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A REVIEW OF GEOPOLYMER MORTARS INCORPORATING INDUSTRIAL ASHES, CONSTRUCTION AND DEMOLITION WASTE (CDW), AND RECLAIMED ASPHALT PAVEMENT (RAP)

Abdul Rehman[*1], Abdul Jabbar[2], Qasim Raza[3], Saira Sidhu[4], Tania Mahar[5]

[1]*Senior Lecturer, Department of Civil Engineering, Ziauddin university, Karachi*
[2,3]*Faculty of Engineering, Science and Technology, Indus University, Karachi*
[4]*USPCASW-Mehran University of Engineering and Technology Jamshoro*
[5]*BS Scholars, Environmental Science Department, Mehran University of Engineering and Technology Jamshoro*

[*1]abdulrehmankhuwaja45202@gmail.com; [2]abdul.jabbar@indus.edu.pk; [3]Qasim.raza@indus.edu.pk;
[4]saira.mustafa13te64@gmail.com; [5]mahartania58@gmail.com;

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Corresponding Author: *
Abdul Rehman

Abstract
The construction sector is facing greater challenges in reducing its impact on the environment, with the rising issue of waste that Construction and Demolition waste (CDW) and Reclaimed Asphalt Pavement (RAP) are creating for construction industries worldwide. An extensive research review on the existing technology for geopolymer ash-based mortar composites using locally available fine materials, with special consideration for building demolition waste and RAP, counted as more favorable cement replacement materials for geopolymer matrices, is conducted. Based on a broad analysis of 67 scholarly articles published between 2015 and 2026, this research presents a summary of existing technology with regard to three vital parameters: (a) the mechanical characteristics of geopolymer mortar composites, including compressive strength, flexural characteristics, durability, and workability; (b) the sustainability factors concerning the impact on the environment, through geopolymer potential for carbon footprint reduction, life cycle analysis, and sustainability assessment techniques; and (c) the chemical aspects concerning geopolymerisation kinetics, microstructure formation, and alkali activation mechanisms for geopolymer composites. The research findings suggested that geopolymer-based matrices using 25-50% demolition waste and RAP potentially have compressive strength values from 15 to 64 MPa with a reduction of 40-72% in carbon footprint compared to conventional PC-based systems. Geographic context, along with various application examples, such as implementation of the method with appreciable success in a variety of climatic conditions worldwide. From pavement-quality concrete to various forms of masonry mortars, the variety of structures is appreciable. Critical analysis of the field reveals existing research gaps with regard to the standardization of mix design methodologies and scaling issues. Review of existing literature offers an exhaustive framework for researchers working on the stream of sustainable construction materials through waste management practices.

1. INTRODUCTION

1.1 Background and Motivation

The global construction sector is at a critical juncture of challenges where the sector is contending with the twin issues of environmental sustainability and waste management issues on one hand, it is essential to note global greenhouse gas emissions from Portland cement production that amount to approximately 8% of global carbon dioxide emissions and significantly contribute to climate change [1], [2]. CDW/RAP wastes are being generated; for instance, a staggering operational waste of 50 million tonnes RAP is produced annually across Europe [3].

Geopolymer material technology has been developed and adopted as a key material technology with important implications for environmental protection while making effective use of industrial by-products/wastes in a sustainable way [4], [5]. The idea of geopolymer material technology is based on alkali activation of aluminosilicate-rich material, such as fly ash, bottom ash, slag, and other wastes, to form three-dimensional polymeric networks with cementitious properties [6], [7]. Modern technology has proved its capability in using CDW and RAP not just as aggregate materials in pavements but also through a chemical reaction in geopolymer material technology [8], [9], [10].

The integration of local sources of fine aggregate present at demolition waste and RAP together with ash geopolymer mortars is a new approach that represents a new "paradigm shift" towards a circular economy construction practice [11], [12]. This approach several sustainability targets: reducing virgin materials demand, promoting waste reduction, reducing greenhouse gas emissions, and possibly offering benefits from material synergies[11], [13]. However, "understanding their advantage in terms of mechanical, environmental, and chemical aspects is essential," though difficult to achieve when dealing with individual materials alone [10], [14].

1.2 Research Objectives and Scope

This review article aims at offering a comprehensive synopsis on the existing knowledge on ash-based geopolymer mortars containing demolished building wastes and RAP as a cement substitute. The specific research aims are:

1. To systematically assess different types of mechanical performance characteristics with varied mix designs and waste application techniques.
2. To quantify the environmental benefits through life cycle assessment/carbon foot prints.
3. To gain insight into chemical mechanisms that control chemistry of geopolymerization process.
4. To identify any geographic and application-specific considerations for implementation.
5. To critically analyze research gaps and propose future research directions

The scope of literature reviewed comprises peer-reviewed articles published from 2015 to 2026. The articles include those using mortar and concrete mix systems that apply ash-based precursors such as fly ash, bottom ash, and slag combined with CDW and/or RAP as aggregates. The review combines laboratory studies, applications, and computational research from a wide range of geographical and climatic conditions.

1.3 Review Methodology

This comprehensive review consists of 67 research papers based on an initial dataset of 1,297 papers retrieved through several online database searches using SciSpace, Google Scholar and others. The review criteria focused on the following: (1) paper applicability to ash-based geo-polymer matrices while incorporating waste, (2) paper publication between 2015-2026, (3) paper availability in full-text formats, (4) impact factor of the papers, as well as (5) paper rigor. The research papers are representative of an amalgamation of mechanical properties analyses, environmental analyses, as well as microstructural analyses, while their geographical coverage encompasses Asia, Europe, North America, South America, and Australia.

2. Background and Theoretical Foundations

2.1 Geopolymer Chemistry and Alkali Activation

Geopolymers represent a group of inorganic polymer materials produced through an alkali-activation mechanism involving aluminosilicate precursors to produce an overall three-dimensional polymer material derived from silicon-oxygen-aluminum linkages [5]. The chemical process and basis for geopolymerization involve the solution of reactive silica and alumina from their sources using highly alkaline solutions, followed by polycondensation to produce amorphous to semi-crystalline products that consist of aluminosilicate gels [6]. The general reaction mechanism can be described as a multi-step process, involving the following steps: dissolution of Si and Al species, transport of the dissolved species and their orientation, polycondensation and gelation, and hardening and crystallization [7].

The type of alkali activator has a significant effect on the reaction rates and the final material properties achieved. Sodium hydroxide and potassium hydroxide are commonly used as alkaline activators; often, sodium silicate solution can be added as a source of silica to optimize the reaction rate [7], [15]. The concentration of the alkaline solution has a direct impact upon the dissolution rate and the final mechanical properties [8], [15]. Higher molarities are known to enhance faster kinetic reactions while, at the same time, they may contribute to an increase in efflorescence [6].

The composition of precursors, in ratio of SiO_2/Al_2O_3, Na_2O/SiO_2, and Na_2O/Al_2O_3, is shown to have effects on the types and specific features of geopolymer gels that are created [6], [16]. In materials based on low-calcium content (fly ash F), sodium aluminosilicate hydrate gels are obtained, while in those based on high calcium content (slag and C fly ash), calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H) gels are obtained [7], [17]. The simultaneous occurrence of these phases in mixed systems may create synergies beneficial for their mechanical properties and durability [18], [19].

2.2 Waste Materials as Precursors and Aggregates

2.2.1 Fly Ash and Bottom Ash

With regard to the fly ash used as a precursor for geopolymerization, previous information suggests that fly ash is a by-product of coal combustion in power plants [1], [4], [7]. Its fine particle size, high surface area, and reactive aluminosilicate content make it ideal for alkali activation. Class F fly ash, with low calcium content ($CaO < 10\%$), is particularly suitable for producing N-A-S-H gel-based geopolymers with excellent long-term strength and durability [12], [20]. In addition, the oxide composition it is comprised of 45-65% SiO_2, 20-35% Al_2O_3, and minor amounts of Fe_2O_3, CaO, and MgO [4].

On the other hand, bottom ash, which is collected at the bottom of the furnace, has received little attention but appears to have potential both as a precursor material and as an aggregate [21]. The Coarse particle size and reactivity of bottom ash with fly ash might be advantageous but might necessitate mechanical treatment to increase the reactivity of the material [22].

2.2.2 Ground Granulated Blast Furnace Slag (GGBFS)

GGBFS has highly reactive chemical properties with high calcium content, normally around 30 to 45% CaO [1], [18], [19]. Its Use as a cementitious material within geopolymers made of fly ash has several advantages, such as early development of strength, easier workability, reduction of drying shrinkage, and improvement of durability [8], [12], [18]. The optimum proportion of fly ash to GGBS generally lies between 60:40 and 80:20 depending on concrete requirements and curing [1], [19], [23]. Presence of calcium enhances the creation of C-S-H and C-A-S-H as well as N-A-S-H microdomains, leading to a denser matrix [17].

2.2.3 Construction and Demolition Waste (CDW)

CDW are a range of materials such as crushed concrete, bricks, ceramic tiles, and mixed demolition wastes [9], [16], [24], [25]. They have an added advantage of providing dual functionality in geopolymer materials. They can be finely ground and utilized as reactants, and sometimes their size is appropriate to be incorporated as aggregates [6], [8], [16]. CDW derived from bricks is one such promising candidate because of their high content of aluminosilicate and their pozzolanic potential [16], [18], [26]. But the variability of CDW often generates problems in ensuring durability [14], [27].

The usage of CDW as fine aggregates, namely recycled fine aggregates (RFA), in geopolymer mortars has produced conflicting outcomes. Investigations have demonstrated compressive strength losses of between 27-50% due to high RFA replacement ratios of 50-100%, resulting from enhanced porosity of adhered mortars that was due to increased water absorption [9], [11], [12]. Nevertheless, optimization of formulations of RFA, namely between 10-30%, significantly contributes to sustainability improvements [15], [16], [28].

2.2.4 Reclaimed Asphalt Pavement (RAP)

RAP is defined as a mixture of materials that are removed from pavements and recycled that is composed of aged asphalt binder and aggregates [29], [30], [31], [32]. The availability of RAP materials globally is significant, with millions of metric tonnes produced every year due to maintenance and rehabilitation works on paved roads [3], [33], [34]. Conventional recycling techniques have only used RAP for hot mix and warm mix, while recent research has also used RAP for geopolymer concrete and base materials [2], [35], [35], [36], [37].

RAP's incorporation into geopolymer systems is marked by specific challenges and opportunities. RAP with an aged asphaltic binder on the aggregates' surfaces influences bonding properties, workability, and mechanical properties [2], [13], [38]. critical reductions in strengths as high as 39-58% for higher RAP contents (100%) were attributed to inadequate bonding properties between aggregates with the aged asphaltic binder and the geopolymer matrix [13], [38]. However, the moderate RAP contents ranging from 25 to 50% may allow for satisfactory properties for pavement construction while promoting environmental benefits [13], [38], [39].

2.3 Environmental Imperatives

The environmental advantages of employing the geopolymer technology are significant. Additionally, researchers have also reported that studies by LCA analysis have confirmed that the carbon footprint, energy efficiency, and the footprints created on the environment by employing the geopolymer technology have significantly decreased compared to the traditional materials and the Portland cement-based materials [4], [40], [41], [42], [43], [44]. significant reductions have been achieved related to the global warming potential by employing the geopolymer technology, up to 49.7% for the ordinary Portland cement [4]. The LCA study that analyzed the geopolymer technology for the construction of pavement also reported that the ordinary Portland cement was replaced by the geopolymer technology, and consequently, approximately 50% lower CO2 emissions and 72% lower energy were anticipated [41].

These environmental advantages are not limited to the emission of carbon dioxide. Manufacturing geopolymer materials is done under either ambient or moderately elevated conditions (60-80°C), whereas cement kiln production is performed under much higher conditions of 1450°C [7], [42]. This translates to substantial energy savings and reduced fossil fuel consumption. Furthermore, the use of industrial by-products/wastes will solve the problem of waste management while conserving natural resources on a large scale [45], [46], [47], [48].

However, recent critical analyses have pointed out that the complete LCA, including all the production steps like manufacture of alkali activator and processing of waste materials, the environmental credits for reclaimed fly ash in the geopolymer production might be overestimated if the upstream effects are not appropriately considered [43].

3. Methods and Approaches in Literature

3.1 Mix Design Strategies

3.1.1 Precursor Selection and Proportioning

The choice and proportioning of precursor materials are important factors in geopolymer mix design. The proportion of fly ash, slag, and waste-based precursors blended together as a binary or ternary mixture is a widely adopted approach to achieve maximum reaction, workability, and cost implications for geopolymer blends [1], [18], [23], [32]. The proportion of fly ash and GGBFS is an important parameter that influences the kinetics of strength development: increasing slag proportion accelerates early-age strength development while inducing greater drying shrinkage [18], [32]. he proportioning of fly ash and GGBFS, as reported by literature sources, may vary from 70:30 to 80:20 for fly ash/GGBFS blends [1], [32].

Another layer of complexity arises through the incorporation of wastes, such as powder material bricks, ceramic wastes, and concrete wastes, as mentioned in various studies [8], [18], [26]. The inclusion of 15% waste red brick powder WRBP as a binary binder replacement with metakaolin and GGBFS achieved an improved compressive strength of 30.7%. However, WRBP at higher replacement levels in the 30-45% range reduced strength [18]. This points to a need for optimization of the incorporation levels of wastes in relation to sustainability objectives versus performance requirements.

3.1.2 Alkali Activator Design

The alkali activator system consists of the alkaline solution NaOH or KOH-added sodium silicate. Molarity of alkaline solution is considered as a primary variable, which generally varies from 2 to 14 M [8], [15]. Rohit et al. showed that the increment of NaOH molarity from 2 to 10 M in slag-based geopolymer mortars with CDW fine aggregates enhances compressive and flexural strengths by 20.73% and 10.63%, respectively [15]. However, molarity (> 12 M) may result in rapid setting, loss of workability, and efflorescence [19].

silica modulus affects the kinetics of gel formation and final microstructure; hence, a higher silica modulus normally results in the more polymerized gel structures with better mechanical properties but when too excessive, it leads to the premature setting of the silicate and reduces workability [6], [17]. Liquid-to-solid ratio normally varies between 0.35 and 0.50 and controls the workability and porosity in which lower ratios would normally lead to much denser and stronger materials but at a reduced workability [49].

3.1.3 Aggregate Incorporation Strategies

When working with aggregates, it is important to consider size distribution, water absorption, and surface properties [6], [11], [12]. It has been noted that RFA derived from CDW can have a higher water absorption characteristic of 5-15%, compared with sand materials with water absorption characteristics of 1-3% [11], [12]. According to Abuowda et al., incorporating geopolymer binder has been noted to improve flowability and water retention of masonry mortars containing up to 100% RFA, although compressive, pull-off, and flexural strengths are reduced by 36%, 44%, and 27%, respectively [11].

RAP incorporation techniques differ on the basis of applications. For pavement, asphalt can be used as a replacement for coarse aggregates in the range of 25-100% [11], [13], [38], [39]. Ghosh et al. investigated that geopolymer concrete using 50% coarse RAP fulfilled Pavement Quality Concrete (PQC) strength requirements, while RAP content of 100% experienced a reduction in compressive strength by 57.6% and flexural strength by 39.7% [13]. The results also showed that the porosity-reducing effect of asphalt provides unexpected durability benefits [13].

3.2 Characterization Techniques

3.2.1 Mechanical Testing

Compressive strengths according to ASTM C109 standards or equivalent may be the most commonly used test method for the mechanical properties of concrete; the test is conducted after 7, 28, and 90 days, flexural strength or modulus of rupture may also be an interesting test for concrete components like pavements [9], [11],

[12], [13], [15]. Split tensile strengths may also provide other ways for studying the tensile properties of a specimen [1], [12], [19].

Various test protocols, including water absorption and porosity measurements, rapid chloride penetration test (RCPT), sulfate attack resistance, freeze-thaw cycling, and acid attack resistance, cover the test protocols for the durability assessment [1], [2], [13], [47]. To have a better insight into the fresh-state properties of WGPs, rheological tests, including viscosity, yield stress, thixotropy, etc., can be performed [10], [16].

3.2.2 Microstructural Analysis

Scanning electron microscopy (SEM) test wiaccompanying energy-dispersive X-ray spectroscopy is particularly useful for evaluating microstructural textures and provides crucial information on gel textures, pores, and interfacial transition zones [7], [12], [18], [25]. X-ray diffraction (XRD) for the identification of crystalline phases and to follow the course of the reaction by monitoring variations in amounts of amorphous content [17], [25], [50]. Fourier-transform infrared spectroscopy (FTIR) for the formation of chemical bonds and the geopolymerization process by monitoring variations in Si-O-Al and Si-O-Si bands [50].

3.2.3 Environmental Assessment

The main method for quantification of environmental impact conducted was through 'life cycle assessment,' as per ISO 14040/14044 guidelines [4], [40], [41], [43], [44], [44]. The majority of LCA studies have been conducted with 'cradle to gate' or 'cradle to grave' system boundaries, where various processes are considered, including the raw material, transportation, manufacturing, use, and end of life [4], [42], [44]. The assessed impact categories considered within LCA studies include global warming potential, energy, water depletion, depletion of the ozone layer, and impacts on human health [4], [42].

In the specific case of carbon footprint analysis, the focus will be exclusively on greenhouse emissions; the latter are normally calculated in terms of CO_2 equivalent per functional unit (per cubic meter or with a specific MPa compressive strength) [41], [42], [43].

3.3 Testing Protocols

Through standardized testing procedures, the reproducibility of results is facilitated. However, due to the complexity of the geopolymer systems, multiple types of waste materials used, and the various combinations of these, alternatives to standardized testing procedures were developed. The curing process was cited as a major factor that influenced the values of the properties of the geopolymer paste. Applications of ambient curing, oven curing conducted at 60°C to 80°C [19], [20], [25]. Curing temperature and duration significantly affect strength development, with elevated temperature generally accelerating reaction kinetics and improving early-age strength [19], [20].

Preparation of the samples depends on the type of materials involved. RAP can be subjected to treatments such as crushing, screening, and washing to remove extra asphalt. Alternatively, it can be subjected to as-received treatment based on the application [2], [35], [35]. CDW can be subjected to processes such as crushing, grinding, and sieving for particular size composition [8], [9], [49].

4. Key Findings and Comparative Analysis

4.1 Mechanical Performance

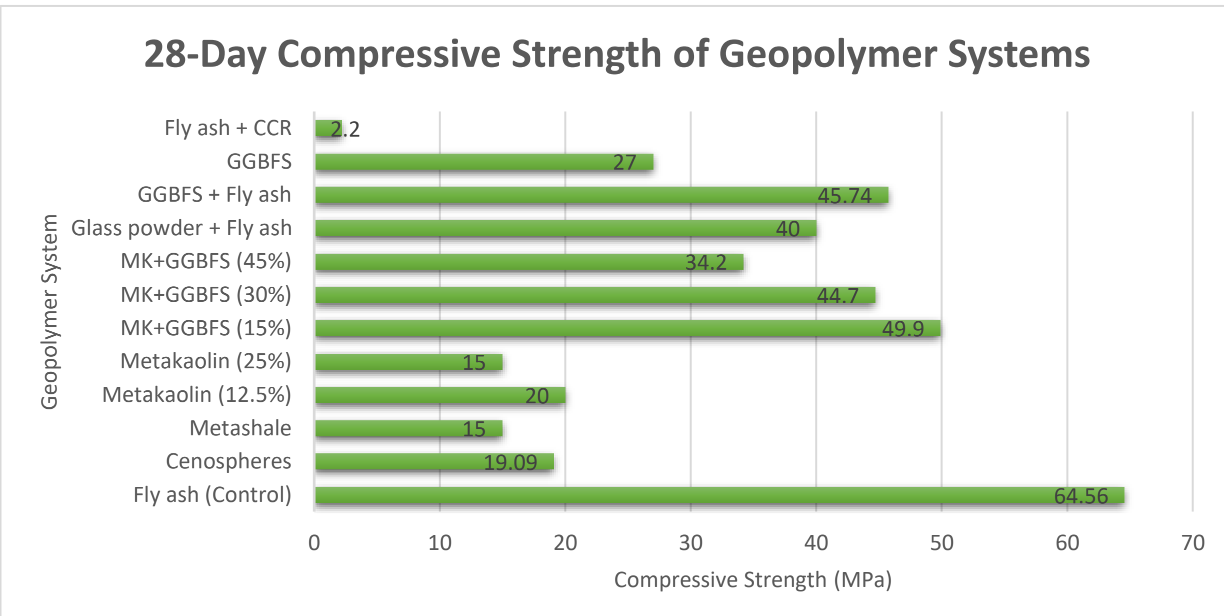
4.1.1 Compressive Strength

Compressive strength is the key measure of the performance of geopolymer mortars/concretes. A review of the literature indicates that the compressive strengths reported vary over a substantial range depending upon the mix design, the incorporation of wastes, and the curing conditions. The compressive strengths reported in the studies on representative waste incorporation strategies have been summarized in table 1 and the figure.

Table 1: Compressive Strength of Geopolymer Systems with Waste Incorporation

Precursor System	Waste Type	Replacement Level	28-Day Compressive Strength (MPa)	Reference
Fly ash	None (control)	0%	64.56	[4]
Cenospheres	None	0%	19.09	[4]
Metashale	Waste cementitious aggregate	~85%	15	[51]
Metakaolin	Recycled concrete aggregate	12.5%	20	[9]
Metakaolin	Recycled concrete aggregate	25%	15	[9]
MK+GGBFS	Waste red brick powder	15% binder	49.9 (30.7% increase)	[18]
MK+GGBFS	Waste red brick powder	30% binder	44.7	[18]
MK+GGBFS	Waste red brick powder	45% binder	34.2	[18]
Glass powder + Fly ash (1:3)	Waste glass	25%	40	[7]
GGBFS + Fly ash	Recycled asphalt waste	Fine aggregate	45.74	[2]
GGBFS	Brick demolition waste	10% sand + 6M NaOH	27	[8]
Fly ash + GGBFS	RAP coarse aggregate	50%	Meets PQC criteria	[35]
Fly ash + GGBFS	RAP coarse aggregate	100% (14M)	57.6% reduction	[35]
Fly ash	RAP stabilization	Various	Up to 32 (365 days)	[30]

Precursor System	Waste Type	Replacement Level	28-Day Compressive Strength (MPa)	Reference
Fly ash + GGBFS	Demolition waste fine aggregate	25-50%	Lower drop in properties	[12]
Slag	CDW fine aggregate	10-40%	20.73% increase at 10M NaOH	[15]
Fly ash + CCR	Waste mud solidification	Optimal ratio	2.2	[17]



Pure fly ash-based geopolymers without waste incorporation achieve the highest compressive strengths, with Tang et al. reporting 64.56 MPa for fly ash geopolymer and 6.03 MPa flexural strength [4]. However, the incorporation of waste materials generally reduces compressive strength, with the magnitude of reduction depending on waste type, replacement level, and mix optimization.

The incorporation level of recycled concrete aggregate (RCA) shows moderate reduction in strength. The RCA replacement level of 12.5%, 20 MPa compressive strength (35% reduction), 25% replacement level resulted in 15 MPa (50% reduction), and the RCA replacement level indicated that the primary cause of loss in compressive strength is porosity due to mortar films around the RCA particles, which inhibits alkali activation of precursor materials like metakaolin [9].

The incorporation of waste brick powder as a partial binder in geopolymer found promising results in its effect. Thus, an increase in strength of 30.7% with 15% waste red brick powder

(WRBP) replacing metakaolin and GGBFS to reach a value of 49.9 MPa. Though higher percentages of waste brick powder (30-45%) resulted in reduced strength to 44.7 and 34.2 MPa, respectively. The increase in strength at lower values of waste brick powder in geopolymer mixture can be attributed to enhanced geopolymerization reaction and gel structure [18].
The addition of RAP poses serious challenges to compressive strength: geopolymer concrete formed with 100% RAP coarse aggregate and 14 M NaOH exhibits a reduction of 57.6% in 28-day compressive strength relative to the control mixes. However, the strength requirements of PQC could be satisfied with the inclusion of only 50% RAP replacement, therefore encouraging its use in pavement applications. [35]. The presence of adhered asphalt binder on RAP aggregates creates weak interfacial zones, reducing load transfer efficiency [35], [38].
"Concentration of alkali activator plays a significant role in the development of strength." Rohit et al. found that the compressive strength increased by 20.73% for slag geopolymer mortars using CDW fine aggregate due to the increased molarity of NaOH from 2 M to 10 M [15]. Even though high molarity is required for increasing the compressive strength, it also causes quick setting, hence requiring optimization [6], [15].

4.1.2 Flexural and Tensile Strength
Flexural strength is of particular significance in pavements and structural properties. In this regard, literature suggests that flexural strengths are generally between ranges of 2.5 and 6.03 MPa for geopolymer materials [4], [11], [51]. Tang et al. achieved 6.03 MPa for fly ash-based geopolymer material, whereas cenosphere-based material showed a flexural strength of 3.13 MPa [4]. Moreover, according to Hotěk et al., flexural strength of alkali-activated metashale mortar with waste cementitious aggregate was approximately 2.5 MPa at 28 days [51].
Generally, the use of waste aggregates has an adverse impact on the flexural strength. Studies by Abuowda et al. reported a reduction in the flexural strength by 27%, caused by the addition of recycled fine aggregates to geopolymer masonry mortars [11]. Roy et al. reported that an increase in the proportion of brick sand leads to a corresponding decrease in flexural strength in GGBFS-based geopolymers [8]. Ghosh et al. reported a reduction of 39.7% in flexural strength after using 14 M-100% RAP-based geopolymers [35].
Split tensile strength characteristics are comparable to flexural strength. However, waste proportion reduction decreases tensile strength. But optimized mix design can ensure acceptable levels of tensile strength for some applications [1], [12], [19].

4.1.3 Durability Characteristics
Durability assessment involves a number of performance indicators such as water absorption, porosity, chloride penetration resistance, sulfate attack resistance, and freeze/thaw resistance. Information from literature indicates dynamic interactions between waste usage and durability.
Water absorption and porosity tend to increase as a result of the inclusion of waste aggregates due to higher porosity and water absorption of recycled materials [8], [11], [12]. Higher water absorption was observed as brick sand content increased in geopolymer mortars. However, capillary water absorption after 24 hours was still satisfactory [8]. Geopolymer binder showed an increase in sorptivity and abrasion resistance after incorporating 100% RFA in geopolymeric mortars [11].
Chloride penetration resistance shows interesting behavior with RAP incorporation. Ghosh et al. found that the presence of asphalt adhesions in RAP aggregates actually decreased porosity and increased resistance to chloride penetration [35]. The test results obtained from the Rapid Chloride Penetration Test (RCPT) also showed decreased chloride penetration rates with increased RAP levels because of their hydrophobic characteristics [35].
Sulphate resistance and freeze-thaw resistance of CDW-based geopolymer concretes show satisfactory results. According to a study conducted by Yıldırım, sulfate and freeze-thaw resistance of CDW-based geopolymer concretes did not induce a significant reduction in the

weight and compressive strength of the concretes [52]. However, drying shrinkage of the geopolymer concretes is high, leading to microcracks. Yet such microcracks can be reduced by incorporating fly ash and slag instead of CDW [52].

Acid attack resistance varies depending on the geopolymer system. Dokuzlar et al. assessed acid effect on alkali-activated mortars with recycled asphalt waste, finding acceptable durability performance [2]. The dense microstructure and low permeability of well-designed geopolymer systems contribute to acid resistance [2].

Long-term durability assessment still remains a critical research need. Goldoni et al. assessed the durability and mechanical long-term performance of alkali-activation-stabilized RAP, reaching up to 32 MPa unconfined compressive strength at 365 days [30]. It also showed performance even against seasonal humidity and temperature variation, hence indicating promising long-term stability [30].

4.1.4 Workability and Fresh Properties

Workability is a critical practical consideration for geopolymer mortar and concrete placement. The incorporation of waste materials significantly affects fresh-state properties through multiple mechanisms: particle shape and texture, water absorption, and chemical interactions [11], [16], [30].

Recycled fine aggregates typically reduce workability due to irregular particle shape, rough surface texture, and high water absorption [11], [12]. However, Abuowda et al. found that geopolymeric binder enhanced flow and water retention in masonry mortars with up to 100% RFA, partially compensating for the negative effects of recycled aggregates [11]. The setting time was reduced by up to 75% with geopolymeric binder, requiring adjustments to placement procedures [11].

Rheological characterization provides deeper insight into workability behavior. Mahmoodi et al. conducted comprehensive rheological analysis of geopolymer mortars with CDW-based precursors and aggregates, finding that all geopolymer mortars exhibited shear-thinning properties [10], [16]. Rheological parameters (flow, apparent and plastic viscosity, yield and shear stresses, thixotropy) generally increased with enhanced SiO_2/Al_2O_3 molar ratio [16]. Waste materials like ceramic tile powder as precursor and crushed brick aggregate enhanced rheological parameters due to higher specific surface area and particle irregularity [16].

4.2 Environmental Impact Assessment

4.2.1 Carbon Footprint Reduction

Life cycle assessment studies consistently demonstrate substantial carbon footprint reductions for geopolymer systems compared to Portland cement concrete. Table 2 summarizes carbon footprint and environmental impact data from representative LCA studies.

Table 2: Environmental Impact Assessment of Geopolymer Systems

System	Carbon Footprint Reduction	Energy Reduction	Key Findings	Reference
Fly ash geopolymer	49.7% GWP reduction vs OPC	-	23.7-41.6% human health benefit	[4]
Geopolymer pavement	50% CO2 reduction (total)	72% energy reduction	39% CO2 and 63% energy for 1 km pavement	[41]
Brown coal fly ash bricks	Substantial reductions in ozone, water, metal depletion	-	Primary impacts from raw material manufacturing	[42]
Reclaimed fly ash geopolymer	Potential overestimation if upstream impacts not accounted	-	Critical analysis of LCA boundaries	[43]
CDW bricks	Focus on CO2 emission parameters	-	LCA with reverse logic for CDW blocks	[45]

Tang et al. conducted comprehensive LCA on fly ash and cenosphere-based geopolymer materials, finding global warming potential (GWP) reductions up to 49.7% compared to ordinary Portland cement [4]. The study also identified benefits on human health damage category of 23.7% for fly ash geopolymer and 41.6% for cenosphere geopolymer [4]. Sodium silicate manufacture and industrial waste treatment (fly ash preparation) were identified as key factors affecting sustainability [4].

A simplified LCA of rigid pavements made with waste materials as binders showed that substitution of OPC with geopolymer binder resulted in a 50% reduction in total CO_2 emissions and a 72% reduction in energy consumption for the same application [41]. For a 1 km pavement section, a 39% reduction in CO_2 emission and 63% reduction in energy consumption were recorded using waste clay brick, fly ash, and slag [41].

Zhang et al. carried out an LCA study on geopolymer concrete bricks produced with brown coal fly ash. The impact of ozone depletion, water depletion, and metal depletion is significantly reduced compared to Portland cement bricks. The major environmental impacts were related to raw material manufacturing and use, which relate to the process optimization [42].

However, critical analysis by Danish et al. indicates that the footprint related to the reclaimed fly ash may even be overrepresented if appropriate consideration is not taken for the front-foot causes that are related to the reclaiming of the ash [43]. The study highlights the need for transparent LCA methods that also take into account the production of the alkali activator, the processing of the wastes, and the transportation impact.

4.2.2 Waste Utilization and Resource Conservation

The use of waste materials in geopolymer systems satisfies several environmental requirements: waste diversion from landfills, preservation of natural resources, and decrease in the level of environmental pollution from waste disposal [45], [46], [48], [52].

Construction and demolition wastes represent a huge waste stream globally. Hotěk et al. had attained about 85% utilization of input waste materials comprising crushed defective concrete products and waste concrete from auto-mixers in alkali-activated metashale mortar [51]. The high rate of waste utilization here underlines the potential geopolymer technology could have for badly reducing the disposal needs of CDW.

Reclaimed asphalt pavement utilization provides both environmental and economic benefits. Jagadish et al. noted that using RAP can cut costs associated with highway projects by 25-30% while providing sustainable and eco-friendly alternatives for road construction [32]. Widayanti et al. emphasized that RAP usage decreases RAP accumulation and reduces damage from mining or excavation of natural materials [33]. The reuse of RAP guarantees substantial optimization of non-renewable material resources, emissions reduction, and decreasing landfill space [34].

Industrial by-products utilization, particularly fly ash and slag, addresses waste management challenges in the power generation and steel industries. The global availability of fly ash exceeds 1 billion tonnes annually, with only a fraction currently utilized in construction applications [4]. Geopolymer technology provides a high-value application for these materials, transforming waste liabilities into construction assets [7], [53].

4.2.3 Life Cycle Assessment Methodologies

Comprehensive LCA according to ISO 14040/14044 standards is the most rigorous method for the environmental assessment[4], [40], [44]. Some methodological considerations:

System Boundaries: Cradle-to-gate analysis is limited to material production, while for cradle-to-grave analysis, use phase is also included with end-of-life scenarios as well [4], [42], [44].

Functional Unit: Selection of the appropriate functional unit is vital to enable effective comparison. Suitable functional units could be expressed on a per cubic meter basis in the concrete, per MPa of compressive strength, per square meter of pavement, or per unit of service life [4], [41], [42].

Impact Categories: The goal of the comprehensive LCA should be to investigate various impact categories rather than focusing exclusively on the carbon footprint, like energy consumption, water depletion, ozone depletion, acidification, eutrophication, toxicity, and resource depletion [4], [42], [44].

Allocation Methods: Allocation methods play an important role in multi-functional processes and waste materials. Economic allocation, mass allocation, and system expansion methods give different results [43].

Data Quality: The application and collection of primary data from real-world production processes, rather than secondary data from databases, are important for LCA accuracy and reliability. Transparency regarding data sources and assumptions is vital to conducting good and credible LCA studies [43].

A review by Saberian et al. illustrated LCA of waste materials used in concrete mix. This review emphasizes that "producing concrete causes impacts on the environment such as using natural aggregates and energy" [44]. This review emphasizes that LCA of waste materials such as recycled aggregate, fly ash, plastic, glass, rubber, etc., holds great importance [44].

4.3 Chemical mechanisms and microstructure

4.3.1 Geopolymerization Kinetics

The process of geopolymerization is a series of intricate chemical reactions that enable the formation of several polymeric networks. The process of geopolymerization occurs with the help of the mechanism of dissolution, speciation, gelation, reorganization, and polymerization [6], [7].

In low calcium environments (Class F fly ash), the main reaction product is the sodium aluminosilicate hydrate (N-A-S-H) gel, which is a three-dimensional polymeric structure made of linked SiO4 and AlO4 tetrahedrons, held together by shared oxygen atoms [7]. It can be represented by a generalized formula: Mn[-(SiO2)z-AlO2]n·wH2O, where M is the alkali ion, z is the silicon to aluminum molar ratio, and w is the water content [6].

High calcium systems such as slag and Class C FA also form calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H) hydrate gels instead of or along with (N-A-S-H) phases [17]. Wang et al. identified Calcium silicate hydrate (CSH) and aluminosilicate Na hydrate (NASH) are major hydrates responsible for the cementation process in fly ash-based geopolymer for waste mud solidification [17]. These gels fill pores and bond with particles to provide strength [17].

The existence of various gel phases in blended systems can sometimes be used synergistically. Sarkar et al. characterised the reaction product in waste glass powder and fly ash geopolymer systems as a type of calcium/sodium aluminate silicate hydrate (C/N-(A)-S-H) gel [7]. This proposed gel structure was verified in that research through SEM-EDS and 29Si MAS NMR analyses. The optimal ratio between glass powder and fly ash was 1:3, with 8 M NaOH [7].

Reaction kinetics are influenced by multiple factors: precursor reactivity, alkali activator concentration, silica modulus, liquid-to-solid ratio, curing temperature, and curing duration [6], [20], [32]. Rihan et al. investigated the effect of sugarcane bagasse ash addition and curing temperature on mechanical properties and microstructure of fly ash-based geopolymer concrete, demonstrating the importance of thermal activation [20].

4.3.2 Microstructure Development

Microstructural characterization demonstrates the intricate microstructure of geopolymer systems, from nanometer-scale gel microstructure to macrometer-scale pore structure. Scanning electron microscopy is used to inspect the microstructure of geopolymer. It highlights the morphology of the gel, unreacted particles, pore structure, and interfacial transition zones [7], [12], [18], [25].

Alghamdi et al. carried out a microstructure analysis, showing that there was an appreciable improvement in the geo-polymerization process, gel fraction, and surface morphology with WRBP additions [18]. The addition of 15% WRBP showed improvements to compressive and flexural strength due to improvements in gel fraction, whereas high WRBP additions showed reduced compressive and flexural strength due to dilution [18].

The interfacial transition zone, as well as the interfacial region between the aggregates and the geopolymer matrix, was recognized as playing a crucial role in enhancing the totality of the product's mechanical characteristics and service life. According to research findings by Manzi et al., it is suggested that when dealing with RCA, the effect of the adhered mortar that is present on the surface led to an increase in porosity and competitive reactions, which compromised the alkali activation potential inside metakaolin, thereby affecting the end product's strength attained [9].

RAP incorporated using RAP technology leads to specific microstructural characteristics and adhered asphalt content within RAP aggregate. The amount of adhered asphalt content decreases porosity and increases chloride resistance [35]. Micro structural analysis and the use of solid-state NMR were critical tools for determining the behavior of the incorporated matrix content, where porosity and water absorption decreased with increasing molarity and RAP content [35].

The characteristics of the pore structure greatly influence the mechanical properties and durability. Research on lightweight geopolymer composites using brick waste and different CDWs has been characterized using XRD and SEM techniques [25].

4.3.3 Phase Formation and Characterization

The analysis done using X-ray diffraction (XRD) reveals the crystalline phases created, based on the percentage of amorphous material that transforms into crystalline material, tracking the process of geopolymerization. Udvardi et al. characterized geopolymer from waste used in construction, demolition, and industrial activities using FTIR to reveal new phases and SEM for further microscopic analysis [50]. The use of aluminum dross formed foamed geopolymer, which is a result of the chemical properties of the wastes used in the production of geopolymer [50].
Fourier-transform infrared spectroscopy (FTIR) formation of chemical bonds and the geopolymerization process. As geopolymerization occurs, the vibration absorption peaks of Si-O-Al bonds and Si-O-Si bonds shift to the lower wavenumber region due to increased polymerization reactions and gel formation [50].

4.3.4 Influence of Waste Materials on Chemical Mechanisms

The incorporation of waste materials introduces chemical complexity that affects geopolymerization mechanisms. Mahmoodi et al. found that waste materials, such as ceramic tile powder used as a precursor and brick aggregate, have improved rheological properties due to the increased specific surface area and surface irregularities. Non-colloidal frictional interactions and colloidal flocculation contribute to improved thixotropy in the initial geopolymeric gelation process. The ceramic tile, brick, and glass waste materials [16].
Brick-based demolition waste haspozzolanic activity attributable to their aluminosilicate composition originating from fired clay products. In addition, Roy et al. successfully proved the complete applicability of brick-based demolition wastes for geopolymer mortar and concrete, however, water absorption increases with brick sand content[8]. The reactive nature of brick powder contributes to gel formation when used as a partial precursor replacement [8], [18].
Glass waste incorporation provides additional silica for geopolymerization. Sarkar et al. found that glass powder initially acts as an inert filler with slow reaction kinetics, but later contributes to significant strength improvement through reaction with fly ash [7]. The optimal glass powder to fly ash ratio of 1:3 balances reactivity and gel formation [7].
Ceramic waste demonstrates high reactivity due to its aluminosilicate composition and amorphous content. Rashad et al. investigated valorization of ceramic waste powder for compressive strength and durability of fly ash geopolymer cement, finding beneficial effects on mechanical properties [54].
RAP incorporation presents unique chemical challenges. The presence of aged asphalt binder affects interfacial bonding and may release organic compounds that interfere with geopolymerization [2], [13], [38]. However, the mineral aggregates within RAP can participate in alkali activation if the asphalt coating is sufficiently thin or partially removed [37], [38].

4.4 Geographic and Application Contexts

4.4.1 Regional Studies and Climate Considerations

The literature studied is quite diversified in the sense that they cover various geographical regions, which have distinct availability of materials, climatic conditions, and modes of construction. Table 3 and figure given below:

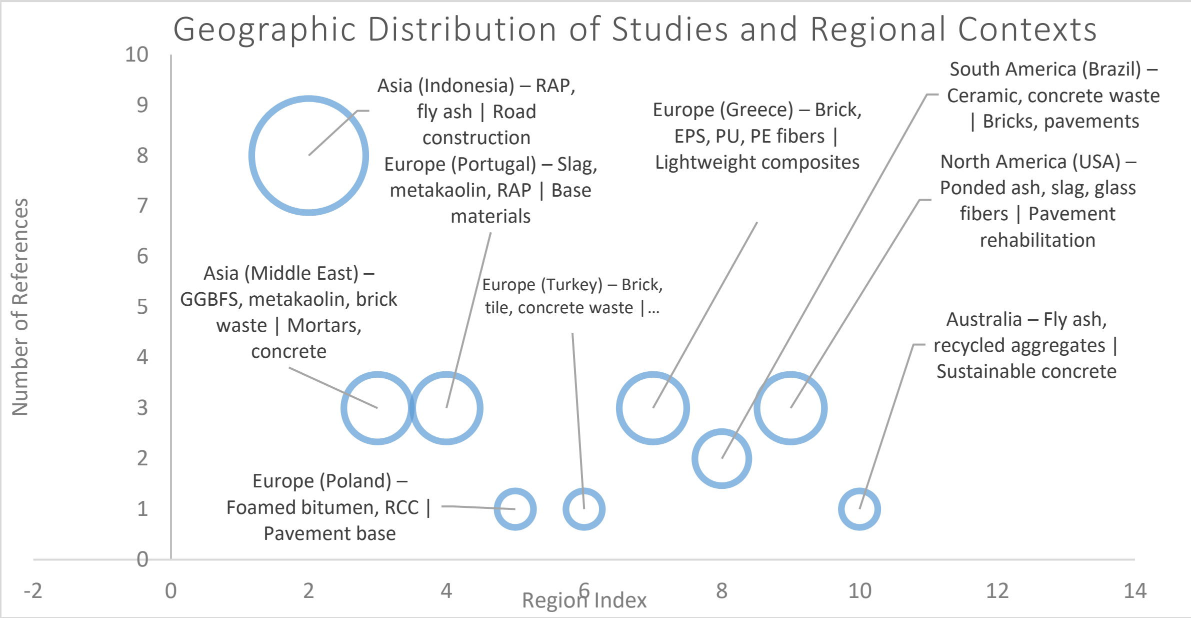


Table 3: Geographic Distribution of Studies and Regional Contexts

Region	Representative Studies	Key Materials	Climate Considerations	Applications	References
Asia (India)	Multiple studies	Fly ash, GGBS, CDW, RAP	Hot, humid, monsoon	Pavements, structural concrete	[1], [12], [15], [31], [32], [36], [55], [56]
Asia (Indonesia)	RAP characterization	RAP, fly ash	Tropical	Road construction	[33], [57], [58]
Asia (Middle East)	Waste brick powder	GGBFS, metakaolin, brick waste	Hot, arid	Mortars, concrete	[13], [18], [38]
Europe (Portugal)	RAP-slag systems	Slag, RAP, metakaolin	Temperate	Base materials	[29]
Europe (Poland)	Reclaimed cement concrete	Foamed bitumen, RCC	Continental	Pavement base	[59]

Region	Representative Studies	Key Materials	Climate Considerations	Applications	References
Europe (Turkey)	CDW geopolymers	Brick, tile, concrete waste	Mediterranean	Structural applications	[2], [27], [52]
Europe (Greece)	CDW composites	Brick, EPS, PU, PE fibers	Mediterranean	Lightweight composites	[25], [60]
South America (Brazil)	CDW bricks, RAP	Ceramic, concrete waste	Tropical, subtropical	Bricks, pavements	[45], [61], [62]
North America (USA)	Full depth reclamation	Ponded ash, slag, glass fibers	Varied	Pavement rehabilitation	[37]
Australia	Recycled aggregate GPC	Fly ash, recycled aggregates	Varied	Sustainable concrete	[46]

Asian studies, particularly from India, dominate the literature on geopolymer systems with waste incorporation. This reflects both the large-scale availability of fly ash from coal-fired power plants and the pressing need for sustainable construction materials in rapidly developing regions [1], [12], [32], [56]. Indian studies have extensively investigated fly ash-GGBS blends with CDW and RAP for pavement and structural applications [12], [15], [36].

Indonesian research focuses on RAP characterization and utilization in asphalt concrete, reflecting the country's extensive road network and maintenance requirements [33], [36], [58]. Widayanti et al. conducted multiple studies on physical and mechanical properties of asphalt concrete containing RAP from national roads in East Java Province [33], [58]. The tropical climate presents unique challenges for asphalt durability, making RAP recycling particularly attractive [33].

Middle Eastern studies have explored waste brick powder incorporation in alkali-activated systems, leveraging the abundance of brick waste from construction activities [13], [18], [38]. Alghamdi et al. investigated strength performance and microstructures of alkali-activated metakaolin and GGBFS-based mortars with waste red brick powder, achieving significant strength improvements [18]. The hot, arid climate of the region influences curing strategies and durability requirements [38].

European research demonstrates geographic diversity, with studies from Portugal, Poland, Turkey, and Greece addressing region-specific materials and applications [2], [24], [25], [27], [29], [59], [60]. Turkish studies have extensively investigated CDW-based geopolymers for structural applications, with Yıldırım conducting comprehensive durability assessments [27], [47]. Greek research has focused on lightweight geopolymer composites combining various CDW streams for thermal insulation applications [25], [60].

South American studies, particularly from Brazil, have investigated CDW bricks and RAP recycling in the context of tropical and subtropical climates [45], [61], [62]. Surgelas et al. developed life cycle inventory for ceramic brick, concrete block, and CDW brick in Belo Horizonte, providing regional LCA data [45].

The researchers of North America have also identified full depth reclamation of asphalt pavements by utilizing geopolymer-based stabilization, particularly considering the significant infrastructure of pavement and the associated maintenance [37].

Australian researchers were at the forefront of developing sustainable concrete technologies that use fly ash geopolymer concrete with recycled aggregate materials, both the environment and the lack of resources in Western Australia [46].

4.4.2 Application-Specific Considerations

The reviewed literature encompasses diverse applications, each with specific performance requirements and constraints:

Pavement Applications: Geopolymer concrete for pavements requires high compressive strength (>30 MPa), adequate flexural strength (>4 MPa), good durability, and resistance to environmental stresses [13], [37], [39], [46]. Ghosh et al. demonstrated that RAP-inclusive geopolymer concrete with 50% RAP met Pavement Quality Concrete (PQC) strength criteria [13]. Tiyasangthong et al. investigated the stabilization of recycled concrete aggregate using a high calcium fly ash-based geopolymer as pavement base material [63]. Rahman et al. conducted a study on mechanical and durability properties of roller compacted geopolymer concrete using RAP [39].

Masonry Mortars: Geopolymer masonry mortars require adequate workability, bond strength, and durability while maintaining cost-effectiveness [11], [49]. Abuowda et al. in their study on geopolymer-based masonry mortars containing RFAs, concluded that incorporating RFAs in geopolymeric binder enhances flow and retention of water despite 100 % RFA usage in the mix [11]. Miraldo et al. developed a design of a fly ash-based AA mortar containing waste glass and different CDW aggregates in order to optimize the compressive strength [49].

Structural Concrete: Structural applications demand high compressive strength, adequate tensile/flexural strength, controlled shrinkage, and long-term durability [9], [12], [14], [47]. Arumugam et al. conducted experimental study on fly ash-GGBS-based geopolymer concrete with demolition waste as fine aggregate, finding that 25-50% replacement showed acceptable performance [12]. Alhawat et al. studied influencing parameters in developing CDW-based geopolymer concretes and their sustainability assessment [14].

Base and Subbase Materials: Pavement base applications require adequate bearing capacity, stiffness, and durability under repeated loading [30], [37], [48], [64],[65]. Goldoni et al. investigated durability and the mechanical long-term performances for pavement bases made of RAP by means of alkali activation, showing a maximum strength up to 32 MPa after 365 days [30]. Doan et al. researched the possibilities for pavement bases by using chemical stabilization of demolition wastes with one-part fly ash and slag-based geopolymers [65]. Hidalgo et al. evaluated ground improvement by CDW soil mixture replacement, finding increased strength and resilient modulus [64].

Lightweight Composites: Lightweight applications require low density, thermal insulation and sufficient mechanical properties. Kioupis et al. fabricated lightweight geopolymer composites with various CDW streams, which reached the value of 1.0-2.1 g/cm3 in densities, whereas their compressive strength varied in the wide range 6.5-22.8 MPa [25].

Waste Solidification: Geopolymer technology shows potential in the solidification and stabilization of hazardous wastes [17]. Wang et al.

investigated the mechanical properties and microstructure of the fly ash-based geopolymer used in the solidification of waste mud. The results showed 2.2 MPa of geopolymer strength with reduction in water content [17].

5. Discussion

5.1 Critical Analysis of Current State

The body of literature reviewed demonstrates substantial progress in understanding and implementing ash-based geopolymer systems with waste incorporation. However, critical analysis reveals several important considerations and limitations.

Performance Variability: A significant challenge is the high variability in reported mechanical properties across studies. Compressive strengths range from 2.2 to 64.56 MPa depending on precursor selection, waste type and content, alkali activator design, and curing conditions [4], [7], [7], [9], [12], [15], [17], [35], [66]. This variability reflects both the diversity of material systems and the lack of standardized mix design protocols. While this flexibility allows optimization for specific applications, it complicates comparative assessment and technology transfer.

Waste Material Heterogeneity: The heterogeneous nature of CDW and RAP presents fundamental challenges for consistent performance [14], [27]. Unlike industrial by-products like fly ash and slag, which have relatively consistent composition within a given source, CDW composition varies significantly depending on demolition source, age of structures, and regional construction practices [6], [8]. This heterogeneity necessitates robust characterization protocols and potentially adaptive mix design strategies.

Optimal Incorporation Levels: The literature reveals clear trends in optimal waste incorporation levels. For most waste types, replacement levels of 10-30% as precursor or 25-50% as aggregate maintain acceptable mechanical properties while achieving sustainability benefits [9], [12], [15], [18], [49]. Higher replacement levels (>50%) generally result in significant strength reductions, though some applications (e.g., lightweight composites, base materials) may tolerate lower strengths [25], [65]. This suggests that complete replacement of virgin materials may not be feasible for high-performance applications, requiring balanced approaches.

Alkali Activator Optimization: The concentration and composition of alkali activators critically influence both performance and sustainability. While higher NaOH molarities (10-14 M) generally improve mechanical properties [15], [35], they also increase chemical consumption, cost, and environmental impacts [43]. The production of sodium silicate, in particular, is energy-intensive and contributes significantly to the carbon footprint of geopolymer systems [4]. This highlights the need for activator optimization that balances performance, cost, and environmental objectives.

Microstructure-Property Relationships: Advanced microstructural characterization has revealed complex relationships between gel composition, pore structure, and macroscopic properties [7], [13], [18], [66]. The coexistence of multiple gel phases (N-A-S-H, C-S-H, C-A-S-H) in blended systems provides opportunities for tailoring properties, but also increases system complexity. The interfacial transition zone between waste aggregates and geopolymer matrix emerges as a critical factor affecting mechanical properties and durability [9], [13].

Environmental Assessment Rigor: While LCA studies consistently demonstrate environmental benefits of geopolymer systems, recent critical analyses highlight the importance of comprehensive system boundaries and transparent methodologies [43]. The environmental benefits may be overstated if upstream impacts of alkali activator production and waste material processing are not properly accounted for [43]. This underscores the need for standardized LCA protocols specific to geopolymer systems.

5.2 Challenges and Limitations

Several significant challenges and limitations constrain the widespread adoption of ash-based geopolymer systems with waste incorporation:

Standardization Gap: The absence of global standards for the mix design, testing, and quality control of geopolymer mixtures is considered to be a significant barrier in their commercialization [5], [6]. Although there are some local standards, in the global construction industry, no comparable standards exist, similar to those established and followed in Portland cement.

Long-Term Performance Data: Most of the literature is on 28-day or 90-day properties, and long-term performance data is limited [30]. Goldoni et al. have provided important 365-day data on the stabilization of RAP materials [30], So far, data over several years or decades, especially on real-world exposure, especially under combined stresses, is scarce.

Workability and Placement: Fresh-state properties of geopolymer systems with waste incorporation present practical challenges. Rapid setting, reduced workability, and sensitivity to mixing procedures complicate field placement [6], [11], [15]. While rheological studies have advanced understanding [10], [16], practical solutions for large-scale placement remain underdeveloped.

Efflorescence and Aesthetics: Alkali-activated material can also experience efflorescence, which is a white crystalline deposit that often occurs on material surfaces [6]. It is attributed to the migration of unreacted alkali to the surface, and while esthetically undesirable, this phenomenon also has implications for material durability. Efflorescence limits the design applications in which this material can be utilized.

Shrinkage and Cracking: Drying shrinkage in geopolymer systems, particularly those with high alkali content or low calcium content, can exceed that of Portland cement concrete [52]. Yıldırım found that drying shrinkage was high in CDW-based geopolymer concretes, causing microcracks [52]. Shrinkage control through mix design optimization and curing protocols requires further research.

Supply Chain and Logistics: The utilization of locally available waste materials offers sustainability benefits but creates supply chain challenges. CDW and RAP availability varies seasonally and geographically, potentially affecting production consistency [14]. Establishing reliable supply chains for waste materials, including collection, processing, and quality control, requires infrastructure development.

Economic Competitiveness: While geopolymer systems offer environmental benefits, economic competitiveness with Portland cement remains a challenge in many markets. The cost of alkali activators, particularly sodium silicate, can offset savings from waste material utilization [4], [43]. Economic viability depends on local material costs, carbon pricing policies, and regulatory incentives for sustainable construction.

Knowledge Transfer: Translating research findings into practice requires effective knowledge transfer to industry practitioners. The complexity of geopolymer systems, with multiple interacting variables, presents a steeper learning curve than conventional concrete technology. Educational programs, technical guidelines, and demonstration projects are needed to facilitate adoption.

5.3 Opportunities and Innovations

Despite challenges, the field presents significant opportunities for innovation and advancement:

One-Part Geopolymers: One-part or "just add water" geopolymer systems, where dry precursors and solid alkali activators are pre-blended, offer improved practicality for field applications [65]. Doan et al. investigated one-part fly ash and slag based geopolymers for chemical stabilization of demolition wastes in pavement bases [65]. This approach simplifies mixing, improves safety, and facilitates adoption by conventional concrete producers.

Hybrid Systems: Hybrid systems combining geopolymer binders with small amounts of Portland cement or lime offer potential for optimizing performance, cost, and practicality [26]. Díaz et al. found improved strength of alkali activated materials based on CDW with addition of rice husk ash [26]. Such hybrid approaches may provide transition pathways toward fully geopolymer-based systems.

Advanced Characterization: Emerging characterization techniques, including in-situ monitoring of geopolymerization kinetics, advanced imaging methods, and machine learning-based property prediction, offer opportunities for deeper understanding and optimization [7], [13]. The integration of computational modeling with experimental validation can accelerate mix design development.

Functional Properties: Beyond mechanical performance, geopolymer systems offer opportunities for functional properties including fire resistance, thermal insulation, acoustic absorption, and electromagnetic shielding [25], [60]. Giannopoulou et al. investigated mechanical behavior of CDW-based alkali activated materials exposed to fire conditions, demonstrating excellent fire resistance [60]. Lightweight geopolymer composites developed by Kioupis et al. showed promising thermal insulation properties [25].

Circular Economy Integration: Geopolymer technology aligns well with circular economy principles, offering pathways for multiple waste stream valorization [8], [16], [25], [66]. Liang et al. investigated synthesis of geopolymers using municipal solid waste incineration fly ash and CDW, demonstrating feasibility of combining diverse waste streams [66]. This multi-waste approach maximizes resource efficiency and environmental benefits.

Digital Technologies: The integration of digital technologies, including Building Information Modeling (BIM), Internet of Things (IoT) sensors, and artificial intelligence, offers opportunities for optimizing waste material utilization and quality control [67]. Wu et al. reviewed intelligent technologies in CDW management, proposing implementation frameworks [67]. These technologies can enhance traceability, quality assurance, and decision-making throughout the material lifecycle.

Policy and Regulatory Support: The increasing focus on carbon reduction, the circular economy, and green construction is also opening favorable avenues for the uptake of geopolymer technology [48]. Llatas et al. studied the environmental impact assessment of the recycling and disposal scenarios of CDWs using LCA-BIM tools to support the design stage [48]. Such tools can drive policy decisions and incentivize sustainable material choices.

Geographic Expansion: While current research concentrates in certain regions, opportunities exist for geographic expansion to areas with abundant waste materials and pressing sustainability needs [46], [53]. Esparham et al. discussed features of geopolymer concrete as a novel approach for utilization in green urban structures [53]. Urban applications in rapidly developing regions offer particularly promising opportunities.

6. Future Research Directions

Based on the comprehensive review and critical analysis, the following research directions are recommended to advance the field:

6.1 Standardization and Protocol Development

Priority: Develop comprehensive standards for geopolymer mix design, testing, and quality control specific to waste-incorporated systems. This should include:

- Standard test methods adapted to geopolymer chemistry and kinetics
- Mix design guidelines for different waste types and applications
- Quality control protocols for heterogeneous waste materials
- Performance specifications for various applications (pavements, structural, masonry)

6.2 Long-Term Durability Assessment

Priority: Conduct multi-year field exposure studies and accelerated aging tests to establish long-term durability performance. Focus areas include:

- Combined environmental stresses (freeze-thaw, sulfate, chloride, carbonation)
- Seasonal and climatic variations across different geographic regions
- Structural health monitoring of demonstration projects
- Service life prediction models validated with long-term data

6.3 Waste Material Characterization and Classification

Priority: Develop robust characterization protocols and classification systems for CDW and RAP to enable consistent performance prediction. Research needs include:

- Rapid characterization methods for heterogeneous waste streams
- Correlation between waste material properties and geopolymer performance
- Quality thresholds for different waste types and applications
- Adaptive mix design strategies for variable waste composition

6.4 Alkali Activator Optimization and Alternatives

Priority: Optimize alkali activator systems to balance performance, cost, and environmental impacts. Investigate alternative activators with lower environmental footprint. Research directions include:

- Low-molarity activation strategies
- Alternative alkali sources (industrial by-products, waste-derived alkalis)
- One-part geopolymer formulations for practical applications
- Activator recovery and recycling strategies

6.5 Microstructure Engineering

Priority: Advance understanding of microstructure-property relationships to enable rational design of geopolymer systems. Focus areas include:

- Multi-scale modeling from molecular to macroscopic levels
- Interfacial engineering for improved waste aggregate bonding
- Pore structure optimization for durability and functionality
- In-situ monitoring of geopolymerization kinetics

6.6 Fresh-State Properties and Workability

Priority: Develop practical solutions for workability, placement, and finishing of geopolymer systems with waste incorporation. Research needs include:

- Rheology modifiers and admixtures compatible with alkali activation
- Placement techniques and equipment adapted to geopolymer characteristics
- Setting time control strategies for field applications
- Finishing methods for aesthetic and functional surfaces

6.7 Comprehensive Life Cycle Assessment

Priority: Conduct rigorous, transparent LCA studies with comprehensive system boundaries and sensitivity analyses. Research directions include:

- Standardized LCA protocols for geopolymer systems
- Regional LCA databases for waste materials and alkali activators
- Dynamic LCA accounting for temporal variations in electricity grid carbon intensity
- Social LCA incorporating labor, health, and community impacts

6.8 Multi-Waste Stream Integration

Priority: Investigate synergistic combinations of multiple waste streams to maximize resource efficiency and environmental benefits. Focus areas include:

- Ternary and quaternary precursor blends
- Combined use of waste precursors and waste aggregates
- Integration of emerging waste streams (e.g., solar panel waste, wind turbine blades)
- Optimization algorithms for multi-waste systems

6.9 Application-Specific Development

Priority: Develop application-specific formulations and guidelines for key market segments. Priority applications include:

- High-performance pavement concrete with RAP
- Precast elements with CDW aggregates
- 3D-printable geopolymer mortars with waste incorporation
- Repair and rehabilitation materials
- Specialty applications (fire-resistant, thermal insulation, acoustic)

6.10 Economic and Policy Analysis

Priority: Conduct comprehensive economic analyses and policy studies to facilitate market adoption. Research needs include:

- Life cycle cost analysis including externalities
- Business models for waste collection, processing, and utilization
- Policy instruments to incentivize geopolymer adoption
- Market barriers and enablers analysis
- Technology transfer and capacity building strategies

6.11 Digital Integration and Smart Manufacturing

Priority: Integrate digital technologies for optimized production, quality control, and performance monitoring. Research directions include:

- Machine learning models for property prediction and mix design optimization
- IoT-enabled quality control and process monitoring
- Digital twins for performance prediction and lifecycle management
- BIM integration for sustainable material selection and waste tracking

6.12 Climate Adaptation and Resilience

Priority: Investigate performance of geopolymer systems under climate change scenarios and extreme weather conditions. Focus area further includes:

- High-temperature performance in warming climates
- Moisture resistance in regions with changing precipitation patterns
- Freeze-thaw resistance in areas with variable winter conditions
- Resilience to extreme events (flooding, hurricanes, wildfires)

7. Conclusions

This comprehensive review article based on 67 peer-reviewed publications from 2015 to 2026 links readers to a thorough overview of existing knowledge around ash-based geopolymer mortar systems using alternative sustainable cements, namely, wastes from building demolitions and reclaimed asphalt pavement. The key findings from existing knowledge around the subject are:

1. Mechanical Performance: The optimized level of waste inclusion within the geopolymer mix (25-50%), in replacing cement content, can provide compressive strengths ranging from 15 to 64 MPa for pavement-quality concrete to structural concrete members. Fly ash-based geopolymer mix systems produce the highest compressive strength, 64.56 MPa, whereas the inclusion of wastes results in a loss in compressive strength ranging from 20 to 50% depending on the type of wastes used in the mix. The strategic inclusion of waste brick powder, i.e., 15%, results in an enhancement in compressive strength up to 30.7% due to geopolymerization improvements. The durability results are generally acceptable, but some wastes, e.g., RAP, surprising result in the enhancement of chloride resistance.

2. Environmental Benefits: In every life cycle assessment of these types of systems, the benefits to the environment were tremendous, including the reduction of the carbon footprint by 40 to 72 percent and energy consumption by as much as 72 percent less than those of the Portland cement systems. For infrastructure applications, like the paving of structures of 1 km, the reduction of the CO2 emissions is by 39 percent, while the energy consumption is by 63 percent. Hence, the waste can be put to use to the extent of 85 percent, thus salvaging millions of tonnes of the waste that otherwise would have gone to landfills, hence the usage of the natural resources. It is, however, important to note that the entire life cycle assessment also includes the consideration of some key issues, like the preparation of the alkali activators or the process of the waste, to avoid the overestimation of the advantages of the eco-friendly process.

3.Chemical Mechanisms: The geopolymerization process is a bit intricate in the case of the dissolution-polycondensation reaction, and the type of gel forms is determined by the chemical composition of the precursors, e.g., N-A-S-H, C-S-H, or C-A-S-H. However, the blended binders might contain more than one type of gel, leading to multiple synergistic effects. Waste materials influence the reaction rate and the evolution of microstructure based on the chemical composition, particle characteristics, and properties of the particle surfaces. Alkali activator concentration varies from 2 to 14 M NaOH and has a dominant influence on reaction rate, the development of the gel phase, and mechanical properties.

4. Geographic and Application Diversity: There are successful case studies where this technology has successfully been implemented with different geography locations like Asia, Europe, Americas, and even Australia, as well as different climate conditions like tropical, desert, continental, and temperate environments, among others. The types of materials that are being used range from pavement quality concrete/base materials, mortars for masonry, structural concrete, composites, and many more.

5. Critical Challenges: Currently, the key problems confronting the mix design of these wastes include the following:

a. the high variability of the wastes in composition requires excellent characterization and the need to make mix design more flexible.

b. there is a lack of standards for mix design, test methods, and quality control.

c. the durability of the mix is only proven for up to 1-2 years.

d. the mix experiences difficulties in workability and placing due to the fast setting and low flow.

e. the mix is at risk for the development of dry shrinkage and efflorescence.

f. the mix is not economically competitive with the traditional portland cement mix in some markets.

g. knowledge transfer.

7. Path Forward: The successful transfer of the success in ash-based geopolymer technology with incorporation of waste from a research/development level in the laboratory environment to the industry can be ensured through various measures from different angles and perspectives like technology development through more R&D by conducting research in the field, standardization and formulation of regulations, execution projects, economic facilitation measures, education/capacity building in the concerned field, and formulation of separate supply chains regarding waste materials. The convergence of driving needs, technological readiness, and regulation can be seen as a driving factor that can ensure fast-tracking in the upcoming years.

In conclusion, the ash-based geopolymer mortar system involving building demolition wastes and reclaimed asphalt pavements possesses the ability to open the gates to a sustainable future owing to the availability of the benefits associated with its utilization despite the challenges that can hamper its utilization. Specifically, the degree of benefits that the utilization of ash-based geopolymer mortar has to offer is quite impressive. To be specific, the process aligns itself with the principles of the circular economy.

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