

## Feasibility of Using Recycled Materials in Construction Materials

Md Monir Hossain 

*Shandong University of Technology, China*

Prodhan Md Safiq Raihan 

*Hobai University, China*

Mithun Biswas 

*Hobai University, China*

Mahnoor Rizwan 

*Hobai University, China*

Aqib Ali 

*Department of Civil Engineering, Hobai University, China*

### Suggested Citation

Hossain, M.M., Raihan, P.M.S., Biswas, M., Rizwan, M., & Ali, A. (2024). Feasibility of Using Recycled Materials in Construction Materials. *European Journal of Theoretical and Applied Sciences*, 2(3), 1082-1107.  
DOI: [10.59324/ejtas.2024.2\(3\).87](https://doi.org/10.59324/ejtas.2024.2(3).87)

### Abstract:

The increasing amount of solid waste has become a significant environmental issue that has garnered significant attention and concern. In an effort to mitigate the adverse effects commonly associated with prominent sectors and simultaneously promote credibility in the energy- and resource-intensive realms of development and construction, significant endeavors have been directed towards competitive areas of strength for the purpose of recycling, with the ultimate goal of utilizing such materials in sustainable development products. The present study provides an overview of the ongoing evaluations pertaining to the utilization of

conventional and enhanced solid waste for the production of geo-polymer composites. Great attention is devoted to the implementation of these geo-polymer composites. The primary findings of this study revealed that both ordinary and sophisticated solid waste have the potential to be integrated into geo-polymer composites in various forms, such as precursor, complete, additive, reinforcement fiber, or filler material. The findings indicate that the utilization of such waste may have a negative impact on certain properties of geo-polymer composites. However, this issue can be mitigated through the implementation of an open degree plan and appropriate treatment techniques, which can facilitate the recycling process. In conclusion, a concise discourse is presented to acknowledge the significant need for future research and enhancement in advancing the utilization of solid waste materials in the emerging sustainable geo-polymer industry. This study proposes an improved ecological solution for managing municipal and industrial solid waste by transforming waste materials into environmentally friendly construction materials with consistent properties. Special attention is given to the overall performance of geo-polymer composite products. The primary findings of this study reveal that urban and industrial solid waste can be efficiently incorporated into geo-polymer composites through the use of precursors, aggregates, additives, reinforcing fibers, or filler materials. The results indicate that while the inclusion of waste materials may negatively impact certain properties of geo-polymer composites, a well-designed protocol and effective treatment approach can mitigate these adverse effects and facilitate the recycling process.

Finally, a brief dialogue is presented to differentiate the key needs in forthcoming research and development aimed at enhancing the utilization of solid waste materials in the upcoming sustainable geopolymer sector. This study provides guidance for the sustainable management of urban waste by transforming waste materials into environmentally friendly construction materials.

**Keywords:** *Recycled materials, Solid waste materials, Construction materials.*

## Introduction

Global population growth, a booming economy, and rapid urbanization have all significantly sped up the production of solid waste. Solid waste generation globally has recently approached 17 billion tons per year, and by 2050, it is anticipated to reach 27 billion tons (Laurent, et al., 2014). This issue ought to be of significant concern to all nations, communities, and individuals since it has the potential to gravely impact ecosystems, natural resources, and human health. As a result, employing green chemistry and technology for environmental sustainability has become more popular in recent years. Most importantly, the outdated notion that garbage is treated as pollution is slowly giving way to the new notion that waste is treated as a resource. This undoubtedly helps.

To get civilization closer to sustainability. As an illustration, the energy produced in a few thermal processes of waste materials might lessen the demand for conventional energy producing techniques. Some solid waste items, such paper, plastic, and metal, can be recycled or utilized again, just like it can protect the source of the linked virgin resources. This scenario has prompted an extensive study on the manufacture of construction materials from recycled solid waste (Gomes, et al., 2019). These programs seek to lessen both the volume of solid waste produced and the expanding demand for natural resources in the construction industry. In the past, this industry has had some impressive accomplishments. For instance, Huang, et al. (2007) investigated the efficient use of solid waste materials (such as waste tires, waste glass, steel slag, plastics, etc.) for the building of asphalt pavements. Meng (2018) summarized the research on the use of recycled materials in concrete block buildings, including waste glass,

crushed brick, recycled concrete, ceramic waste, and tile waste. Luhar, Cheng, & Luhar, (2019b) discussed the possible use of several forms of aquacultural and agricultural farming waste as supplementary components in concrete.

Additionally, there have been a number of exciting advancements achieved in the creation of geopolymer composites using solid waste. As a substitute for conventional Portland cement (OPC), alkali-activated material, also known as geopolymer, is typically created by the chemical reaction of aluminosilicate precursor materials with alkaline activators (Provis, 2013). Academic research has witnessed the rapid growth of geopolymer over the past three decades as a result of its exceptional performance in a number of industries. Numerous studies Provis, 2013; Tang 2019b have shown that geopolymer has outstanding mechanical properties in addition to other inherent traits like improved durability, the ability to immobilize dangerous contaminants, and even intelligence. Geopolymer is also distinguished by low greenhouse gas emissions, low energy consumption, and reuse of waste materials, all of which are critical for the long-term sustainability of the architecture and construction sectors Hassan, et al. (2019). Therefore, incorporating solid waste as a component in geopolymer composites would unquestionably result in a greener and more sustainable construction material. Municipal, industrial, construction, and agricultural solid wastes account for the bulk of solid trash (Hoornweg, & Bhada-Tata, 2012). There is a wealth of information in the literature about the use of solid waste, such as industrial and agricultural waste, in the creation of geopolymer composites.

Therefore, the collecting and analysis of earlier achievements in producing geopolymer

composites from construction and municipal solid waste is the main emphasis of this research. The benefits and drawbacks of these geopolymer composites, which include construction and municipal solid waste, are also evaluated. The overall goal of this research is to offer a scientific foundation for the future development of very environmentally friendly geopolymer composites.

## Background

The construction industry plays a vital role in the development of infrastructure and built environments, contributing to economic growth and societal progress. However, this industry is also associated with significant environmental challenges, including high resource consumption, energy consumption, and waste generation. The extraction and production of raw materials used in construction have substantial environmental impacts, leading to resource depletion and greenhouse gas emissions. As the global population continues to grow and urbanization accelerates, the demand for construction materials is expected to rise, exacerbating these environmental concerns.

In recent years, there has been a growing recognition of the need to adopt sustainable practices in the construction sector to mitigate its environmental impact. One promising approach is the incorporation of recycled materials into construction processes and materials. Recycled materials are derived from waste streams generated during construction, demolition, and other industrial processes. By diverting these materials from landfills and reintroducing them into the construction cycle, the industry can reduce resource consumption, waste generation, and environmental pollution.

## Problem Statement

Despite the potential benefits, the use of recycled materials in construction is not yet widespread. There are various challenges that hinder their adoption. Technical concerns, such as the compatibility of recycled materials with existing construction practices, the durability and structural performance of recycled materials, and the need for standardized manufacturing

processes, pose barriers to their widespread use. Additionally, economic considerations, including the cost competitiveness of recycled materials compared to conventional materials, market demand and acceptance, and financial incentives, influence the feasibility of incorporating recycled materials.

To successfully integrate recycled materials into construction practices, it is essential to address these challenges and evaluate their feasibility. By conducting a comprehensive analysis of the technical, economic, and environmental aspects, this thesis aims to provide insights into the viability of using recycled materials in construction materials.

## Significance of the Study

This study is significant for several reasons. Firstly, it contributes to the growing body of knowledge on sustainable construction practices by specifically addressing the feasibility of using recycled materials in construction materials. By evaluating the technical, economic, and environmental aspects, the findings of this research will provide valuable insights for researchers, practitioners, and policymakers involved in sustainable construction.

## Scope and Limitations

This research will focus on the feasibility of using recycled materials in the context of construction materials. It will encompass a wide range of recycled materials, including but not limited to recycled aggregates, reclaimed timber, recycled plastics, and recycled metals. The study will consider various construction applications, such as concrete, asphalt, masonry, and structural elements.

However, it is important to note that the feasibility assessment will be conducted within certain limitations. The availability and quality of recycled materials may vary depending on regional factors and local waste management practices. The study will consider these factors but will not extensively cover specific regional variations. Furthermore, the research will primarily focus on the technical, economic, and environmental aspects and may not extensively

explore social and cultural considerations related to the use of recycled materials in construction.

### Research Objectives Significance of the Study

The primary objective of this research is to assess the feasibility of using recycled materials in construction materials. To achieve this, the following specific objectives will be pursued:

1. Evaluate the technical feasibility of incorporating recycled materials into construction materials by examining their compatibility, structural performance, and durability.
2. Analyze the economic feasibility of using recycled materials by assessing the cost competitiveness, market demand, and financial implications.
3. Conduct an environmental impact assessment to understand the potential environmental benefits of using recycled materials in construction, including reductions in resource consumption, waste generation, and greenhouse gas emissions.
4. Identify the barriers and challenges that hinder the widespread adoption of recycled materials in the construction industry.
5. Provide recommendations and best practices for promoting the use of recycled materials in construction, considering technical, economic, and environmental considerations.

## Solid Waste Materials

### Waste Paper

The utilization of raw waste paper in construction materials is not a widely adopted practice. Rather than disposing of waste paper, a significant amount of it has been repurposed through the process of recycling to create new paper products. This practice has the potential to preserve wood and other forest resources while also reducing the negative environmental effects associated with paper production. The conversion of recycled paper into viable fiber for paper production frequently results in the production of a byproduct generally referred to

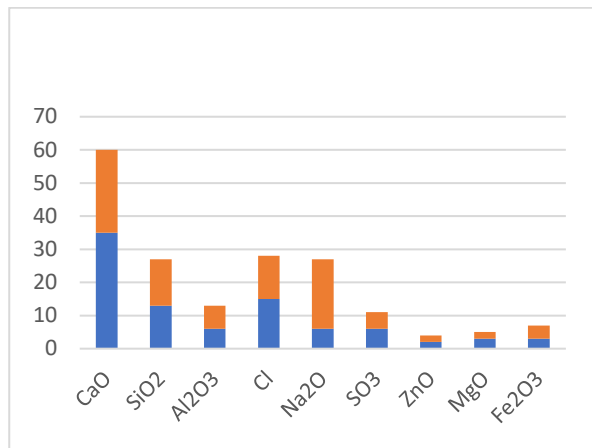
as unwanted paper sludge. The sludge in question exhibits a notable water content, typically ranging from 50% to 70%. As a result, it is customary to subject it to a drying process prior to further handling, incineration, or any potential applications in order to facilitate these procedures. Moreover, it is noteworthy that waste paper sludge comprises comparable proportions of organic constituents, primarily residual cellulose fiber, and inorganic fillers, including kaolin clay and calcium carbonate, as reported by Kinuthia (2018). Prior research has predominantly concentrated on the utilization of waste paper sludge in construction materials that are founded on ordinary Portland cement (OPC). However, the integration of unwanted paper sludge in geopolymer composites signifies a comparatively progressive advancement in this field.

Two primary strategies are often demonstrated by lessons on the use of unwanted paper sludge in geopolymer composites. According to a chemical study, waste paper sludge looks to be compatible with geopolymer chemistry and might be used as a potential supplemental additive to geopolymer composites. As a result, the first strategy uses this content in its unprocessed state. Assessed the qualities of the geopolymer mortar containing 2.5–10% dry unwanted paper sludge by weight of the total precursor, both when it was new and after it had hardened. According to the results, adding unwanted paper sludge to geopolymer mortar lowered its work-ability by 11–33% and its compressive asset by 8–42%. The compressive strength was still more than 31.2 MPa, though. Additionally, it was noted that the drying shrinkage of the geopolymer decreased by up to 64% as waste paper sludge addition increased, in contrast to the OPC matrix, where drying shrinkage increased following unwanted paper sludge inclusion.

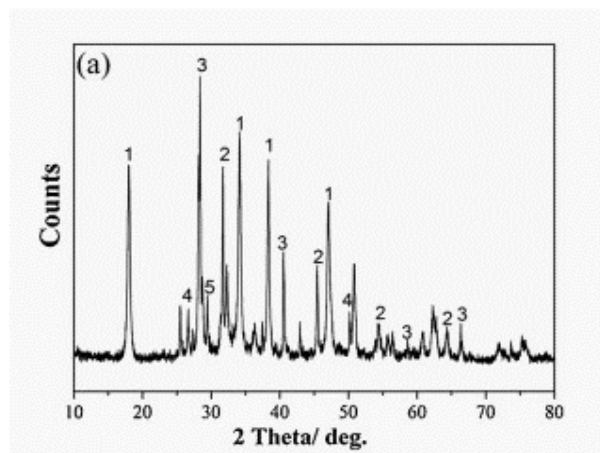
Adesanya, et al. (2018) employed in 2018 unwanted paper sludge as a source of calcium carbonate derived from waste in a one-part geopolymer that requires only the addition of water. The waste paper sludge underwent a pre-treatment process involving a mixture of sodium hydroxide and subsequent oven drying. During



this process, the unwanted paper sludge functioned as both an activator and a filler. The findings indicate that the geopolymer mortar produced demonstrated a compressive strength of up to 48 MPa after 50 days. Furthermore, the sample that was prepared demonstrated a low level of drying contraction, with the maximum contraction recorded at 0.39% and the minimum at 0.14% after a period of 90 days.



**Figure 1. Mineralogy and Chemical Composition of MIFA**

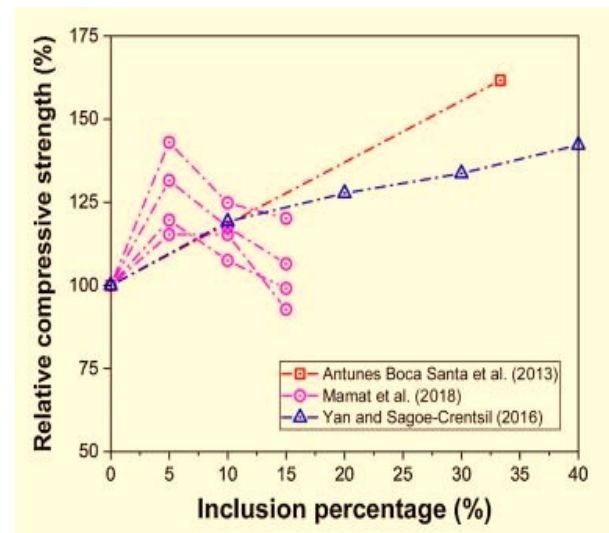


**Figure 2. Chemical Composition of MIFA from the Chosen Studies**

**Note:** 1 - KCl; 2 - NaCl; 3 - CaClOH;  
4 - CaCO<sub>3</sub>; 5 - SiO<sub>2</sub>

An alternative method for incorporating unwanted paper sludge into geopolymer composites involves the utilization of unwanted

paper sludge ash (WPSA), a byproduct resulting from thermal processes such as unwanted paper sludge burning. The recovery of latent energy from the organic component is possible during the process of combustion. Simultaneously, the metakaolin-type phases that exhibit high reactivity and calcined limestone are generated, as reported by Antunes Boca Santa et al. (2013). Figures 1 & 2 illustrate the chemical composition of MIFA.



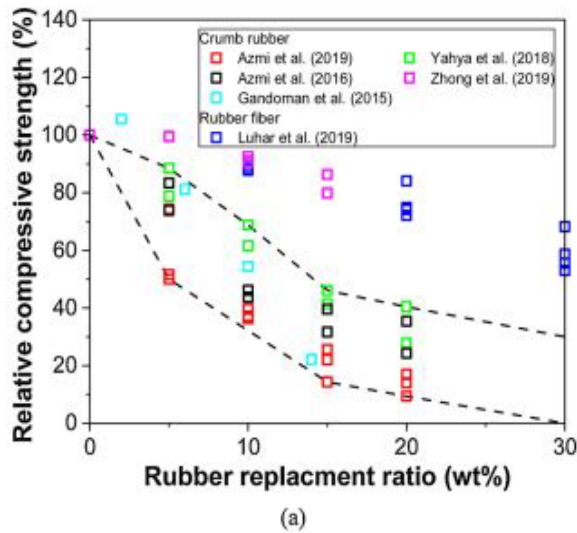
**Figure 3. Relationship Between the Inclusion Percentage of WPSA and Relative Compressive Strength**

### Waste Rubber Products

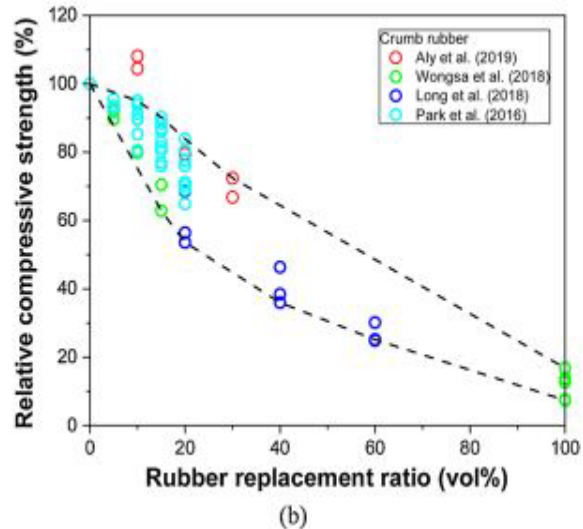
The disposal of rubber waste on a large scale has become a formidable challenge due to the fact that rubber, possessing a complex three-dimensional network structure, undergoes a protracted decomposition process. According to estimation, waste tires are expected to surpass 200 million annually by 2030, making them the primary source of rubber waste. The conventional approach to The management of waste tires encompasses the practices of stockpiling, dumping, and landfilling, which are considered to be temporary measures. In addition, accumulated tires may potentially offer conducive environments for insect and mosquito proliferation. The disposal of tires could potentially result in an adverse

environmental impact due to the leaching of toxins from the tires, leading to soil and groundwater contamination. Therefore, the recycling of waste tires has become a pressing global environmental responsibility. In recent times, by Gandoman and Kokabi (2015) have

introduced the utilization of rubber unwanted, obtained from discarded automotive and truck tires, in the production of geopolymer composites. Figure 4 provides a summary of the studies that currently exist.



(a) Substitution with mass



(b) Substitution with volume

**Figure 4. Relationship Between the Relative Compressive Strength and the Replacement Ratio of Waste Rubber**

The process involves the conversion of shredded tire pieces into granules of specific sizes, commonly referred to as crumb rubber. In the context of geopolymer composites, the utilization of crumb rubber entails the partial or complete replacement of coarse or fine aggregates. The extant literature indicates a consensus that the incorporation of crumb rubber within geopolymer composites significantly modifies the characteristics of said composites. As depicted in Figure 4, there was a consistent decrease in compressive strength as the proportion of crumb rubber used in replacement increased. The reduction in strength resulting from the utilization of crumb rubber as a substitute through mass replacement exceeds that of volume replacement within a specific percentage. The phenomenon of decreased physical strength can be elucidated from multiple perspectives. The primary factor contributing to this phenomenon is the

hydrophobic characteristic of rubber, which results in a feeble adhesion between the rubber and the geopolymer matrix. In their study, Long, et al. (2018) conducted a microstructure analysis, which provided evidence of suboptimal adhesion between the rubber aggregates and the material under investigation. The presence of deep cracks and voids at the interface suggests the existence of the geopolymer matrix. deterioration of the material's mechanical properties This phenomenon can be attributed to the inherently low stiffness of rubber, leading to a reduction in its load-bearing capacity and ultimately resulting in a decrease in its overall strength. The occurrence of fracture in the vicinity of the interface between the rubber and geopolymer matrix Nevertheless, a marginal decrease in mechanical strength may be achieved provided that the proportion of rubber replacement falls within an optimal range that is appropriate for structural applications.

Geopolymer composites that have high replacement ratios are typically restricted to secondary or non-critical structures. This is exemplified in the research conducted by Mohammed, et al. (2018), where a non-load-bearing brick was produced by utilizing crumb rubber as the only fine aggregate in the geopolymer mortar. Similarly, the inclusion of crumb rubber resulted in a decline in various mechanical performance indicators, physical properties, and durability. The findings of Zhong, et al. (2019) have revealed that the

incorporation of steel fibers in waste rubber geopolymer composites can result in comparable compressive strength (as depicted in) and enhanced flexural strength. The integration of steel fibers within geopolymer composites has the potential to offset the reduction in strength resulting from the presence of crumb rubber while simultaneously preserving its beneficial effects. Consequently, the utilization of rubber waste in geopolymeric composites can be optimized.

**Table 1. The Utilization of Elastic Waste in Geopolymer Composites Has Recently Come under Study**

Composites	Form	Substitution	Content <sup>1</sup>	Precursor	Activator	Curing condition	Mechanical properties <sup>2</sup>	Reference
	Rubber fiber (width; 2-4 mm; length; 22 mm)	Fine aggregate	0, 10, 20, and 30 wt. %	CFA	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	90°C for 48 hours	30.01–48.30 MPa (28-day compressive Strength) 8.4–8.8 MPa (28-day flexural strength) 5.1–5.3 MPa (28-day indirect tensile Strength)	Luhar et al. (2018, 2019a 2019b)
	Crumb rubber	Fine aggregate	0, 5, 10, 15, and 20 wt. %	CFA	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	11.3–33.2 MPa (28-day compressive Strength)	Azmi et al. (2019)
	Crumb rubber (0-4mm)	Fine and coarse aggregate	0, 10, 20, and 30 vol %	GGBFS	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	24.60–40.0 MPa (28-day compressive Strength) 1.80–2.00 MPa (60-day flexural strength) 2.30–2.80 MPa (60-day indirect tensile strength)	Aly et al. (2019)
	Crumb rubber (5-10 mm)	Coarse aggregate	0, 5, 10, 15, and 20 wt. %	CFA	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	Seawater	14.10–40.00 MPa (28-day compressive strength)	Yahya et al. (2018)
Concrete Mortar	Crumb rubber (0–3.75 mm)	Fine aggregate	0, 5, 10, 15, 20 wt. %	CFA	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	15.80–48.00 MPa (28-day compressive strength)	Azmi et al. (2016)
	Crumb rubber (0–4.750 mm)	Fine aggregate	0, 5, 10, 15, and 20 vol %	CFA	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	46°C for 7 days (stream-curing)	17.50–40.60 MPa (7-day compressive strength)	Park et al. (2016)

Crumb rubber (0–1 mm)	Fine aggregate	0, 2, 6, 10, and 14 wt. %	MK	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	65 °C for 48 hrs	9.00–42.90 MPa (28-day compressive strength)	Gandoman and Kokabi (2015)
Crumb rubber (0–6 mm)	Fine aggregate	0, 5, 10, and 15 wt. %	CFA + GGBFS	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	30.90–35.60 MPa (28-day compressive strength) 3.60–3.90 MPa (28-day flexural strength)	Zhong et al. (2019)
Crumb rubber (0–4 mm)	Fine aggregate	0 and 100 vol %	CFA	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	25, 60, 90 °C for 48 hrs	2.70 MPa (28-day compressive strength)	Wongsa et al. (2018a)
Crumb rubber	Fine aggregate	100 vol %	CFA	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	2.80–4.30 MPa (28-day compressive strength)	S Mohammed et al. (2018)
Crumb rubber (0–4.25 mm)	Fine aggregate	0, 20, 40, and 60 % vol %	GGBFS	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	14.60–31.30 MPa (28-day compressive strength) 8.60–14.70 MPa (28-day flexural strength)	Long et al. (2018)

### The Issue of Plastic Waste

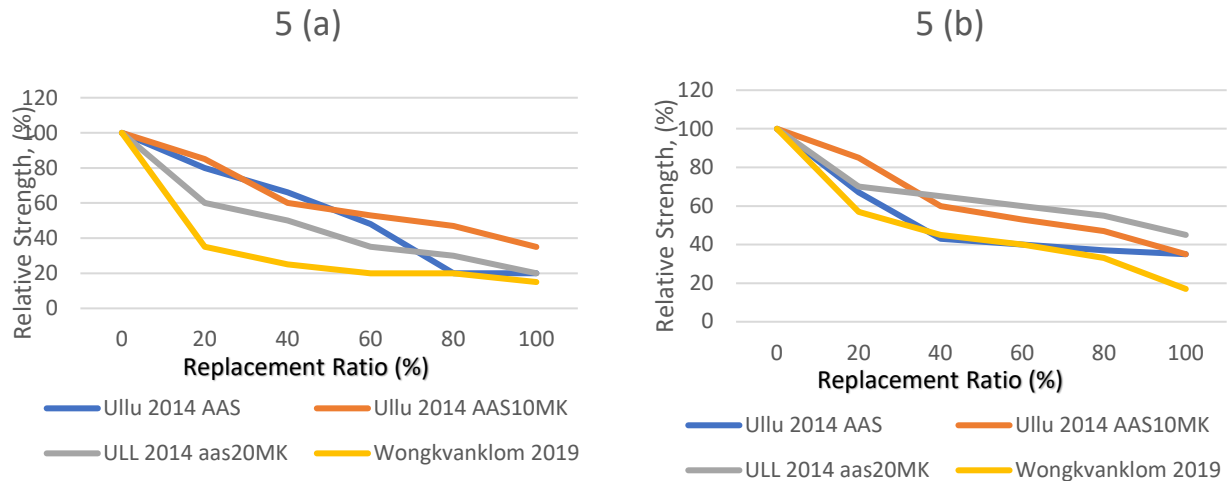
The proliferation of plastic waste has emerged as a paramount ecological concern, given the exponential growth in the manufacture of plastic goods that surpasses the global capacity to manage them. down in the environment. The disposal of plastic products through landfilling has a significant negative impact on the environment due to the fact that plastic does not biodegrade and remains in a state of degradation. Moreover, due to the involvement of hazardous chemicals in the production of plastics, the disposal of plastic through land-filling poses a significant concern. Improper disposal of waste could lead to the emission of hazardous substances. Recycling plastic waste to manufacture new materials like mortar or concrete has been identified as a highly effective approach to mitigating the adverse impacts caused by plastic waste. Numerous studies have been conducted to assess the characteristics of Geopolymer composites incorporate plastic waste as an aggregate. The research conducted by Wongkvanklom, et al. (2019) involved the utilization of plastic waste, which was transformed into lumps and subsequently

ground into particles measuring approximately 2.1 mm in diameter. These particles were utilized as fine aggregate in the preparation of geopolymer composites. In a study conducted, waste PET bottle granules with particle sizes below 4 mm were utilized as a replacement for fine aggregates in geopolymer mortar. The substitution levels ranged from 20% to 100%. integrated polystyrene foam particles, ranging from 2.36 mm to 4.75 mm in size, obtained from discarded packaging foam into geopolymer concrete. In general, it was observed that the density of geopolymer composites decreased as the replacement ratios of waste plastic aggregate increased. This trend can be primarily attributed to the relatively low density of the plastic material. The mechanical properties, such as compressive strength and flexural strength, exhibited a decline with the rise in waste plastic aggregate replacement ratios, as depicted in Figure 5. According to Posi, et al. (2015), the utilization of waste plastic as an aggregate replacement can result in the production of geopolymer concrete that possesses satisfactory strength and density. This type of concrete can potentially serve as a substitute for lightweight



structural concrete, provided that the appropriate ratio is employed. Furthermore, noted that an augmentation in the quantity of waste plastic aggregate resulted in a decrease in surface abrasion resistance as well as an increase in porosity and water absorption. The

incorporation of plastic waste in geopolymer composites results in improved thermal insulation properties due to the low thermal conductivity coefficient of plastic, as reported by Posi, et al. (2015).



**Figure 5. Relationship between Relative Strength and the Replacement Ratio of Waste Plastic: Compressive and Flexural Strength, Respectively**

Dave, Bhogayata, & Arora (2017) conducted a study wherein waste plastic granules with diameters ranging from 7 mm to 9 mm were utilized to replace virgin coarse aggregate in geopolymer concrete. The researchers then evaluated the impact resistance of the resulting geopolymer concrete through the implementation of a drop-hammer test. The findings indicate that the incorporation of waste plastic aggregate at a rate of 10% resulted in a significant enhancement of impact resistance, as evidenced by an increase from 179.77 kJ to 193.02 kJ. The plastic aggregate has been demonstrated to exhibit superior ductile properties, enabling it to effectively absorb abrupt impact energy and consequently impede the propagation of cracks at the microscale.

The researchers sought to investigate the potential of incorporating plastic waste fiber into geopolymer composites, building upon the positive outcomes observed in the use of this material in OPC-based concrete. As anticipated, it has been demonstrated that plastic waste can

be effectively employed as a reinforcement fiber in the composition of geopolymer composites. Bhogayata and Arora conducted in 2019 an experiment wherein plastic waste fiber, with an average length of 20 mm and width of 1 mm, was incorporated in geopolymer concrete at different volume proportions ranging from 0% to 2%. The plastic waste fiber was acquired through the process of shredding metalized plastic films. These films are typically composed of a polypropylene base and feature a layer of aluminum on one surface. They are commonly utilized as food packaging materials. The inclusion of plastic waste fiber was observed to have a negative impact on the workability, density, and compressive strength of geopolymer concrete. Regarding the splitting tensile strength, there was an observed increase of approximately 8%, 18%, 16%, and 12% as the plastic waste fiber dosage was incrementally increased from 0.5% to 2%. Moreover, an improvement was noted in both the strength and deformation capacity when subjected to flexural

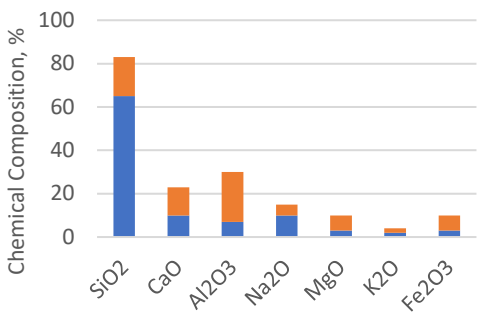
loading, as well as in the energy absorption during impact.

## Others Solid Waste Materials

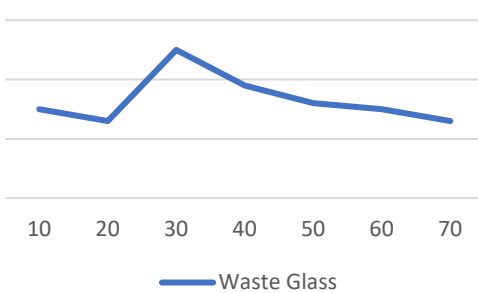
### Waste Glass

Furthermore, apart from the aforementioned MSW, diverse forms of MSW have demonstrated varying degrees of advancement in their re-utilization within geopolymer composites. One of the prevailing practices is the utilization of glass waste through recycling. According to Hoornweg and Bhada-Tata (2012), the worldwide yearly production of glass waste is approximately 65 million tons, representing roughly 5% of the municipal solid waste composition. However, the complete recycling or efficient reuse of waste glass has not yet been achieved. In the United States, the recycling rate for waste glass was found to be 28% out of a total of 11.54 million tons. According to Liu et

al. (2019c), the annual production of waste glass in Mainland China amounts to 40 million tons, with a mere 13% of it being subjected to recycling. Figure 3. 1 presents the chemical composition and mineralogy of glass. The substance in question is characterized by a significant presence of amorphous silicon and calcium, as well as a notable level of reactivity. Extensive research has confirmed the viability of utilizing waste glass in the production of geopolymer composites. Broadly speaking, glass waste has the potential to be repurposed as aggregates, precursors, and alkali activators within the realm of geopolymer, as evidenced by studies conducted. Numerous studies have been conducted to examine the potential of utilizing glass waste in geopolymer composites. As a result, researchers seeking to enhance the value of glass waste by creating geopolymer composites can refer to these works, including those by Liu et al. (2019c).



a) Chemical Composition of Waste Glass



b) XRD Pattern of Waste Glass

Figure 6. Chemical Composition and Mineralogy of Waste Glass

### Tire Steel and Textile Fiber

In the course of the tire granulation procedure, byproducts in the form of steel and textile remnants are concurrently generated. The feasibility of utilizing the aforementioned materials obtained from tires as fiber reinforcement for geopolymer composites has been investigated by several scholars. Empirical evidence suggests that the incorporation of tire steel fiber into geopolymer composites may have a detrimental effect on compressive strength.

However, a noteworthy improvement in flexural performance has been observed in such composites when reinforced with tire steel fiber. Onuaguluchi, et al. (2017) observed in 2017 that the incorporation of 1% and 2% tire steel fiber resulted in a significant enhancement of the flexural peak strength by 71.5% and 45.1%, respectively. Moreover, the toughness of the material was found to increase from 0.14 J to 1.70 J and 2.18 J, respectively, upon the addition of the aforementioned percentages of tire steel fiber. Comparable outcomes have been

observed in geopolymer composites that are strengthened with tire textile fibers, as reported by Ach et al. (2018) in 2018. The incorporation of tire textile fiber resulted in a shift of the failure mode from brittle to ductile and a notable enhancement of the flexural strength by as much as 10%.

### Application of Spent Coffee Grounds

The residual solid granules of coffee grounds that remain after the completion of the liquid coffee-making process are typically discarded in landfills. Several studies have been carried out to evaluate the viability of integrating coffee grounds with geopolymer precursors to create eco-friendly subgrade construction materials. The fill materials utilized in this study were coffee grounds, which were combined with geopolymer precursors (such as CFA, slag, or glass waste) in a carefully controlled ratio. Subsequently, an alkali solution was employed to activate the mixture. The assessment of the manufactured materials was conducted with regards to their compressive strength, elastic modulus, microstructural characteristics, and leaching of contaminants. Overall, the findings of the study indicate that the utilization of geopolymers has the potential to effectively stabilize coffee grounds and produce a subgrade material that satisfies the necessary criteria for strength, stiffness, and environmental considerations.

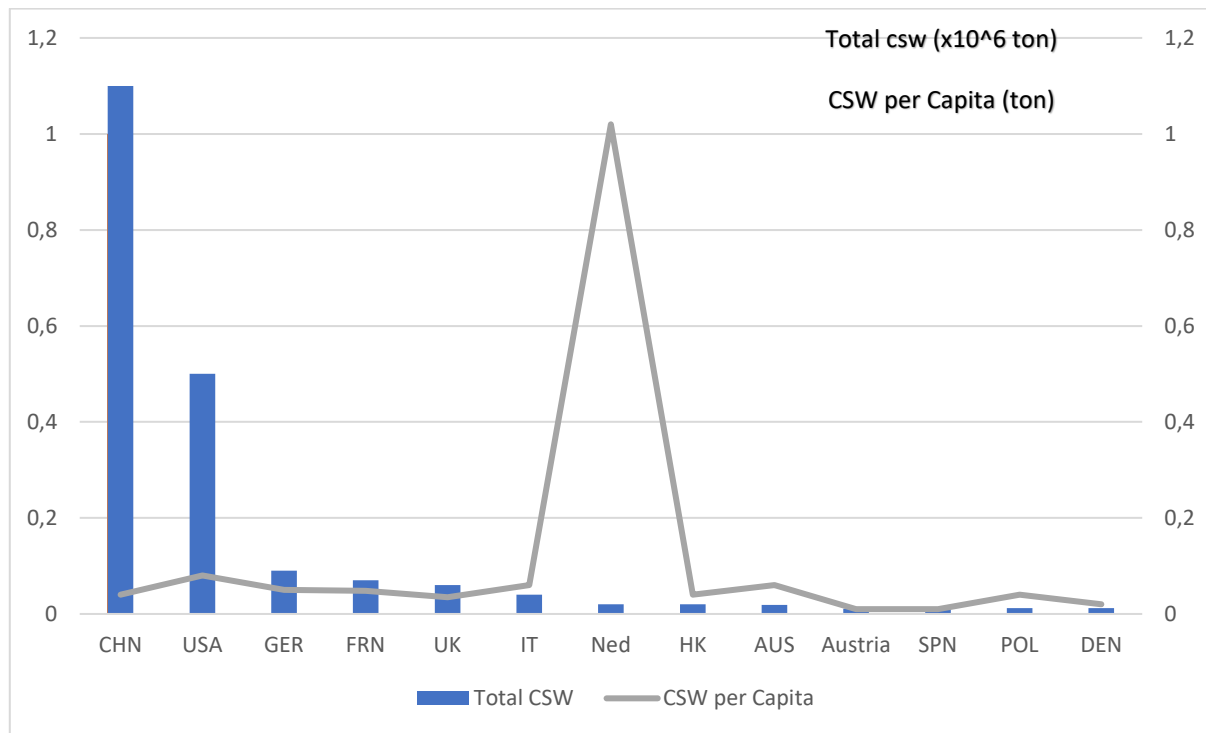
### Cork Waste

Novais, et al. (2019) employed in 2019 pyrolyzed waste cork to synthesize geopolymer-cork composites, marking the first instance of such an application. Corks that had been previously used as wine stoppers were subjected to a heating process in a graphite furnace under a nitrogen atmosphere, reaching a temperature of 900 °C. The resulting product was then ground into a fine powder with a particle size below 75 µm. Pyrolyzed cork at concentrations of 2.5% and 3.75% was incorporated into the geopolymer composites without any intermediary steps. Pyrolyzed cork, with a carbon content of 90.74

wt.%, has the potential to serve as a carbon source for improving the electromagnetic interference shielding properties of geopolymer composites. The findings indicate that the cork-geopolymer composites demonstrated a notable increase in specific shielding effectiveness when compared to the standard geopolymer matrix. In the case of samples with a thickness of 3 mm, the inclusion of 2.5% and 3.75% pyrolyzed cork resulted in an increase in specific shielding effectiveness from 4.7 to 6.0 -dB g<sup>-1</sup> cm<sup>3</sup> to 8.8–10.8 and 11.7–13.5 -dB g<sup>-1</sup> cm<sup>3</sup>, respectively. Incorporating pyrolyzed cork into geopolymer composites presents an environmentally sustainable approach for applications related to shielding against electromagnetic interference.

### Construction Solid Waste

Construction solid waste (CSW) is an inevitable outcome of construction, renovation, or demolition endeavors. It encompasses a diverse range of materials such as concrete, metals, bricks, timber, ceramics, asphalt, soil, plaster, and polymers. The aforementioned waste constitutes the primary contributor to the solid waste stream in numerous countries globally. The annual generation of Construction and Demolition Waste (CSW) from the chosen countries in the year 2014 is presented in Figure 7, as reported by Menegaki, & Damigos, (2018). The issue of addressing the CSW problem has garnered significant attention from economic, environmental, and societal standpoints. In recent years, there has been a significant amount of research dedicated to enhancing the recycling rate and decreasing the landfill rate of municipal solid waste (CSW). This section presents a comprehensive examination of the progress made in recycling construction and demolition waste (CSW) through the use of geopolymer composites. The review encompasses various types of waste materials, such as waste concrete, waste clay brick, ceramic waste, and waste asphalt pavement, among others.



**Figure 7. Annual CSW Generation from Different Countries**

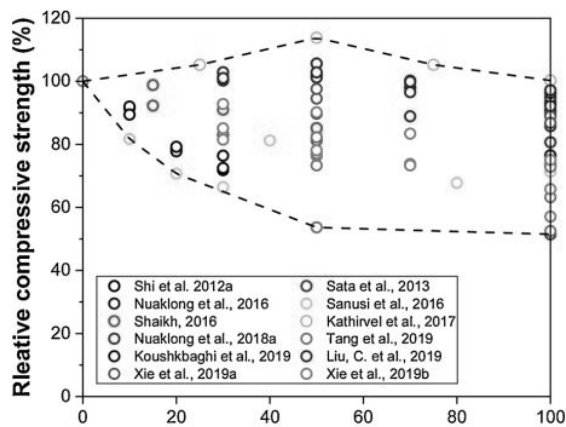
### Concrete Waste

Concrete is a highly prevalent construction material due to its favorable attributes, such as its cost-effectiveness, accessibility of raw materials, and commendable mechanical and durability characteristics. As per reports, around 33% of construction and demolition waste (CSW) is composed of concrete. In the past, waste concrete was commonly transported to landfills for disposal. However, recycling has emerged as a viable alternative due to its numerous benefits, particularly in light of stricter environmental regulations, heightened environmental awareness, and the need to minimize construction expenses. The reuse and recycling of concrete have garnered significant attention since the late 1980s or early 1990s, as noted by Xu et al. (2017). Initially, waste concrete was repurposed into new concrete that was based on OPC. Subsequently, there has been a concerted effort to explore the potential of waste concrete in geopolymer composites, which has been facilitated by the rapid advancement of geopolymer technology. The predominant approach for utilizing waste concrete in geopolymer composites involves its

incorporation as recycled aggregates, encompassing both coarse and fine aggregates. The literature has predominantly concentrated on examining the impacts of diverse elements, such as chemical activators, raw materials, curing regimes, and replacement ratios, on the efficacy of geopolymer composites that incorporate recycled concrete aggregates. This examination pertains to the mechanical, durability, and microstructural characteristics of said composites. Figure 8 provides a summary of previous research studies that have employed waste concrete as an aggregate in geopolymer mortar and concrete. Incorporating recycled concrete aggregate has been found to have a negative impact on the performance of geopolymer composites, specifically in terms of mechanical and durability properties. The decline in compressive strength of geopolymer composites can be observed in Figure 8, specifically in relation to the increase in replacement ratio of recycled concrete aggregate. Table 3 demonstrates that the incorporation of recycled concrete aggregate in geopolymer composites has the potential to meet various strength requirements by modifying the



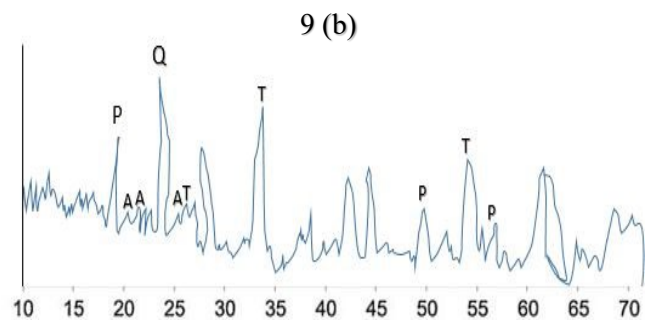
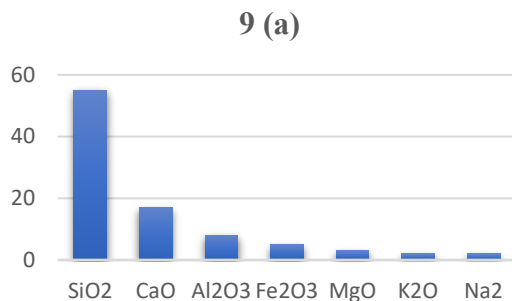
properties of the source materials or alkaline activating solution, optimizing the ingredient proportion, and selecting an appropriate curing technique, as reported by Koushkbaghi et al. (2019).



**Figure 8. Relationship between the Relative Compressive Strength and Replacement Ratio of Waste Concrete**

Conversely, certain benefits of utilizing geopolymer composites that integrate recycled

concrete aggregates have been documented. The geopolymer paste is characterized by a higher degree of homogeneity and density in comparison to the OPC paste, owing to the distinct matrix formation mechanism. Additionally, it has been suggested by Khedmati et al. (2018) that the geopolymer matrix has the potential to occupy the deficient interphase present in the recycled concrete aggregate. The study conducted by Liu in 2019 suggests that a strong bond was formed between the geopolymer matrix and the recycled concrete aggregate, leading to the absence of any discernible interfacial transition zone (ITZ) between the two materials. The incorporation of recycled concrete aggregates in geopolymer mortars resulted in lower autogenous and drying shrinkage. This can be attributed to the internal curing agent function of the recycled concrete aggregate. In a recent study conducted by Sedaghatdoost, et al. (2019), it was observed that the incorporation of recycled concrete aggregates resulted in an enhancement of the thermal resistance of geopolymer composites, withstanding temperatures as high as 800 °C.



**Figure 9. Chemical Make-Up and Mineralogy of WCP: (a) Chemical make-up of WCP according to the chosen studies. Information derived from (A: an orthite, M: mullite, P: portlandite, Q: quartz, and T: 1.1-nm tobermorite)**

Prior research has proposed effective methods to mitigate the negative impacts resulting from the substitution of recycled concrete aggregate, thereby enhancing the efficacy of geopolymer composites that incorporate recycled concrete aggregate. The most practical and effective

method, as suggested by Tang, is the inclusion of calcium-carrying materials like slag and OPC. Xie, et al. (2018) reported notable enhancements in compressive strength, elastic modulus, and energy absorption as the proportion of slag content increased. The findings of Hu in 2019

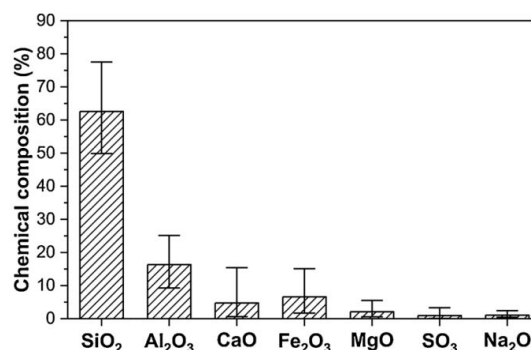
corroborate the aforementioned statement, as they observed enhanced microstructural characteristics subsequent to the integration of calcium-containing substances.

A limited number of Komnitsas, et al. (2015) in 2015 have conducted research on the utilization of waste concrete as a source material for geopolymer precursors. Figure 9 (a) presents the mean, highest, and lowest values of the chemical constituents found in waste concrete powder (WCP) as reported in various studies. Furthermore, Figure 9 (b) depicts the mineralogy of WCP have proposed the existence of a low quantity of amorphous aluminosilicate. Hence, it is common in current methodologies to combine WCP with other customary geopolymer precursors, followed by its activation through an alkaline solution. The present study evaluated the effects of various factors on the outcome of the experiment, including the content of WCP, the composition and concentration of the alkaline solution, and the type of curing. The attainment of desirable characteristics in the end product was found to be contingent upon the implementation of a fitting design. Ahmari conducted in 2018 a test wherein the addition of WCP below a certain content was found to enhance the compressive strength of a geopolymer binder that was based on CFA. However, an increase beyond this threshold resulted in a decline in strength. Abdel-Gawwad, et al. (2018) have produced a single-component geopolymer through the activation of waste ceramic powder (WCP) blended with a specific quantity of sodium hydroxide at high temperature. The geopolymer product obtained exhibited the ability to form a solidified matrix that possessed a compressive strength of up to 79 MPa after a period of 28 days.

### Waste Clay Brick

Clay bricks are widely recognized as the second-most prevalent building material, following concrete. The waste clay brick (WCB) is derived from both demolition activities and the discarded bricks that result from manufacturing, transportation, and construction processes. The production process of clay bricks involves the

amalgamation of finely ground clay with water, shaping the resultant clay mixture into the desired form, and subsequently subjecting it to drying and firing. Figure 4.4, displays the mean, maximum, and minimum values pertaining to the chemical composition of WCB as obtained from the studies that were chosen for analysis. The clay brick material is characterized by elevated concentrations of  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ , which render it a promising candidate for serving as a geopolymer precursor.



**Figure 10. Chemical Composition of WCB from the Selected Studies**

Figure 10 presents a summary of prior research endeavors that have evaluated the practicality of utilizing waste ceramic bodies (WCB) as a precursor for the production of geopolymer composites. The study conducted by Payne, Et al. (2017). in 2017 suggests that WCB has the potential to serve as a suitable substitute for precursor material in the production of geopolymer composites. Several researchers have conducted optimization studies on the formation of geopolymers based on waste ceramic brick (WCB) in order to enhance their performance. This was achieved by manipulating various parameters of the alkaline solution, including the type of alkaline, silica modulus, and alkaline concentration, as well as the curing condition and water/binder ratio. Conducted a study to examine the impact of various factors, including alkali concentration (ranging from 4% to 10%), silica modulus (ranging from 0 to 2.2), curing temperature (ranging from 50 to 90 °C), and curing duration (ranging from 1 to 7 days), on the consistency and strength of geopolymer

mortar that is based on waste ceramic bricks (WCB). The experimental findings indicate that the most effective activator composition comprises an alkali concentration of 10% and a

silica modulus of 1.6. The highest achievable compressive strength was observed after curing at 90°C for 5 days.

Composites	Precursor <sup>1</sup>	WCB content (wt.%)	Activator	Curing condition		Compressive strength (MPa)
				Temperature	Duration	
Mortar	WCB	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	65 °C	3 or 7 days	7.1–50.0 (7 days)
	WCB + GGBFS	20, 40, 60, 80, 100	NaOH + Na <sub>2</sub> SiO <sub>3</sub> ; NaOH	95 °C, RT	12 hrs	26–112.3 (28 days)
	WCB	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub> ; SH	50, 60, 70, 80, 90, 100 °C, RT	1, 3, or 7 days	4.0–36.2 (7 days)
Paste	WCB + GGBFS	50, 60, 70, 80, 90, 100	NaOH + Na <sub>2</sub> SiO <sub>3</sub> ; NaOH	RT	—	23.1–91.3 (28 days)
	WCB	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	60, 80, or 90 °C	7 days	4.7–49.5 (7 days)
	WCB + CAC	50, 60, 70, 80, 90, 100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	65 °C, RT	3 or 7 days	4.1–93.7 (7 days)
	WCB + OPC	80, 90, 95, 100	NaOH + Na <sub>2</sub> SiO <sub>3</sub> ; NaOH	70 °C, RT	1 or 2 days	7.5–102.6 (28 days)
	WCB + GGBFS	20, 40, 60, 80, 100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	—	11.7–79.2 (28 days)
	WCB + OPC	70, 80, 90, 100	Na <sub>2</sub> SiO <sub>3</sub> ; NaOH; Na <sub>2</sub> SO <sub>3</sub>	RT	—	10.2–102.7 (28 days)
	WCB	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	—	10.3–41.9 (28 days)
	WCB	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	—	27.5–38.8 (28 days)
	WCB + MK	25, 50, 75, 100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	40 °C	20 hrs	6.6–26.5 (14 days)
	WCB + TMWM	10, 20, 30, 40, 50	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	—	25–59 (28 days)
	WCB + GGBFS + CFA	60, 100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	—	38.2–68.2 (28 days)
	WCB + DCP	70, 80, 85, 90, 95, 100	NaOH	80 °C	1 day	3.0–51.4 (28 days)
	WCB + NP	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	65, 80, 95 °C	1, 3, or 7 days	0.7–37.0 (28 days)

**Figure 11. Recent Analysis of Clay Brick Waste-Derived Geopolymer Composites**

However, it is important to acknowledge that the WCB-based geopolymer composites were predominantly produced using high-temperature curing conditions (typically exceeding 60°C) and extended timeframes to achieve adequate mechanical durability. The primary reason for this phenomenon can be attributed to the significant presence of crystalline minerals and the comparatively lower concentration of amorphous matter in WCB. Consequently, the geopolymerization reaction is relatively feeble, leading to insignificant strength development during the initial stages. The aforementioned curing condition is known to elevate both the production cost and energy demand, thereby impeding its utilization in cast-in-situ construction. Consequently, it is advisable to incorporate WCB in conjunction with other reactive substances, including metakaolin, fly ash, and OPC, to attain a successful geopolymerization procedure at lower temperatures. Hwang conducted in 2018 a study wherein they developed high-strength geopolymer pastes through the utilization of a significant amount of WCB as source materials.

The curing process was done at ambient temperatures. The mixtures were comprised of a starting material mass consisting of 60% WCB and 40% CFA and GGBFS in varying proportions. The samples obtained exhibited compressive strength values within the range of 36 to 70 MPa. Conversely, the control mixture that solely comprised WCP did not solidify even after 24 hours of being cast. According to Robayo, et al. (2016), the addition of 20% OPC resulted in the development of geopolymer pastes based on WCB that exhibited a compressive strength of 102.6 MPa after 28 days of ambient curing. This strength was found to be twice that of the mixture that did not contain OPC.

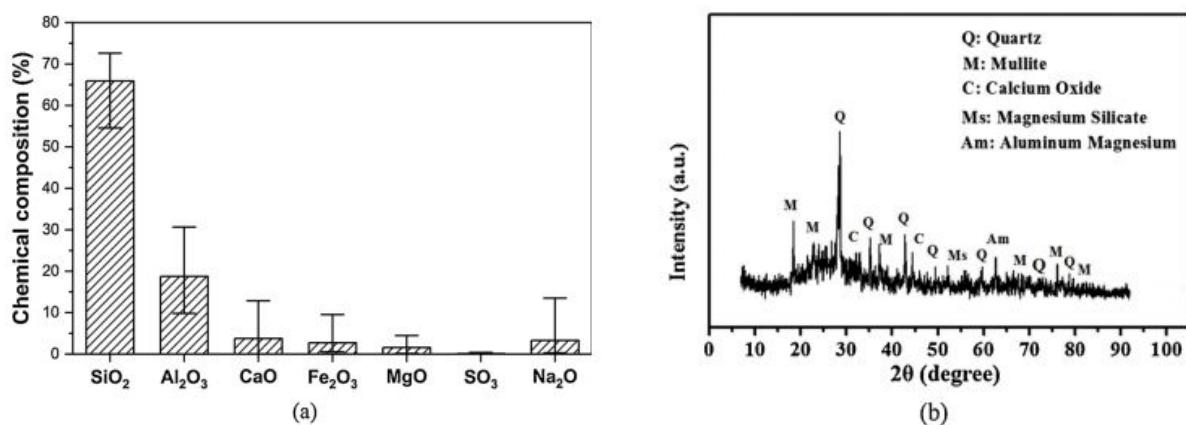
Additional research has been conducted on the utilization of crushed clay brick as either coarse or fine aggregates in geopolymer materials, as evidenced by studies conducted. The utilization of recycled brick as an aggregate substitute in geopolymer concrete and mortar has resulted in a notable decrease in mechanical strength due to the relatively weaker and more porous nature of brick aggregate in comparison to virgin

aggregate, as reported by Wongsu (2018b). The utilization of the low density characteristic of clay brick was employed by Wongsu (2018b) to create lightweight geopolymer concrete through the use of clay brick aggregate. The resulting densities of the concrete ranged from 1685 kg/m<sup>3</sup> to 1749 kg/m<sup>3</sup>. The findings of the study indicate that incorporating crushed clay brick as coarse aggregate can enhance the thermal insulation and resistance of geopolymer concrete when exposed to temperatures ranging from 400 to 800 °C. successfully produced pervious geopolymer concrete by utilizing crushed clay brick aggregate that had consistent voids and exhibited notable water permeability.

### Ceramic Waste

Ceramic materials and products are frequently utilized in construction and design endeavors, including but not limited to floor and wall tiling, garden ceramics, terracotta products, and sanitary ceramics. The process of manufacturing ceramics bears resemblance to that of clay brick,

typically commencing with the acquisition of raw materials, followed by mixing, molding, firing, polishing, and glazing. Ceramic materials are typically subjected to higher firing temperatures compared to bricks, resulting in the re-crystallization of silica to produce a glassy substance. This glassy material exhibits enhanced density, strength, hardness, chemical, and frost resistance, as well as improved dimensional stability. Figure 12 displays the mean, highest, and lowest measurements of the chemical makeup of ceramic waste powder (CWP) sourced from the chosen research studies, alongside the X-ray diffraction (XRD) pattern. The possibility of producing geopolymer composites is attributed to the chemical composition of ceramic, which predominantly consists of highly amorphous aluminosilicate. The use of CWP as a precursor material in geopolymer formulations has garnered significant attention in academic circles.



**Figure 12. Chemical Makeup and Mineralogy of CWP:**  
**(a) CWP's chemical makeup as determined by the research that were chosen**  
**(b) CWP XRD pattern**

Figure 12 provides a summary of the latest research on geopolymer composites that are based on CWP. Within this set of studies, a portion of the research was dedicated to examining the characteristics of geopolymer composites that were exclusively composed of CWP. Geopolymer mortars utilizing CWP were initially developed, who further investigated the

influence of alkali activator concentration on the microstructure and mechanical strength of the resulting mortars. The results indicate that, under consistent water-to-binder ratios, a rise in alkali concentration from 6.0% to 9.0% led to an increase in the compressive strength of CWP-derived geopolymer mortar from 25 MPa to 29 MPa. Subsequent investigations have been



conducted with the objective of comprehending the geopolymerization mechanism of CWP and enhancing the technical knowledge concerning the impact of particle dimensions, curing circumstances, and alkaline solution characteristics on the efficacy of end. In summary, the CWP material demonstrates a

notable capacity for geopolymerization, surpassing that of both waste bricks and concrete. Furthermore, through the optimization of the initial reaction system and the alkaline activating solution, it is possible to achieve a proficient geopolymerization process and enhance the efficacy of the end products.

Composite type	Precursor	WCT content (wt.%)	Activator	Curing condition		Compressive strength (MPa)
				Temperature	Duration	
Mortar	CWP	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	60, 75, 90, 105 °C	24 hrs	22.2–27.9 (28 days)
	CWP + GGBFS + CFA	50	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	—	45.9–66.2 (28 days)
	CWP + GGBFS + CFA	50, 60, 70	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	—	22.2–70.1 (28 days)
	CWP + GGBFS	10, 20, 30	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	60 °C, RT	3 hrs	10.3–17.9 (28 days)
	CWP + GP + GGBFS + CFA	15	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	—	30.1–54.0 (28 days)
	CWP + GGBFS	60, 80, 90, 100	NaOH, KOH	60 °C, RT	24 hrs	6.2–32.8 (7 days)
	CWP	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	65 °C	3 days	9.4–32.3 (3 days)
	CWP	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	35, 45, 55, 65, 75 °C	24 hrs	7.1–26.5 (28 days)
	CWP	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	65 °C	7 days	25.6–29.5 (7 days)
	CWP	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	—	34.6–58.0 (28 days)
Paste	CWP	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	—	20.5–71.6 (28 days)
	CWP + GGBFS + CFA	60, 100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	—	2.3–8.0 (28 days)
	CWP + MK	15, 30, 45	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	RT	—	1.5–57.8 (7 days)
	CWP	100	NaOH + Ca(OH) <sub>2</sub>	RT	—	30.5–71.2 (28 days)
	CWP	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	60, 80, 90 °C	7 days	
	CWP	100	NaOH + Na <sub>2</sub> SiO <sub>3</sub> ; KOH + Na <sub>2</sub> SiO <sub>3</sub> ; NaOH + KOH; NaOH	60 °C	27 days	

**Figure 13. An Overview of the Geopolymer Composites Made from Ceramic Waste Powder**

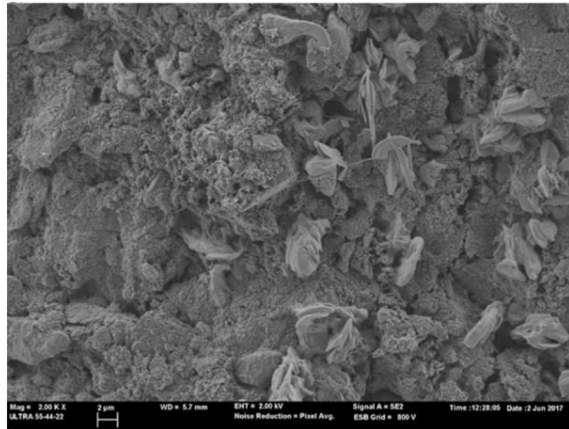
Moreover, several research studies have assessed the efficacy of geopolymer composites that are formulated by amalgamating CWP with other aluminosilicate precursors. Huseien and colleagues conducted a series of investigations to assess the workability, strength, and durability properties of multi-blend geopolymer pastes and mortars that incorporated CWP. These investigations were reported in two separate publications by Huseien, et al (2018) in 2018 and 2019. The predominant constituent of the initial substance was CWP, while the residual components were comprised of CFA and GGBFS. According to the results, it was indicated that the utilization of high-volume CWP has the potential to generate geopolymer composites that exhibit a compressive strength exceeding 70 MPa. Moreover, it has been observed by Sun that the geopolymer

composites developed in the study displayed improved tolerance to high temperatures as the proportion of CWP was increased. Researchers have combined CWP with metakaolin and waste glass powder to create geopolymer composites. The resulting products have demonstrated satisfactory performance, as noted in studies conducted by Huseien, et al. (2018a).

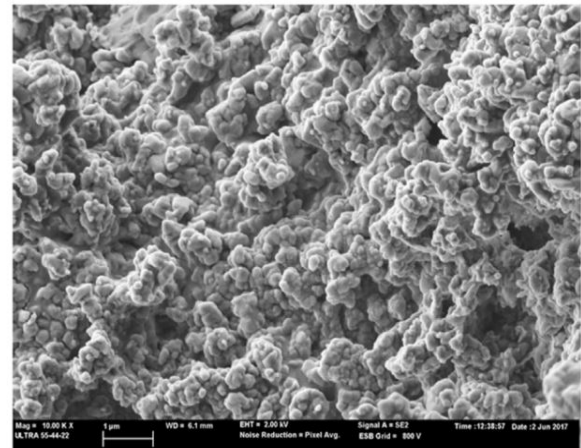
Apart from employing ceramic waste as precursor materials, another potential use of ceramic waste is as a substitute for aggregate in geopolymer mortar and concrete, as demonstrated in studies conducted. Abdollahnejad, et al. (2019) employed ceramic waste as a precursor and recycled aggregate in their respective studies. The results indicate that upon immersion in the activating solution, the initial rounded morphology of the ceramic waste aggregates underwent significant alteration, with

the pore network becoming obscured by the accumulation of crystalline particles, as depicted in Figure 14. The alterations observed in the aforementioned study indicated the disintegration of the ceramic waste aggregates through the activating solution, ultimately resulting in the formation of a favorable

interfacial transition zone (ITZ). The inclusion of ceramic waste aggregates led to an enhancement in the robustness of geopolymer mortar, with a maximum value of 43 MPa achieved at the optimal proportion of 50 wt.%, as reported by Abdollahnejad, et al. (2019).



(a) General view



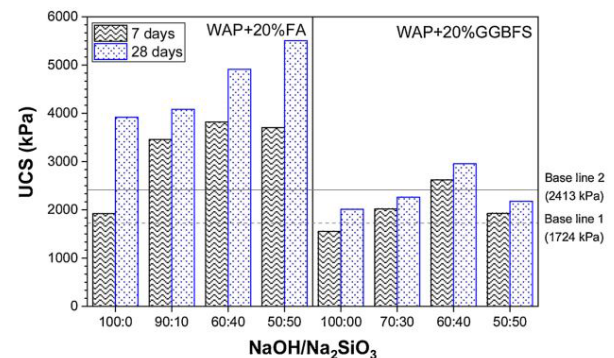
(b) Solid-phase magnification

**Figure 14. Microstructures of the Ceramic Waste Aggregates after Immersion**

### Waste Asphalt Pavement

The production of waste asphalt pavement (WAP) occurs as a result of the removal of pre-existing asphalt pavements for the purposes of reconstruction, resurfacing, or the facilitation of access to subterranean utilities. Upon appropriate crushing and screening procedures, WAP is comprised of meticulously sorted and graded aggregates that are coated with aged asphalt, resulting in a premium-quality product. The recycling of waste asphalt pavement (WAP) has garnered considerable attention in academic circles, with reported rates of up to 47% in Europe and 84% in the US. This is primarily achieved through the utilization of hot and warm mix asphalt processes. Nevertheless, there is a significant amount of waste asphalt pavement (WAP) materials that have not been utilized as of yet, as noted by Zaubanis. Recent research has indicated that the issue of WAP can be resolved through the utilization of WAP as both base and subbase aggregate materials. Geopolymers have been effectively utilized by

multiple researchers for the purpose of stabilizing WAP material in applications such as pavement bases or subbases.



**Figure 15. Unconfined Compressive Strength (UCS) at 7 and 28 days of WAO-CFA and WAO-GGBFS Blends**

The authors, Mohammadinia, et al. (2016), have provided evidence that the utilization of CFA and/or slag-based geopolymer stabilization has

resulted in a significant improvement in the mechanical properties, such as unconfined compressive strength and elastic modulus, of WAP. Furthermore, it has been demonstrated that the mechanical robustness of stabilized waste activated sludge ash materials exhibits a positive correlation with the augmentation of geopolymer binder concentration. The findings of this study align with those who conducted a study on the efficacy of samples stabilized by CFA-based geopolymer at different ratios of WAP and natural aggregate. Furthermore, Saride discovered that the strength properties of WAP particles were significantly influenced by the extent of exposed aggregate surface area. It has been posited that the presence of an amorphous asphalt layer on WAP particles may result in a reduction in the potency of the cementitious bond that is established by geopolymer binders. In addition, the research team led by Hoy conducted an assessment of the potency enhancement and microstructural characteristics of geopolymer-stabilized WAP, as documented in their publications from 2016a and 2018. The CFA or slag blends were subjected to activation by means of a sodium hydroxide solution and a sodium silicate solution, following which they were utilized for the purpose of stabilizing the WAP. The findings of the test indicate that the aforementioned products satisfy the relevant specifications, as illustrated in Figure 15, and thus are suitable for utilization as a foundational material in road construction. According, the superior performance observed in Fig. 16 can be attributed to the more stable three-dimensional formation of the aluminosilicate geopolymer structure, which is a result of the increased NaOH content. The present research has examined the permanency of geopolymer-stabilized waste activated sludge (WAP) in relation to wet-dry cycles and toxic leaching. Hoy have conducted previous studies on this topic, and their findings indicate that the geopolymer stabilized WAP has demonstrated satisfactory performance.

## Other Wastes

### Asbestos

Asbestos-containing materials have been utilized for insulation purposes in construction and diverse commodities such as roofing materials, water supply lines, and wall cladding due to their exceptional tensile strength, inadequate heat conduction, and elevated resistance to chemical degradation. Nevertheless, due to its highly carcinogenic nature, asbestos has been prohibited for mining and utilization in most nations since the early 1980s. However, there are still obstacles to overcome in regards to the proper disposal of waste materials contaminated with asbestos, which is a matter of worldwide significance. Various methods, including physical, thermal, chemical, and biological treatments, have been suggested as potential solutions for converting asbestos-contaminated materials into non-hazardous substances. However, there is a search for a recycling solution that is both appropriate and appealing for these final products. The utilization of asbestos-cement products subsequent to thermal treatment was effectively implemented by Gualtieri (2012). in the creation of geopolymers. The asbestos cement that was subjected to treatment was found to contain silicates rich in Al, Ca, and Mg (with SiO<sub>2</sub> comprising 30.8%, Al<sub>2</sub>O<sub>3</sub> comprising 5.4%, CaO comprising 48.5%, and MgO comprising 7.5%). The findings of the study suggest that the incorporation of treated asbestos cement has the ability to enhance the geo-polymerization reaction while also improving the physical and mechanical properties of the resulting geopolymers. These results highlight the potential for the utilization of treated asbestos waste in the development of geopolymer composites.

### Mineral Wool

Mineral wool is a fibrous substance that is produced through the spinning or drawing of molten materials derived from minerals or rocks. Mineral wool finds its primary applications in the domains of thermal insulation, encompassing structural and pipe insulation, and soundproofing. The scholarly investigation into the repurposing of mineral wool waste in



literature is currently limited. The present investigation involved the utilization of mineral wool waste, comprising stone wool and glass wool, which was procured from building demolition and construction sites. The waste was subjected to milling to obtain a powdered form, which was subsequently employed as a geopolymer precursor. The compressive strength of the geopolymer pastes was reported to be within the range of 25–45 MPa after 28 days. In addition, the geopolymer pastes that were prepared exhibited exceptional durability when subjected to the harsh freeze-thaw conditions. The findings of this research offer significant insights into the promotion of mineral wool waste as a geopolymer precursor.

## Conclusions

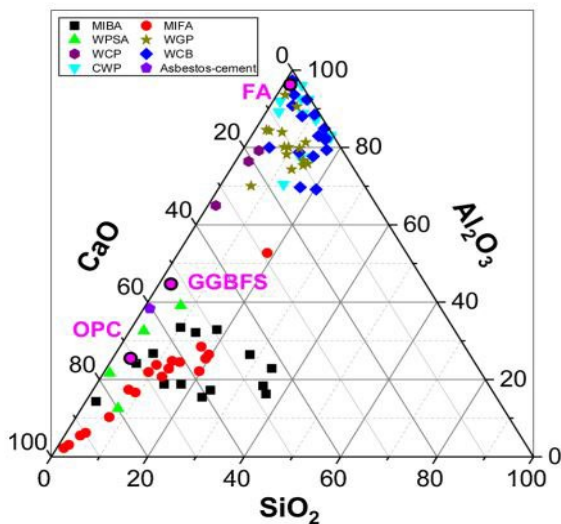
Table 2 provides an overview of the properties of the solid waste analyzed, along with their applications and the corresponding efficacy of the geopolymer composites produced. It is noteworthy that the recycling of solid waste materials into geopolymer composites exhibits certain similarities, thereby facilitating the exchange of knowledge and expertise among stakeholders. In general, it is possible to recycle both municipal and construction solid waste materials in various forms, such as precursors, aggregates, additives, reinforcement fiber, and filling materials. These materials can be utilized to create sustainable geopolymer composites, which align with the green concept. The incorporation of solid waste materials in geopolymer composites yields advantageous outcomes. However, it is imperative to exercise caution in light of the potential adverse effects associated with waste utilization. This can be accomplished by judiciously determining the content of the inclusion. In the event that the utilization of municipal and construction solid waste is contemplated for the purpose of large-scale production of geopolymer composites, it is imperative to evaluate the uniformity and accessibility of the materials supply in the waste streams, as well as the proximity to the geopolymer product manufacturers.

In addition, various effective methods, including the water-wash treatment, appropriate incineration processes, and mechanical grinding, have been widely acknowledged to enhance the performance of geopolymer products that contain solid waste. It is possible to optimize the utilization of waste materials in geopolymer composites while maintaining the performance of the resulting geopolymer products. Nevertheless, there are certain obstacles that need to be surmounted. According to Gualtieri (2012), the environmental sustainability of products may be compromised on a global scale due to the high expenses and energy consumption required, particularly in the context of physical and thermal treatments. Moreover, with regards to the chemical treatment procedures, the utilization of numerous reagents is imperative. However, the ultimate destiny of the reagents used in post-treatment continues to be a significant area of apprehension, as highlighted by Spasiano and Pirozzi. Therefore, it is highly recommended to gather and analyze the effects related to energy and material inputs, as well as environmental emissions, for every treatment scenario. Life cycle assessment is a valuable tool that can aid decision-makers in evaluating waste treatment options and furnish information on associated risks. This has been demonstrated by various. Moreover, there is a significant need for sophisticated and innovative technical approaches to address the limitations of traditional treatment modalities. Shi (2016) proposed the utilization of carbonation treatment as a means of improving the properties of recycled concrete aggregates. This approach is not only effective but also environmentally sustainable.

Figure 16 presents a comparison of the primary chemical constituents, namely calcium, silica, and alumina oxides, among various solid waste materials. It has been observed that significant disparities in the primary chemical constitution arise as a result of variations in both the classification and origins of said substances. Furthermore, it is evident from the preceding sections that the composition of additional chemical compounds is subject to variation



based on the various origins of solid waste. Moreover, it is worth noting that distinct solid waste materials exhibit diverse physical characteristics and mineralogical compositions, as highlighted in the works of Provis (2013). The various diversities present in synthesized geopolymer composites are responsible for their distinct behavior, as noted by Provis (2015).



**Figure 16. The Proportion of Silica, Alumina, and Calcium Oxide in Municipal and Construction Solid Waste is Shown in the Ternary Diagram**

Thus, this underscores the importance of elucidating and modeling the kinetics and mechanisms of geopolymerization reactions using various source materials. The reason for this is that a comprehensive comprehension of the subject matter can function as a reference point for geopolymer researchers to determine the essential factors during the planning and production phases. Additionally, it can establish a connection between the characteristics of the source materials and formulation conditions and the performance of the resulting geopolymer composites. Therefore, the actual worth of solid

waste materials can be recognized and unleashed. Furthermore, due to the mineralogical heterogeneity and complexity of solid waste materials, as well as their wide range of particle shapes and sizes, advanced characterization techniques for precursor materials are crucial in order to facilitate the aforementioned step.

The effective management of solid waste is crucial to promoting the recycling of such materials in geopolymer composites or other recycling methods. This underscores the need for well-designed solid waste management plans and strategies. Waste sorting is a crucial aspect of waste management that plays a pivotal role in enhancing the recycling rate. The reason for sorting municipal and construction solid waste is due to the presence of a diverse range of materials within the waste stream. Mixed and contaminated waste is unsuitable for recycling purposes. Sorting facilitates the separation of waste into distinct groups based on their respective components. The process of waste sorting is essential in order to extract more valuable components that can be recycled. In light of this situation, it is recommended that improved methods of separation and sorting, along with appropriate equipment, for the waste stream, irrespective of whether the operations are conducted on-site or off-site. Furthermore, the crucial elements in the management program of municipal and construction waste are the rising consciousness and involvement of the public and pertinent stakeholders. Last but not least, it is crucial to augment government intervention and support. The provision of support for recycling initiatives may encompass various measures such as the disbursement of tax refunds to contractors who engage in waste material recycling, the creation of recycling markets, the implementation of incentive-based market support mechanisms, and the allocation of interest-free loans to small enterprises seeking to initiate or expand their recycling endeavors.

**Table 2. An Overview of the Characteristics, Applications, and Performance of the Resulting Geopolymer Composites**

Waste materials	Characteristics	Solid waste usage	Inclusion content	Performance of resulted geopolymer composites
Bottom ash from municipal solid waste incinerators	includes heavy metals, has a porous structure, and contains metallic aluminum.	Precursor	After the alkaline pretreatment, up to 100% can be utilized.	- A reduction in compressive strength - Extremely porous construction - Immobilized dangerous substances - Extremely porous construction.
Fly ash from municipal solid waste incinerators	Low reactivity and high concentrations of chlorides and sulfates in heavy metals	Additive Fine aggregate Precursor	Useable up to 50% It is advised to use no more than 50% volume. Only 20 weight percent or less is advised; following water-wash pretreatment, 100% may be utilized.	-Controlled hazardous element leaching, -Reduced workability, -Reduced drying shrinkage, -Increased setting time, Increased compressive strength, -Increased drying shrinkage, -Reduced workability
Paper waste sludge	high calcium concentration and strong reactivity	Precursor	Only 10 weight % can be utilized.	- Increased ductility - Increased impact resistance and damping modulus) -
Paper waste sludge and ash	Calcium concentration that is both high and reactive	Precursor	It is possible to utilize 100%.	Increased thermal and sound insulation
Rubber scrap	High deformability, strong acoustic and heat insulation, low density, hydrophobic nature, low stiffness, low stiffness, low stiffness, high toughness, and impact resistance	Aggregate  fiber augmentat ion	The suggested limit is 10 weight percent or 20 volume percent. You can use up to 30% by weight.	- Decreased density compressive, splitting tensile and flexural strength, elastic
Waste plastic	Low density, low stiffness, great deformability, excellent insulation for sound and heat, and difficult to degrade	small aggregate  fiber augmentat ion	20 vol.% is the suggested maximum. Only 2 weight percent can be utilized.	- Decreased mechanical characteristics (e.g.,
tire steel and fiber textile	High tensile strength, high density, and probable corrosion in tire steel fiber High tensile strength, low density tire textile fiber  High tensile strength, low density tire textile fiber	fiber augmentat ion	A maximum of 2 vol.% of tire steel fiber may be utilized.  Maximum tire textile fiber content of 20% is advised	- Enhanced flexural power - Enhanced fortitude - A more ductile attitude
discarded coffee grounds	High compressibility, low shear strength, and high organic content	Filling substance	It's advised to use no more than 70% by weight.	- The right mechanical characteristics, such as compressive strength and stiffness, for the subgrade material.
used cork	After thermal treatment, there is a high carbon content.	Additive	3.75 wt% is the most that may be utilized.	- Improved protection against electromagnetic interference - A reduction in compressive strength

Solid construction waste				
leftover concrete	a lack of strength, a high porosity, and a low level of reactivity	Precursor	It is possible to utilize 100%.	-decreased elastic modulus, splitting tensile and flexural strength, and other mechanical parameters
discarded clay brick	High porosity, strong fire resistance, mediocre strength, low density, and comparatively low reactivity	Aggregate		- Lessened resistance to abrasion and chemical assault, for example, - Enhanced heat resistance and insulation (waste clay brick and ceramic waste)
Ceramic debris	High porosity, strong fire resistance, weak strength, low density, and high reactivity			-Appropriate mechanical characteristics (such as compressive strength and stiffness) for base/subbase applications
Asphalt pavement leftovers	high porosity, substantial metal content, and old asphalt covering	Filling substance	It's advised to keep it at a maximum of 80%.	- A reduction in cementitious bond
cement with asbestos	high reactivity, chemically similar to a Mg-rich clinker (after heat treatment)	Additive	A maximum of 2.5 weight percent is advised.	Porosity was reduced, and flexural strength was increased.
Mineral fiber	extreme responsiveness	Precursor	may use up to 100%.	- Enhanced freeze-thaw resistance

## Author Contributions

Md Monir Hossain investigation, funding acquisition, and writing – original draft preparation writing; Prodhan Md Safiq Raiha: original draft preparation, data analysis, writing, review and editing, and checking the original draft; Mahnoor Rizwan: writing – review and editing and checking the original draft; Mithun Biswas: investigation, funding acquisition, checking the original draft, and writing, review and editing; Aqib Ali: checking the original draft and data analysis. All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

## References

- Abdel-Gawwad, H., Hekal, E., El-Didamony, H., Hashem, F. & Mohammed, A. (2018). Recycling of concrete waste to produce ready-mix alkali activated cement. *Ceramics International*, 44, 7300-7304. <https://doi.org/10.1016/j.ceramint.2018.01.042>
- Abdollahnejad, Z., Luukkonen, T., Mastali, M., Kinnunen, P. & Illikainen, M. (2018). Development of One-Part Alkali-Activated Ceramic/Slag Binders Containing Recycled Ceramic Aggregates. *Journal of Materials in Civil Engineering*, 31, [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002608](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002608)
- Adesanya, E., Ohenoja, K., Luukkonen, T., Kinnunen, P., Kinnunen, P., & Illikainen, M. (2018). One-part geopolymer cement from slag and pretreated paper sludge. *Journal of Cleaner Production*, 185, 168–175. <https://doi.org/10.1016/j.jclepro.2018.03.007>
- Aly, A.M., El-Feky, M.S., Kohail, M., & Nasr, E.S. (2019). Performance of geopolymer concrete containing recycled rubber. *Construction and Building Materials*, 207, 136–144. <https://doi.org/10.1016/j.conbuildmat.2019.02.121>
- Antunes Boca Santa, R.A., Bernardin, A.M., Riella, H.G., & Kuhn, N.C. (2013). Geopolymer synthesized from bottom coal ash and calcined paper sludge. *Journal of Cleaner Production*, 57, 302-307. <https://doi.org/10.1016/j.jclepro.2013.05.017>
- Bernal, S., Ball, R., Hussein, O., Heath, A., & Provis, J.L. (2014). Paper sludge ash as a precursor for production of alkali-activated

materials. Proceedings of the *Second International Conference on Advances in Chemically-Activated Materials* (CAM 2014).

Dave, S., Bhogayata, A., & Arora, N., (2017). Impact resistance of geopolymer concrete containing recycled plastic aggregates. *Kalpa Publications in Civil Engineering 1*, 137–143. <https://doi.org/10.29007/nwsh>

Dombrowski-Daube, K., Buchwald, A. & Weil, M. (2007). The Influence of Calcium Content on the Structure and Thermal Performance of Fly Ash Based Geopolymers. *Journal of Materials Science*, 42, 3033–3043. <https://doi.org/10.1007/s10853-006-0532-7>

Gandoman, M., & Kokabi, M. (2015). Sound barrier properties of sustainable waste rubber/geopolymer concretes. *Iranian Polymer Journal*, 24, 105–112. <https://doi.org/10.1007/s13726-014-0304-1>

Gomes, S.D., Zhou, J.L., Li, W., & Long, G. (2019). Progress in manufacture and properties of construction materials incorporating water treatment sludge: A review. *Resources, Conservation and Recycling*, 145, 148–159. <https://doi.org/10.1016/j.RESCONREC.2019.02.032>

Hassan, A., Arif, M., & Shariq, M. (2019). Use of geopolymer concrete for a cleaner and sustainable environment – A review of mechanical properties and microstructure. *Journal of Cleaner Production*, 223, 704–728. <https://doi.org/10.1016/j.JCLEPRO.2019.03.051>

Hoornweg, D., & Bhada-Tata, P. (2012). *What a Waste: A Global Review of Solid Waste Management*. World Bank, Washington, DC.

Huang, Y., Bird, R., & Heidrich, Oliver. (2007). A review of the use of recycled solid waste materials in asphalt pavements. *Resources, Conservation and Recycling*, 52, 58–73. <https://doi.org/10.1016/j.resconrec.2007.02.002>

Huseien, G.F., Sam, A.R., Mirza, J., Tahir, M.M., Asaad, M.A., Ismail, M., & Shah, K.W. (2018). Waste ceramic powder incorporated alkali

activated mortars exposed to elevated Temperatures: Performance evaluation. *Construction and Building Materials*, 187, 307–317.

<https://doi.org/10.1016/J.CONBUILDMAT.2018.07.226>

Ji, Z., & Pei, Y. (2019). Bibliographic and visualized analysis of geopolymer research and its application in heavy metal immobilization: A review. *Journal of environmental management*, 231, 256–267.

<https://doi.org/10.1016/j.jenvman.2018.10.041>

Khedmati, M., Kim, Y. R., & Turner, J. A. (2019). Investigation of the interphase between recycled aggregates and cementitious binding materials using integrated microstructural-nanomechanical-chemical characterization. *Composites Part B: Engineering*, 158, 218–229. <https://doi.org/10.1016/j.compositesb.2018.09.041>

Kinuthia, J. (2018). Wastepaper sludge ash. In: Siddique, R., Cachim, P. (Eds.), *Waste and Supplementary Cementitious Materials in Concrete*. Woodhead Publishing.

Komnitsas, K., Zaharaki, D., Vlachou, A., Bartzas, G., & Galetakis, M. (2015). Effect of synthesis parameters on the quality of construction and demolition wastes (CDW) geopolymers. *Advanced Powder Technology*, 26, 368–376.

<https://doi.org/10.1016/J.APT.2014.11.012>

Koushkbaghi, Mahdi & Alipour, Pedram & Tahmouresi, Behzad & Mohseni, Ehsan & Saradar, Ashkan & Sarker, Prabir. (2019). Influence of different monomer ratios and recycled concrete aggregate on mechanical properties and durability of geopolymer concretes. *Construction and Building Materials*, 205, 519–528.

<https://doi.org/10.1016/j.conbuildmat.2019.01.174>

Łach, M., Kiszka, A., Korniejenko, K., & Mikula, J. (2018). The Mechanical Properties of Waste Tire Cords Reinforced Geopolymer Concretes. *IOP Conference Series: Materials Science and Engineering*, 416, 012089.



<https://doi.org/10.1088/1757-899X/416/1/012089>

Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M. Z., & Christensen, T. H. (2014). Review of LCA studies of solid waste management systems--part I: lessons learned and perspectives. *Waste management (New York, N.Y.)*, 34(3), 573–588. <https://doi.org/10.1016/j.wasman.2013.10.045>

Liu, C., Deng, X., Liu, J., & Hui, D. (2019). Mechanical properties and microstructures of hypergolic and calcined coal gangue based geopolymer recycled concrete. *Construction and Building Materials*, 221, 691–708. <https://doi.org/10.1016/j.conbuildmat.2019.06.048>

Long, W.-J., Li, H., Wei, J., Xing, F., & Han, N. (2018). Sustainable use of recycled crumb rubbers in eco-friendly alkali activated slag mortar: Dynamic mechanical properties. *Journal of Cleaner Production*, 204. <https://doi.org/10.1016/j.jclepro.2018.08.306>

Luhar, S., Cheng, T.-W., & Luhar, I. (2019b). Incorporation of natural waste from agricultural and aquacultural farming as supplementary materials with green concrete: A review. *Composites Part B: Engineering*, 175, 107076. <https://doi.org/10.1016/j.compositesb.2019.10.7076>

Menegaki, M., & Damigos, D. (2018). A review on current situation and challenges of construction and demolition waste management. *Current Opinion in Green and Sustainable Chemistry*, 13, 8–15. <https://doi.org/10.1016/j.COGSC.2018.02.010>

Mohammadinia, A., Arulrajah, A., Sanjayan, J., Disfani, M., Bo, M. & Darmawan, S. (2016). Stabilization of Demolition Materials for Pavement Base/Subbase Applications Using Fly Ash and Slag Geopolymers: Laboratory Investigation. *Journal of Materials in Civil Engineering*, 28, 04016033. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001526](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001526)

Mohammed, B., Liew, M.S., Alaloul, W., Al-Fakih, A., Ibrahim, W. & Adamu, M. (2018).

Development of Rubberized Geopolymer Interlocking Bricks. *Case Studies in Construction Materials*, 8, 401–408. <https://doi.org/10.1016/j.cscm.2018.03.007>

Novais, R. M., Saeli, M., Caetano, A. P., Seabra, M. P., Labrincha, J. A., Surendran, K. P., & Pullar, R. C. (2019). Pyrolysed cork-geopolymer composites: A novel and sustainable EMI shielding building material. *Construction and Building Materials*, 229, 116930. <https://doi.org/10.1016/j.conbuildmat.2019.11.6930>

Onuaguluchi, O., Ribeiro Borges, P., Bhutta, A. & Banthia, N. (2017). Performance of scrap tire steel fibers in OPC and alkali-activated mortars. *Materials and Structures*, 50. <https://doi.org/10.1617/s11527-017-1026-6>

Peyne, Julie & Joussein, Emmanuel & Gautron, Jérôme & Doudeau, Julie & Rossignol, Sylvie. (2017). Feasibility of producing geopolymer binder based on a brick clay mixture. *Ceramics International*, 43. <https://doi.org/10.1016/j.ceramint.2017.04.162>

Posi, P., Ridditirud, C., Ekvong, C., Chammanee, D., Janthowong, K., & Chindaprasirt, P. (2015). Properties of lightweight high calcium fly ash geopolymer concretes containing recycled packaging foam. *Construction and Building Materials*, 94, 408–413. <https://doi.org/10.1016/j.CONBUILDMAT.2015.07.080>

Provis, John. (2013). Geopolymers and Other Alkali Activated Materials: Why, How, and What? *Materials and Structures*, 47. <https://doi.org/10.1617/s11527-013-0211-5>

Robayo-Salazar, R., Mulford, A., Munera, J. & Mejia, R. (2016). Alternative cements based on alkali-activated red clay brick waste. *Construction and Building Materials*, 128, 163–169. <https://doi.org/10.1016/j.conbuildmat.2016.10.023>

Sedaghatdoost, A., Behfarnia, K., Bayati, M., Sadegh Vaezi, M. (2019). Influence of recycled concrete aggregates on alkali-activated slag mortar exposed to elevated temperatures. *Journal*

of *Building Engineering*, 26, 871-879.  
<https://doi.org/10.1016/j.jobbe.2019.10087>

Wongkvanklom, Athika & Posi, Patcharapol & Homwuttiwong, Sahalaph & Sata, Vanchai & Wongs, Ampol & Tanangteerapong, Duangkanok & Chindaprasirt, Prinya. (2019). Lightweight Geopolymer Concrete Containing Recycled Plastic Beads. *Key Engineering Materials*, 801, 377-384.  
<https://doi.org/10.4028/www.scientific.net/KE.801.377>

Wongsa, A., Sata, V., Nuaklong, P., & Chindaprasirt, P. (2018b). Use of crushed clay brick and pumice aggregates in lightweight geopolymer concrete. *Construction and Building Materials*, 188, 1025-1034.  
<https://doi.org/10.1016/j.conbuildmat.2018.08.176>

Xie, J., Wang, J., Rao, R., Wang, C., & Fang, C. (2019). Effects of combined usage of GGBS and fly ash on workability and mechanical properties of alkali activated geopolymer concrete with recycled aggregate. *Composites Part B: Engineering*, 164, 179-190.  
<https://doi.org/10.1016/j.compositesb.2018.11.067>

Xu, J., Chen, Z.-P., Xiao, Y., Demartino, C. & Wang, J.-H. (2017). Recycled Aggregate Concrete in FRP-confined columns: A review of experimental results. *Composite Structures*, 174, 277-291.  
<https://doi.org/10.1016/j.compstruct.2017.04.034>

Zhong, H., Poon, E., Chen, K., & Zhang, M. (2019). Engineering properties of crumb rubber alkali-activated mortar reinforced with recycled steel fibres. *Journal of Cleaner Production*, 238.  
<https://doi.org/10.1016/j.jclepro.2019.117950>