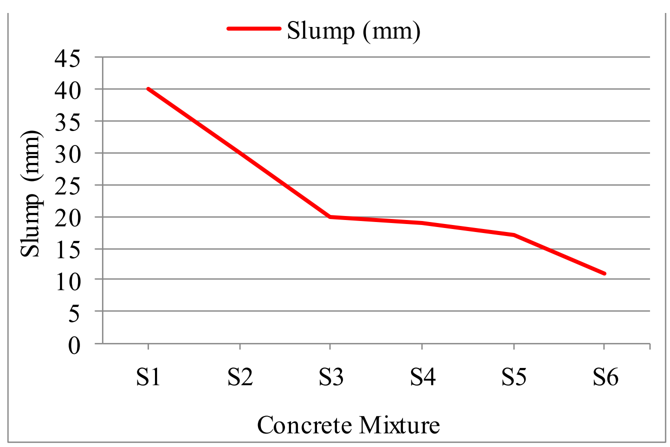


Fig. 9 Workability of geopolymer concrete [47]

5. Results

5.1. Compressive Strength of Agro Waste Ash

The 8% RHA mixes exhibited lower compressive strengths than the control mix, while 4% RHA mixes demonstrated slightly higher compressive strengths due to RHA's ability to fill small voids [54]. Increasing RHA content at the initial stage of concrete development may enhance compressive strength. Over a 120-day curing period, the compressive strength of various mix proportions was found to increase significantly. This was particularly evident when comparing the influence of particle size on concrete compressive strength. The compressive strength decreased when coarser cement concrete was used instead of OPC at both 20% and 40% by weight. The highest compressive strength was achieved with a 20% mix [42, 45]. The compressive strength of Geopolymer Concrete (GPC) increased over curing periods of 7, 14, and 28 days, showing a direct correlation between the curing duration and strength enhancement under ambient curing conditions [55] Furthermore, irrespective of the concrete's molarity, thermally cured specimens exhibited a remarkable 20% strength improvement compared to those subjected to normal curing [46, 56]

Microwave-Incinerated RHA (MIRHA) also contributed significantly to the geopolymer matrix, particularly as the system benefits from temperature increases during curing. This improvement in performance was especially pronounced in fly ash-based geopolymer concrete [57]. Denser gel structures were observed, improving the interconnection within the geopolymer frameworks, which enabled load distribution. In addition to pulverized granulated blast furnace slag, RHA can be used as a source material in geopolymer concrete. However, when RHA content exceeded 1 %, the compressive strength was delayed. The target strength was achieved at up to 2% replacement, and at 28 days, mechanical properties as high as 55 MPa were attained [21, 27]. It was observed that adding rice husk ash to GPC increased compressive strength by about 25 % up to a 40 % replacement level, after which the strength begins to decrease. Compressive strength increased by 5% when the RHA content was increased from 0 % to 30 %, with a maximum increase of 25 % compared to normal concrete. One-part geopolymer compressive strengths were also noted after 1, 3, and 7 days of curing [58]. However, curing times longer than 24 hours were found to be ineffective. RHA produced higher compressive strengths of nearly 30% at 1-day curing, 35% at 3 days, with a slight decrease of 1–2% at 7 days [45, 55, 59]. Several studies observed that substituting RHA in fine aggregates in self-compacting concrete reduced the compressive strength by 0 % to 100 %. After a 10 % replacement, the compressive strength of RHA concrete began to decrease [21]. A combination of RHA and Nano-silica was found to be beneficial: RHA contributed to early strength development, while Nano-silica improved durability and long-term strength. RHA concrete's compressive strength increases by 8% and 2.6% with a replacement of 5 %-20 % at 28 days before decreasing by 5.8 % and 11 % respectively, with a 0.50 water binder ratio [18, 44]. The rapid reaction between RHA particles, water and calcium hydroxide resulted in a dense microstructure, producing more Calcium Silicate Hydrate (C-S-H). [34, 42]

Table 3. Compressive strength of AWA with GPC

Study	Molarity (M)	Compressive Strength (MPa)							
		RHA		SBA		BLA		CHA	
		Number of days-Curing							
		7	28	7	28	7	28	7	28
[10, 59, 62, 63, 64]	8	31.0	37.8	16.34	25.6	13.64	30.25	17.53	31.84
		30.8	49.5	19.25	22.56	10.29	32.15	20.35	33.5
		38.5	43.5	13.2	19.5	12.0	20.56	14.6	36.00
	10	33.6	36.9	25.6	38.27	15.65	31.33	22.35	32.33
		29.5	52.8	19.2	30.24	11.22	35.25	20.33	34.9
		39.7	48.6	23.4	28.56	13.65	19.56	18.56	38.9
[8, 36, 43, 52, 59, 65]	8	29.5	36.8	17.85	36.83	16.50	20.6	17.85	36.83
		36.5	43.5	20.2	29.20	18.96	20.56	20.2	29.20
		49.6	66.9	14.5	22.90	27.56	23.5	14.5	22.90
	10	35.6	33.5	19.5	35.62	20.23	33.27	19.5	35.62
		28.5	38.6	20.2	22.52	29.56	25.24	20.2	22.52
		36.6	33.2	16.5	19.53	31.75	28.56	16.5	19.53
[27, 39, 66, 67]	8	28.6	44.5	13.64	30.25	17.53	31.84	23.6	44.5
		31.2	46.8	10.29	32.15	20.35	33.5	29.2	46.8
		29.5	44.7	12.08	20.56	14.6	36.00	30.5	44.7
	10	29.5	39.5	15.65	31.33	22.35	32.33	29.5	39.5
		33.4	44.6	11.22	35.25	20.33	34.9	33.4	44.6
		27.5	38.2	13.65	19.56	18.56	38.9	27.5	38.2

The compressive strength increased at 10 % replacement compared to 20 % with minor reductions after 10% due to the material's higher water demand, which reduced flow properties [56]. The use of the pozzolans leads to a dilution effect, contributing to the reduction in strength. The increase in SBA content also explained the decrease in compressive strength, as SBA does not possess the same binding properties as cement. Being finer than sand, SBA increased concrete strength by reducing voids in the specimen [52, 60]. Tests on 28-day mortar with a 16M NaOH concentration achieved a maximum compressive strength of 20 MPa, while an 8M NaOH concentration resulted in 9.22 MPa. It was concluded that NaOH concentration is directly proportional to compressive strength [14]. Testing SBA-blended concrete cubes after 28 days of curing, as per IS 516:1959, revealed compressive strength increased up to a 10% SBA replacement, after which it began to decrease [24, 60]. For a 10 % banana leaves ash replacement by the weight of cement and curing at 7 and 28 days, compressive strength was lower than conventional cement, attributed to entrapped air within the concrete [52]. A reduction in compressive strength was also observed in ternary cementitious matrices reinforced with sisal fiber. However, a slight increase in strength was noted in concrete reinforced with banana fibers and fly ash at days, attributed to fly ash's pozzolanic reactivity, which reduces voids in the concrete matrix [38, 58]. In another study, a 10% banana leaf ash replacement yielded lower compressive strength than conventional cement after 7 and 28 days of curing due to air entrapment [14, 15, 29]. Additionally, sisal fibre-reinforced cementitious matrices showed a decrease in compressive strength. Increasing CSA content initially led to a rise in compressive strength due to additional calcium silicate hydrate formation from CSA's pozzolanic reaction. However, strength began to decline when CSA content reached 4%, as excess magnesium oxides inhibited further calcium silicate hydrate formation. [61]

5.2. Flexure Strength of Agro Wash Ash

When Rice Husk Ash (RHA) was replaced at 5%, the maximum flexural strength was observed. However, at a 10% replacement, a decrease in strength comparable to that of the control mix was noted. The stress at rupture and the displacement at which the material broke on the 28th day were measured to study the flexural strength. Across all testing days, the stress at rupture for the control and 10 % replacement is observed to be the same. This suggests that a 10 % replacement could be used in structural applications where the control mix is used. A 30% replacement demonstrated a response of 86.8% compared to the control mix, indicating that a 30% to 40% RHA replacement could be suitable for non-structural elements (i.e., non-load-bearing structures) [13, 68]. For minor Civil engineering projects and smaller building applications, replacing Ordinary Portland Cement (OPC) with 5% RHA can be effective, particularly when using calcined RHA. The calcination process is detailed below in Table 4 [69, 70]

Flexural strength testing was carried out according to BS:516 (1959). Using a universal testing machine, beams were tested for flexure. While flexural strength increased with curing age, increasing SBA content led to a reduction in flexural strength. The flexural strength at 5% SBA was comparable to that of the control sample. The weaker Calcium-Silicate-Hydrate (C-S-H) gel formation, due to SBA's pozzolanic reaction and the dilution of Portland cement, caused the decline in strength as the SBA content increased. A graph illustrating these trends is presented below in Figure 10. At a 10% replacement, samples incorporating bagasse ash exhibited optimal flexural strength; however, a rapid increase in bagasse ash relative to fly ash led to a decline in strength. In comparison, geopolymer concrete samples containing metakaolin achieved superior flexural strength compared to those containing bagasse ash [27, 49, 70]

Concrete specimens incorporating 10 % and 15 % fly ash replacement achieved higher flexural strength at 90 days compared to plain concrete, but when the fly ash replacement reached 20 % or exceeded that level, the flexural strengths were consistently lower than those of plain concrete at all curing ages [52]. Research demonstrated that concrete containing coconut fiber experienced a reduction in flexural strength, with a decrease of 3.2 MPa and 28.2 % when 20 % and 30 % fly ash replacement levels, respectively. The flexural strength of glass-fiber reinforced fly ash-containing concrete was reduced with the rise in the cement replacement percentage with fly ash. Similarly, banana fibre-reinforced concrete experienced adverse effects in flexural strength when fly ash replaced a high percentage of cement [23, 58]

Table 4. Flexure strength properties of rice husk ash (N/mm2) [12]

S. No	Percentage replacement (%)	Flexure strength (MPa)			
		RHA	SBA	BLA	CHA
1	0	5.52	6.61	7.1	6.8
2	5	5.23	6.68	6.3	6.2
3	10	3.66	6.82	5.6	5.4
4	15	4.26	6.78	4.2	4.1
5	20	3.20	6.39	4.6	3.5

5.3. Split Tensile Strength

Concrete with 15% and 25% replacements of agro waste ash achieved split tensile strengths between 1.2 and 1.9 MPa. After 28 days, the split tensile strength for concrete with a 10% replacement of banana leaf ash reached 3.3 MPa, which was higher than that of traditional concrete. A comparison of split tensile strengths between the banana leaf ash concrete and conventional concrete is provided in Figure 10. The results showed an increase after 14 days for banana leaf ash-replaced concrete [17]. The split tensile strength increased proportionally to the compressive strength, reaching 3.3 MPa at 28 days, higher than conventional concrete [71, 72]. Significant increases in splitting tensile strength were observed with increased curing age. For all Cement-Slag-Ash

(CSA) percentages, splitting tensile strength was higher than the control at 3 and 7 days [73]. The addition of 4%, 6%, 8%, and 10% CSA resulted in lower strengths compared to the control at all curing ages, whereas 2% CSA showed superior splitting tensile strength at 28 and 56 days [40].

The enhanced strength could be attributed to the increased cementitious properties of the concrete from the 2% CSA, which improved the paste matrix formation and the cement-aggregate bond. Conversely, the strength reduction with higher CSA percentages may result from alkali content in the cement due to the CSA addition [48]. A strong relationship between compressive and splitting tensile strength was observed, with both increasing proportionally [43, 74].

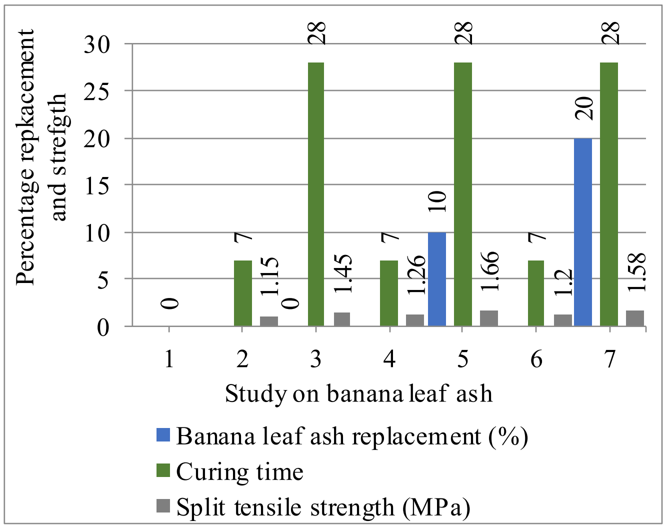


Fig. 10 Split tensile strength property of Banana leaf ash [14, 52, 71]

5.4. Microstructural Analyses

X-Ray Diffraction (XRD) is used to analyze material structures by measuring the angle and intensity of X-rays scattered by the material. The ultrafine slag-based geopolymer paste exhibited higher peak intensities in SEM analysis, resulting in a homogeneous and dense microstructure [55]. However, the polymerization process is slowed with the introduction of excess calcium-rich products, leading to microstructural degradation in the ultrafine slag with concentrations above 30%. Calcium-based products, like CSH and CASH, enhanced strength to a certain degree, but beyond that, they hindered polymerization [58].

After 28 days of curing, geopolymer mortar containing 15% SSA replacement reached the highest strength when cured in an oven using NaOH solutions of 4M, 6M, and 8M concentrations. The RHA and SSA exhibited diffraction angles between 16° and 30° and 24° and 50°, respectively. Alkaline activation of RHA and SSA particles resulted in a shift from 20° to 40°, indicating geopolymer formation [48]. The major crystalline phases observed were quartz and cristobalite. The presence of these phases suggested incomplete dissolution of the alkaline activator [7, 9, 15, 25]. XRD analysis of sugarcane bagasse ash revealed a chemical composition predominantly consisting of SiO_2 (approximately 85.55% by weight), along with Ca, Al, P, K, and Fe, consistent with the XRD results.

The high silica content is likely due to sugarcane bagasse combustion in sugar plants. The resulting ash consisted primarily of calcite and quartz, contributing to reduced pozzolanic activity [41]. SEM images of banana leaf ash and sugarcane bagasse ash show that coconut shell ash particles are spherical with a density of 2.04 g/cm³ and an average particle size of 42 µm [30]. In contrast, coconut husk ash exhibited an irregular structure due to thermal changes at 800°C, resulting in particle shrinkage and splitting [65]. Calcined CBWA, fired at 900°C for 3 hours in an electric arc furnace, displayed crystalline phases in its XRD analysis, indicating reactive and finer products with low organic content [49, 52].

6. Influences of Molarity of Activators on Aba Compressive Strength

The strength of agro-waste-based AAB specimens is significantly influenced by the molarity of the solution or the alkaline activator used. ABA specimens using low molarity activators tend to exhibit lower compressive strengths compared to those employing higher concentrations [1]. The study showed that an increase in concentration by molarity leads to higher compressive strength in AAB specimens containing RHA, FA, and BA. This rise in hydroxyl ion concentration associated with increasing molarity promotes the dissolution of aluminates and silicates from the precursors, subsequently enhancing strength and polymerization [17, 19, 27, 31].

In the case of POFA-blended AAB specimens, the increase in 28-day compressive strength with rising molarity is not as pronounced. However, a reduction in strength is evident at 8M molarity after 7 days. Another phenomenon, efflorescence, is reported to occur with increasing molarity [75]. For CCA-based AAB specimens, a marginal increase in compressive strength is observed from 12M to 14M at 7 days, but an additional increase in molarity for FA, BA, and RHA-based AAB specimens to 16M results in reduced compressive strengths [39, 59, 75].

Similar trends are reported for CCA-based AAB specimens at 28 days. Efflorescence is observed in CCA-based AAB specimens when high molarity activators are used. Furthermore, the molarity's influence on slag-CCA-based AAB (where 40 % of CCA is replaced with slag) has been kept to that of 100 % CCA-based AAB specimens. However, in CCA-slag blended AAB, a reduction in compressive strength is noted from 14M to 16M when compared to 100 % CCA-based AAB specimens [67, 76, 77].

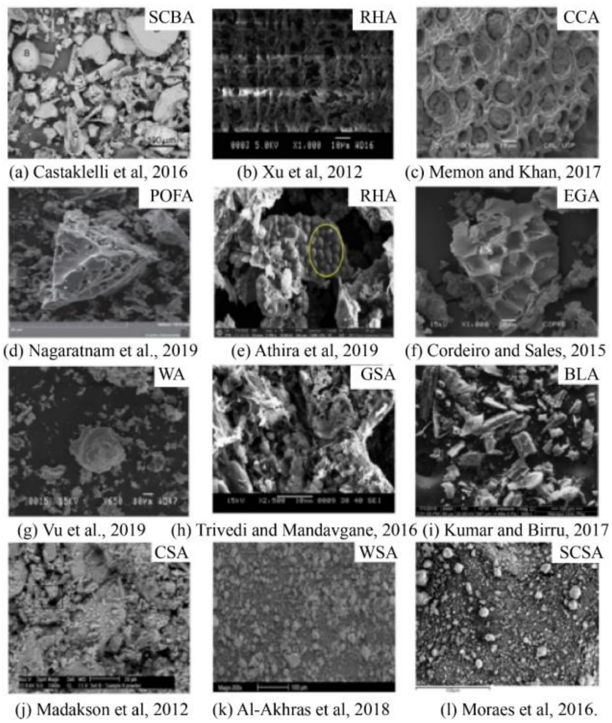


Fig. 11. XRD analysis of agro ash-based gpc [1, 66]

7. Future Scope

From the comprehensive review, agro-waste-based Alkali-Activated Binders (AAB) show similar performance to fly/slag ash-based binders. However, to achieve zero-cement concrete, agro-waste ashes have not been fully utilized. The primary challenge is the lack of detailed performance evaluations, which delays the industrial-level adoption of agro-waste ash-based Geopolymer Concrete (GPC). Further research is needed to understand the impact of different agro-waste ashes on GPC concrete performance. To enhance the utilization of agro-waste ash-based GPC concrete, the following areas of research are recommended:

1) Studies quantifying the availability and accessibility of agro-waste ashes, particularly in agriculture-based countries, are necessary for their recycling in AAB production.
2) Further research on the variability of agro-waste ash sources is essential to ensure consistent GPC concrete performance.
3) Field studies on the performance of agro-waste-based GPC concrete in real-life structures, such as bridges and buildings, are crucial. These studies would help correlate laboratory observations with field performance.
4) Though rice husk, bagasse, coconut husk, and banana leaf ash have been extensively researched, numerous additional agro-wastes remain unexplored. Future research may examine the ashes derived from wheat straw, corn cob, palm kernel shell, and many other localized bio-wastes.

8. Challenges and Limitations on Using Agro Waste Ash in GPC

Considering its potential, the application of agro-waste ash in geopolymer concrete has some practical challenges. Raw material variability is a significant challenge, as ash characteristics vary based on crop type, soil conditions, harvesting methods, and combustion techniques; improper burning reduces amorphous silica, increases crystallinity and Loss on Ignition (LOI), hence reducing reactivity and increasing alkali demand. Agro ashes with high silica content typically require greater alkali levels for dissolution, hence rising costs, handling hazards, and the risk of efflorescence unless balanced by calcium sources like GGBS.

Their tiny, angular particles enhance liquid demand and influence rheology, with early strength under ambient curing typically necessitating optimum SS/SH and liquid/binder ratios; otherwise, heat curing is essential. The durability outcomes remain ambiguous due to the inadequate understanding of the relationships between agro-ash chemistry and carbonation kinetics, pore structure refinement, chloride binding, and associated mechanisms, including sulfate-calcium reactions.

The adoption of structural elements is further hindered by insufficient datasets about modulus, creep, shrinkage, bond, and fatigue behavior, as well as the lack of design rules and specifications. Sensitivity in processing is significant, with strength growth intricately reliant on curing temperature, SS/SH ratio, and liquid / binder proportions, rendering minor variances consequential.

Ultimately, supply chain constraints - seasonal availability, preprocessing necessities like calcination and grinding, and regional transportation logistics-present persistent scalability and cost predictability hurdles.

9. Conclusion

This study provides a comprehensive review of previous research and recent advancements in the field of concrete incorporating agro-industrial waste ashes from agricultural and industrial byproducts. The development of economical, durable, and high-quality construction materials is a significant challenge for the scientific community, driving numerous research initiatives focused on concrete's characteristics when agro-industrial waste ashes are used as pozzolanic additives.

In conclusion, the evaluation of concrete incorporating agro-industrial waste ashes as pozzolanic additives reveals great potential for developing cost-effective, durable, and high-quality construction materials. The use of agro-waste ashes offers a sustainable solution to waste management and enhances the construction industry’s sustainability. Future research should focus on optimizing mix proportions, understanding long-term performance, and standardizing the use of these materials to enable their large-scale adoption. This approach addresses the challenges faced by the scientific community and paves the way for the broader application of zero-cement concrete.

Author's Contribution

Devadharshini investigated reports, methodology, data curation, formal analysis, and writing. Vasugi presented supervision, validation, writing, reviewing and editing.

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