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Review

Sustainable Alkali-Activated and Geopolymer Materials: What Is the Future for Italy?

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Abstract

Using innovative and sustainable materials has become crucial for developed countries. Reusing waste as a secondary raw material in industrial processes central to the circular economy could enhance environmental sustainability and support local economies. Building materials such as Portland cement have a significant environmental impact due to greenhouse gas emissions and construction and demolition waste (CDW), which is challenging to recycle. Research into sustainable alternatives is, therefore, essential. The European Union has set ambitious targets to reduce greenhouse gas emissions by 55% by 2030 and achieve climate neutrality by 2050. The National Recovery and Resilience Plan (PNRR) supports the green transition in Italy by promoting sustainable materials like geopolymers. These ceramic-like materials are based on aluminosilicates obtained through the chemical activation of waste rich in silica and aluminosilicate compounds. Though promising, these materials require further research to address challenges like long-term durability and chemical variability. Collaboration between scientific research and industry is essential to develop specific protocols and suitable infrastructures. This article provides a critical review of the advancements and challenges in using alkali-activated waste as construction binders, focusing on Italy, and encourages the exploration of alternative sustainable materials beyond conventional Portland cement.

Keywords: geopolymer; alkali-activated material; sustainability; aluminosilicate waste

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1. Introduction

1.1. Global Context

The development and deployment of innovative, sustainable construction materials have become imperative for every industrialized nation. Reusing and valorizing industrial waste as a secondary raw material, one of the cornerstones of the circular economy, offers a decisive route to lowering environmental impacts while invigorating local economies and shortening supply chains. Among industrial sectors, building products possess the largest share of the embodied carbon budget because the manufacture of ordinary Portland cement (OPC) releases substantial quantities of greenhouse and hazardous gases [1–3]. Current lifecycle assessment (LCA) models indicate that cement production alone accounts for approximately 7% of global anthropogenic CO_2 emissions, a figure that could rise to 12% by 2050 if no corrective action is taken [3]. Moreover, the difficulty of recycling

construction and demolition waste (CDW) exacerbates landfill pressures and increases the volume of the hazardous solid waste that must be managed. Therefore, the United Nations Sustainable Development Goals, especially SDG 9 (industry, innovation, and infrastructure) and SDG 12 (responsible consumption and production), call for a paradigm shift towards low-carbon, resource-efficient binders capable of closing material loops within regional value chains. In this context, cementitious alternatives derived from industrial waste are not only desirable but increasingly necessary to support decarbonization policies.

1.2. Policy Drivers in Europe and Italy

At the policy level, the European Union has legislated for a 55% net reduction in greenhouse gas emissions by 2030 and full climate neutrality by 2050, formalized through successive amendments to Directive 2002/49/EC and reinforced by the delegated Directive (EU) 2021/1226 [4]. Complementing these targets, the EU Taxonomy for sustainable activities and the revised construction products regulation incentivize manufacturers to quantify and minimize the embodied carbon of building components by means of harmonized product category rules. The unprecedented Next Generation EU (NGEU) program and, more specifically for Italy, the National Recovery and Resilience Plan (PNRR) direct significant investment towards low-carbon technologies, renewable energy, and green public procurement. Synergies between EN 197-6 (which will permit higher clinker replacement levels) and the forthcoming CEN/TC 350 standards on circularity metrics create an unprecedented opportunity for integrating alternative binders into mainstream construction practice. In parallel, the Green Public Procurement criteria introduced for public works projects in Italy explicitly prioritize low-impact construction materials, providing an additional market pull. Taken together, these policy instruments transform once-marginal research on alkali-activated materials into a strategic priority for both public authorities and private investors, as they are now aligned with measurable environmental and financial performance indicators.

1.3. Alkali-Activated Materials (AAMs) and Geopolymers (GPs) as a Technical Solution

Aluminosilicate-rich wastes dissolve and polycondense in strongly alkaline media, yielding AAMs and GPs: amorphous, ceramic-like networks built from tetrahedrally coordinated Si^{4+} and Al^{3+}. Synthesized below 100 °C, these binders attain compressive strengths that rival, and often exceed, OPC and display exceptional resistance to heat, acids, and chloride-induced corrosion [5]. Early work by Glukhovsky and Krivenko on alkali-activated slag concretes [6], followed by Davidovits's formalization of geopolymer chemistry [7–9], laid the scientific foundations of the field, while the attribution of pyramid stone to geopolymerization [7] stimulated public interest. A wide spectrum of precursors, including metakaolin, fly ash, CDW fines, rice husk ash, blast furnace slag, red mud, photovoltaic glass cullet, and even some industrial sludge, has since been investigated [10]. The activator choice (NaOH, KOH, mixed hydroxide–silicate solutions, carbonates, and even seawater brines) crucially influences dissolution kinetics, gel chemistry, and rheology. Hybrid formulations incorporating $Ca(OH)_2$ or sodium carbonate have recently demonstrated a $\geq$ 45% CO_2 reduction relative to CEM I (CEMent) while retaining setting times compatible with industrial concrete practices. However, challenges, such as feedstock variability, alkali–silica reactivity, and the occurrence of surface efflorescence, continue to hinder full-scale industrial adoption. Furthermore, research into the influence of minor oxides (e.g., MgO, TiO_2) on the geopolymerization process is still limited and may offer additional levers for performance optimization.

1.4. Durability, Environmental Assessment, and Current Research Gaps

Long-term performance data for AAM- and GP-based concretes are limited compared with the century-long datasets available for OPC [1,2]. Although numerous studies report excellent acid and sulphate resistance [10], concerns persist regarding carbonation-induced strength loss, alkali migration and the potential leaching of trace metals held within the amorphous gel network [10]. Recent field exposure trials in marine and industrial atmospheres have demonstrated mass losses below 0.2% after three years [3], yet standardized durability protocols (e.g., EN 206 exposure classes) remain to be fully validated for alkali-activated systems. From an environmental perspective, comparative LCAs performed under ISO 14040/44 [11] rules consistently show cradle-to-gate CO_2 savings of 40–70%, provided that industrial residues are allocated a zero-burden credit and that activator solutions are sourced locally [12,13]. However, the energy demand and occupational health considerations associated with handling highly alkaline activators necessitate rigorous risk management strategies. In addition, the lack of harmonized environmental product declarations for geopolymer-based materials impairs transparency and slows down market acceptance. Future research must, therefore, integrate materials science, geochemistry, and structural engineering with advanced modeling and probabilistic design tools to quantify service-life and whole-life carbon more robustly [14–16]. The cross-validation of lab-scale findings with field-scale pilot applications will be essential to confirm the long-term viability under realistic exposure conditions [17].

1.5. Aims and Structure of This Review

In the Italian context, the ISPRA Waste Report indicates that special waste generation rose to 165 Mt in 2021 (+12.2% over 2020) [18], of which a significant fraction comprises aluminosilicate- or silica-rich streams suitable for alkaline activation. Major contributors include mining tailings, CDW (particularly ceramic waste), sewage sludge, biomass and incinerator ash, waste glass, and non-metallic fractions from electronic waste. Yet industrial uptake is hindered by the absence of dedicated collection logistics, the insufficient characterization of feedstock variability and regulatory uncertainty surrounding the end-of-waste status. Bridging these gaps demands a cohesive, multidisciplinary effort that unites chemical engineering, materials science, and civil engineering while engaging policy-makers and industrial stakeholders. Consequently, the present review (i) summarizes the chemical principles governing alkaline activation and identifies how precursor chemistry translates into microstructural development; (ii) examines the state-of-the-art manufacturing routes, including extrusion, 3D printing, and foam geopolymer technologies; (iii) evaluates mechanical performance and durability against established design codes; and (iv) appraises the economic and regulatory landscape, with particular emphases on Italian raw material flows and market drivers. By clarifying such interdependencies, the review aspires not only to guide future academic research but also to furnish designers, contractors, and policy-makers with actionable insights capable of accelerating the transition towards low-carbon, circular-economy binders within the built environment.

2. Chemistry of the Alkaline Activation of Aluminosilicate Materials

GPs and alkali-activated binders are hardened systems that gain strength and other properties through a chemical interaction between alkaline solutions and aluminosilicate-rich source materials. A geopolymer is an inorganic aluminosilicate polymer composed of tetrahedrally coordinated Si^{4+} and Al^{3+}, producing a polymer chain. These geopolymer precursors chemically link and form oligomers, which results in the creation of a three-dimensional structure [19–22]. In contrast, alkali-activated binders are made using the activation of calcium-rich source materials under highly alkaline conditions. Following the

dissolution of the precursors in an alkaline solution, a binder paste with a hydraulic potential is formed, resulting in the simultaneous synthesis of C-S-H gels and aluminosilicate polymers [19]. Figure 1 compares the reaction mechanism of AAMs and GPs [19].

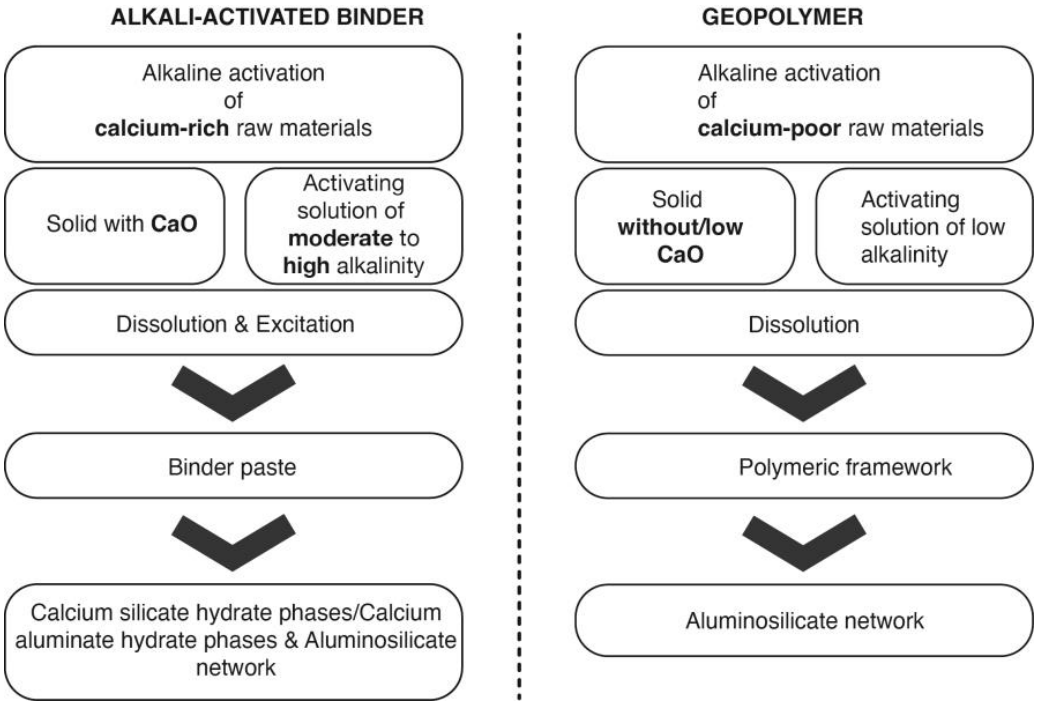


Figure 1. A comparison of the reaction mechanism of AAMs and GPs.

Several variables, such as the chemical composition of the raw materials [23], the curing temperature [24], the curing humidity [25], the curing method [26], and chemical additives [27], greatly influence the reaction mechanism between the alkali source and the aluminosilicate, which controls the microstructure development and the final properties of the systems.

According to earlier descriptions of AAMs and GPs, two kinds of chemical reactions occur between the alkaline activators and the aluminosilicate sources: the high-calcium/magnesium systems and the low-calcium/magnesium systems (Figure 2). The calcium/magnesium aluminosilicate hydrates in a high-calcium/magnesium system are represented by the hydration product, commonly written as C(M)-A-S-H. This typically takes the form of a Q2 layered structure. In contrast, in a low-calcium/magnesium system, the silicon and aluminum sites coordinate to form a tetrahedral structure, primarily Q3 or Q4. The positively charged alkaline ions in the Q4 structure will counterbalance the negatively charged tetrahedral aluminum silicon coordination to create a three-dimensional gel structure. The Si/Al ratio [28] and the reaction environment determine the presence of the Q1, Q2, Q3, and Q4 structures.

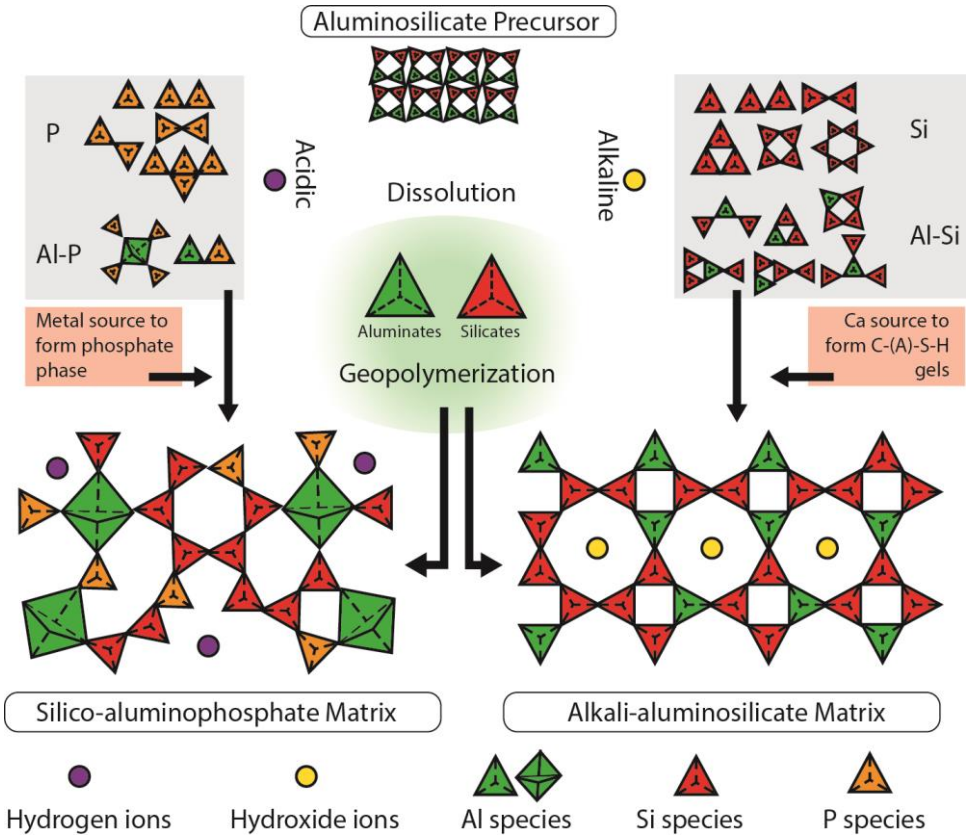


Figure 2. The reaction mechanism of the acidic and alkaline activation of a solid aluminosilicate precursor [29].

Furthermore, the chemical structure of GPs can be modified and made into hybrid or composite systems in order to produce new materials for cutting-edge technological applications [15–17,30–38].

GPs and AAMs have versatile applications across both conventional and specialized sectors. In construction, they are utilized for structural development, repair, restoration, marine infrastructure, road foundations, 3D printing, and the production of fire-resistant, high-temperature, thermal, and acoustic insulating materials. Their specialized uses extend to environmental remediation, including heavy metal immobilization, pH regulation, catalysis, and the development of conductive materials for moisture sensing and thermal energy storage [39–45]. Additionally, they serve functional roles in critical infrastructure, such as fire-resistant barriers, insulation panels, and protective components in nuclear facilities, contributing to fire safety, thermal regulation, and hazardous ion adsorption [46–53].

3. Performance Comparison of Geopolymers (GPs) and Alkaline-Activated Materials (AAMs) Versus Ordinary Portland Cement (OPC)

GPs and AAMs have attracted increasing interest in recent decades as promising alternatives to ordinary Portland cement (OPC) due to their ability to significantly reduce environmental impacts while maintaining, or even exceeding, the technical performance of conventional binders. Their development is particularly relevant in the context of sustainable construction practices and circular economy strategies, where the reuse of industrial by-products and waste materials is becoming increasingly important. This section provides an extended comparative overview, focusing on mechanical behavior, energy and economic requirements, and environmental aspects.

3.1. Mechanical Properties

GPs and AAMs are increasingly appreciated for their remarkable mechanical performance. Many studies report compressive strength values generally varying between 40 and 90 MPa, depending on several factors, such as the type of precursor used (e.g., fly ash, metakaolin, or slag), the nature and concentration of the alkaline activator, the curing conditions, and the water/solids ratio employed [11,28]. These performances are often equivalent, if not superior, to those of ordinary Portland cements (OPCs), which usually range between 20 and 60 MPa [1,3].

A particularly interesting aspect is that geopolymers tend to develop a more compact and homogenous microstructure, with reduced porosity and a more uniform distribution of gel phases. This results in a better load-bearing capacity and greater durability over time [10,27].

In terms of chemical resistance, these materials also show superior behavior, especially in particularly aggressive environments, such as those containing sulphates, chlorides, or acidic agents. The main reason lies in their composition: unlike OPC, which is rich in calcium and, therefore, more vulnerable, GPs are based on aluminosilicate gels (N-A-S-H or C-A-S-H) that are much more stable and less prone to degradation [10,27].

Finally, it is believed that GPs and AAMs have exceptional thermal stability, even when exposed to high temperatures (600–800 °C). In fact, they showed that 60% of their mechanical properties were still present after exposure to high temperatures, indicating their potential for use in extreme temperatures and fire conditions [30,31].

3.2. Cost and Energy Demand

The economic feasibility of GPs and AAMs largely depends on the availability of suitable precursors and the cost of alkaline activators. Although many precursors, such as fly ash, blast furnace slag, or calcinable clays, are widely available and often low-cost or derived from waste, the use of alkaline solutions, such as sodium hydroxide or sodium silicate, can significantly increase the overall cost, particularly on a small production scale [10,12]. Economies of scale and industrial symbiosis models could reduce these costs, but economic sustainability remains a challenge for large-scale implementation in many contexts.

From an energy point of view, the production of GPs is unquestionably less energetic than that of OPC. The production of OPC involves the thermal treatment of raw materials at around 1450 °C to generate clinker, which is a highly energetic and CO_2-emitting process. On the other hand, geopolymerization reactions occur at ambient or moderately high temperatures (usually 60 to 90 °C), resulting in a significantly lower energy improvement [13]. However, the energy required to produce the sodium-based activator is not traceable, and the variability of the procedures, alongside the requirement of international standards, continues to reveal a wide-scale dissemination [5,29].

3.3. Environmental Impact

LCA (life cycle analysis) studies have shown that GPs and AAMs possess low environmental impacts, especially when compared to OPC. In fact, the CO_2 production (which is highly dependent on the raw materials used and the energy for the production of the activating solutions and the thermal curing of the materials) involved in the production processes of these materials is 40–80% lower [8,12,13]. In fact, OPC production processes require the use of high temperatures (due to limestone decarbonation) with emissions of 0.8 to 1.0 tons of CO_2 per tonne of cement produced [2,14].

Furthermore, GPs can be formulated entirely from recycled materials or industrial by-products, avoiding the use of virgin limestone and bypassing the carbon-intensive

calcination process [12,15]. However, it is important to consider some environmental trade-offs: the production of hydroxide and sodium silicate is itself energy-intensive and may mitigate some of the environmental benefits if not supported by renewable sources [12,20]. That said, when GPs are produced within integrated systems that utilize local resources and industrial symbiosis, e.g., in co-localized chemical plants, their overall environmental profile is much more favorable, strengthening their position as a low-carbon alternative to OPC.

A summary of the main technical and environmental differences between OPC and alternative binders is presented in Table 1, which highlights the comparative performance of geopolymers and alkaline-activated materials concerning key parameters of sustainable construction.

Table 1. Comparison of key performance, environmental, and production characteristics of ordinary Portland cement (OPC) and geopolymer/alkali-activated materials (GPs/AAMs).

Property	OPC	GPs/AAMs
Compressive strength (MPa)	20–60	40–90
Acid/sulphate resistance	Moderate to poor	High
Fire resistance	<300 °C	Up to 800 °C
Raw material origin	Virgin (limestone, clay)	Industrial by-products, waste-derived
Production temperature	~1450 °C	Ambient to <100 °C
CO_2 emissions (tCO_2/t binder)	~0.9	0.2–0.6
Cost variability	Stable, standardized	Variable (dependent on activator type)
Standardization and codes	Fully established	Limited, under development

The validity of GPs and AAMs as concrete alternatives to traditional Portland cement (OPC) clearly emerges from this comparison, especially when prioritizing durability and environmental sustainability.

4. Main Aluminosilicate Sources from Italian Waste

4.1. Construction and Demolition Waste

Construction and demolition waste (CDW) is a by-product material from construction or demolition activities, mainly consisting of bricks, masonry, and concrete fragments, including reinforced concrete, cladding, and ceramic products; and waste from the precasting industry, including reinforced concrete, fragments of road or railway superstructures, cold-milled bituminous conglomerates, plaster, and bedding.

In Italy, between 2020 and 2021, the increase in the production of special non-hazardous waste is attributable mainly to the increase in the amount of construction and demolition waste, which rises from 64.8 million tonnes to 77.2 million tonnes (+19.2%, corresponding to 12.4 million tonnes) [18]. The analysis information from the "Single Environmental Declaration Form—MUD" database shows an increase of 6.6%, approximately 4.6 million tonnes compared to 2020, for a total quantity of over 73 million tonnes (+3.1%, corresponding to 2.2 million tonnes compared to 2019) [18].

According to a 2019 report [54], 10–15% of material is wasted during the construction phase, while among demolition waste materials, as much as 54% ends up in landfills: there is still much to be done for recovery, understood as reuse and recycling, to become a part of the circular building system.

The alkaline activation of CDW has attracted considerable attention in recent years thanks to its potential to reduce waste and increase sustainability in the construction industry. Generally, these wastes are treated to produce fine and coarse aggregates.

These have geotechnical uses, including stabilizing slopes, deep and shallow foundations, granular bases, and sub-bases, and can be added to mortar and concrete mixtures

as a partial or complete replacement for natural aggregates [55,56]. Nevertheless, using recycled aggregates does not offer a worldwide answer to the problem of CDW exploitation, mainly due to their low commercial competitiveness when comparing their economic (non-environmental) cost with that of natural aggregates in many cities and countries. This drawback is made worse by the absence of laws intended to prevent the indiscriminate use of natural quarries and to encourage the widespread use of recycled aggregates as a replacement for natural aggregates. Because of this, there is a global emphasis on finding recycling substitutes and/or higher-value commercial applications that guarantee the actual use of CDW.

The few results published thus far, as indicated in Table 2, regarding using CDW as precursors of AAMs are encouraging and illustrate the potential for this type of waste to be reused by this technology. These publications, however, are relatively new and, for the most part, only address the acquisition and characterization of pastes, without extrapolating the findings to the level of their intended use (mortars, concretes, building components, and/or applications). Similarly, thermal curing procedures were often conducted between 50 and 90 °C to obtain sufficient mechanical strength, which restricts their technical transfer to industry. It should be highlighted that, as Table 1 illustrates, these investigations begin with the use of separated residues, or "clean," and do not take into account mixtures or combinations of these components.

Robayo-Salazar et al. [57], report on a study of the alkaline activation of a real CDW source, made of masonry, concrete, ceramic, and mortar, that was removed from a nearby landfill in Cali, Colombia. Hydroxide and sodium silicate mixtures were utilized as an alkaline activator solution. To encourage the curing of the pastes at room temperature (about 25 °C), a 10% proportion (by weight) of Portland cement (OPC) was added to the CDW precursor in order to create a hybrid cement.

Table 2. Main papers on CDW as precursors of GPs and AAMs (OPC: ordinary Portland cement; MK: metakaolin; FA: fy ash; GBFS: blast furnace slag).

Waste	Addition (Wt/Wt)	Activator	Curing		Compressive Strength Max (MPa)	Sample	Ref.
			°C	Days			
Concrete	20% MK	$NaOH + Na_2SiO_3$	60	3	33	Paste	[58]
Masonry	—	$NaOH + Na_2SiO_3$	60	7	50	Paste Mortar	[59]
Concrete	—	$NaOH + Na_2SiO_3$	90	7	13	Paste	[60]
Masonry					58		
Tile					50		
Masonry	0%	$NaOH + Na_2SiO_3$	25	—	54	Paste	[61]
	20% OPC				103		
Concrete	0%	$NaOH + Na_2SiO_3$	25	—	26	Paste	[62]
	30% OPC				34		
	10% MK				46		
Concrete	—	$NaOH + Na_2SiO_3$	80	1	8	Paste	[63]
Masonry					39		
Tile					58		
Masonry	—	$NaOH + Na_2SiO_3$	50	1	—	Coating	[64]
Ceramic	15% OPC	$NaOH + Na_2SiO_3$	25	—	58	Paste	[65]
					25	Mortar	

Table 2. *Cont.*

Waste	Addition (Wt/Wt)	Activator	Curing		Compressive Strength Max (MPa)	Sample	Ref.
			°C	Days			
Ceramic	5% $Ca(OH)_2$	NaOH + Na_2SiO_3	65	3	43	Mortar	[66]
Masonry	0%	NaOH	25	—	7	Paste	[67]
	10% OPC				41		
	0%	NaOH + Na_2SiO_3			54		
	20% OPC				103		
Ceramic	5% $Ca(OH)_2$	NaOH + Na_2SiO_3	65	3	43	Mortar	[68]
Masonry	0%	NaOH	25	—	7	Paste	[69]
	30% OPC				41		
	0%	NaOH + Na_2SiO_3			54		
	30% OPC				103		
Concrete	0%	NaOH			7		
	30% OPC				10		
	0%	NaOH + Na2SiO3			26		
	30% OPC				34		
Masonry	—	NaOH + Na_2SiO_3	90	5	36	Mortar	[70]
Masonry	—	NaOH + Na_2SiO_3	25	—	42	Paste	[67]
Masonry	30% GBFS + 10% FA	NaOH + Na_2SiO_3	25	—	70	Paste	[70]
Ceramic	30% GBFS + 10% FA	NaOH + Na_2SiO_3	25	—	60		
Concrete	10% OPC	NaOH + Na_2SiO_3	25		42.6	Concrete	[57]

4.2. Mining Waste

Over the past few decades, the mining sector has produced huge amounts of waste rocks and tailings. During the quarrying, grinding, screening, and processing of ores and minerals, enormous residues are generated and typically rejected in large areas within the mine site, creating environmental challenges. The main secondary materials produced during these operations are overburdens and tailings, which are deposited following specific practices depending on the kind of waste.

Approximately 2–12 tons of overburden material are produced as waste rocks for every tonnne of metal extracted [71]. Up to 25 billion tons of solid mining residue are produced annually; the European Union is estimated to store more than 1.2 billion tons of tailings [72].

In Italy, the enormous quantities of mining waste (WEEE) produced during the production activities constitute widespread sources of pollution and areas of geotechnical and hydrogeological instability, implying problems of various kinds, including the following:

- The widespread presence of unattended mining waste;
- Abandoned structures and processing plants that may represent dangerous areas due to their potential collapse;
- Several underground voids can manifest on the surface, such as problems with sinkholes or groundwater imbalance, resulting in sudden water spills at the surface (including water spills outside the abandoned tunnels).

This reality is widespread throughout Italy, as well as in Europe and, clearly, in all countries in the world where raw materials have been exploited. To get an idea of how much waste is produced during mining, consider that, under quarry conditions, the yield

(the ratio of the volume of commercially useful material to the total extracted material) is 28% on average; it can, therefore, be calculated that around 12 million tonnes of waste (mixtures of silica and/or silicates) are landfilled each year in Europe.

From an economically productive point of view, Italian mining history dates back to the mid-eighteenth century when, with the Industrial Revolution, the importance of certain raw materials, such as iron ore and hard coal, was affirmed. Mining prospecting campaigns were then organized with a marked mobility of Italian scientists and technicians who visited Europe's most important mining districts and the largest geological and mineralogical schools. New production models of an industrial nature were developed, with the consequent development of earth sciences. In 1822, the "Regio Corpo delle Miniere Sarde" (with technical and administrative tasks) and the "Consiglio Superiore delle Miniere" (with guidance and control functions) were established; later, with the unification of Italy, these competencies were extended to the entire national territory, and the geological map was also added.

In the late 1870s, the annual mining production is estimated to have been worth around ITL 100 million (around 0.8% of GDP), of which

- About ITL 35 million was due to sulfur from Sicily;
- ITL 12 million was due to lead and zinc ores from Sardinia and Tuscany;
- ITL 10 million was due to Apuan marbles;
- ITL 2 million was due to boric acid from the Larderello dandelions.

To these were added a few fossil fuels: peat from the Alpine Arc, lignites from the Maremma, and coal deposits from Sulcis, worth about ITL 3 million (against ITL 40 million for the import of lithanthrax). The shortage of fossil fuels and the lack of suitable metallurgical plants destined the production of the basic minerals (copper, lead, zinc, tin, and antimony) for export to countries, and they returned semi-finished and processed products. It was not until the beginning of the 20th century that the most important industrial breakthrough in our country in the mining sector took place, with the blast furnaces being built in Portoferraio (later destroyed by bombing during the Second World War), Piombino, and Bagnoli, fed mainly by ore from the Island of Elba (iron).

The marked expansion of the mining and metallurgical sector continued until the Second World War, with the intensification of the cultivation of lignite from central Italy and coal from the Sulcis, the best-quality national coal, for the exploitation of the town of Carbonia. After the Second World War, mining activities, particularly in Tuscany and Sardinia, contributed markedly to the reconstruction of the country's industrial fabric but, from the 1970s in the 20th century, there was a slow decommissioning of the large Italian mining districts until the dismantling, in December 1993, of the Higher Mining Council. Subsequently, mining competencies, except energy materials, were transferred to the regions, the Mining Districts were closed, and the history of the Corps of Mines came to an end. There are currently few more than 100 mines still active, and these are mining mostly open-cast ceramic and industrial minerals. Today, Italy is forced to import most of its raw materials and minerals, thus losing its historical independence.

The constant changes in the world's geopolitical arrangements have made it imperative to increase the independence of each nation with regard to their supply of raw materials. The Italian government recently approved a decree-law for re-opening mines and extraction sites to supply critical and strategic raw materials. Another very topical issue is managing and recovering pre-existing mining waste, but this remains a rather complex subject in Italy.

The accumulation and surface storage of mining wastes poses a significant challenge in terms of environmental, health, and economic opportunities. Thus, recycling and valorizing these mine wastes is one of the most effective approaches to reduce their volume while limiting their negative environmental impact. Geopolymerization technology has several

advantages, including stabilizing polluted mine wastes, valorizing waste, and significantly reducing greenhouse gas emissions in the construction sector.

Much research has been conducted to improve the long-term management of mining waste in various nations. The scientific literature shows that most studies concern the use of mine wastes in construction applications.

For example, Lu et al. summarized various methods for reusing solid wastes in a mine transitioning from open-pit to underground mining [73].

They proposed the use of waste rocks in construction projects such as roads, pavements, dams, concrete aggregates, and bricks. However, mining tailings may be excellent for use as floor tiles, wall bricks, and soil enhancement. Franks et al. investigated several approaches to mining waste disposal in order to promote the notion of sustainable development and adopt these practices now and in the future [74]. Furthermore, the circular economy concept might be applied to the valorization and recycling of waste to produce economically valuable materials, hence fostering symbiotic ties across various industries [75].

As noted in the introduction, the geopolymerization or alkali-activation of mine tailings and wastes could be a viable alternative strategy for the sustainable management of mining wastes. This concept has the potential to employ large amounts of hazardous mine waste to create high-value products while reducing environmental impacts. Table 3 summarizes the data collected on the utilization of mine wastes in the synthesis of the GPs/AAMs mentioned in this work.

Table 3. The utilization of mine wastes in the synthesis of GPs and AAMs (GBFS: blast furnace slag).

Waste	Mineralogical Composition	Waste Activation	Activator	Si/Al	Curing (°C)	Curing (Days)	Compressive Strength (MPa)	Ref.
CT	Qtz, Alb, San, Gyp	—	NaOH	7.78	90	7	22	[76]
CT + FA	Qtz, Alb, San, Gyp	—	NaOH	1.89	60	7	21.02	[77]
CT + AS	Qtz, Alb, San	—	NaOH	2.71	90	7	44.8	[78]
GT	Qtz, Musc, Pyr, Alu, Goe	—	NaOH—Na_2SiO_3	—	70	28	50	[79]
GT	Qtz, Gyp, Pyr, Alb, Dol	—	NaOH	16.10	Ambient	28	3.05	[80]
GT + GGBFS	Qtz, Gyp, Pyr, Alb, Dol	—	NaOH	—	Ambient	28	25	[80]
GT	Qtz, Cal, Verm, Musc	—	Lime sludge, NaOH	—	Ambient	7	5.95	[81]
GT	Qtz, Feld, Plag, Musc	—	NaOH—$Ca(OH)_2$, Al_2O_3	—	170	3	40	[82]
IT + Slag	Qtz	—	NaOH—Na_2SiO_3	—	30	7	63.79	[83]
IT	Qtz, Bir, Goe, Alu, Sod	—	Na_2SiO_3	—	80	7	50.53	[84]
IT + MK	Qtz, Hem	—	NaOH—Na_2SiO_3	—	45	7	49.5	[85]
IT + FA	Qtz, Ant, Alb, Amp, Cal, Dol, Chl, Hem, Gyp	—	NaOH—Na_2SiO_3	—	Ambient	28	50	[86]
TT	Qtz, Musc	Thermal	NaOH—Na_2SiO_3, $Ca(OH)_2$	5.05	Ambient	28	75	[87]
TT + WG	Qtz, Alb, Musc, Na-Al-Si	Thermal	NaOH—Na_2SiO_3	—	80	28	22	[88]
TT + BW	Qtz, Clc, Musc	Thermal	NaOH—Na_2SiO_3	1.36	60	28	59	[89]
TT + Slag	Qtz, Clc, Musc	Thermal	NaOH—Na_2SiO_3	5.02	60	90	30.1	[90]
VT + MK	Qtz, Feld, Dio	Alkaline roasting	NaOH	1.78	60	7	55.7	[91]
VT + FA	Qtz, Feld, Dio	Dry milling	Na_2SiO_3	3.03	Ambient	7	42	[92]
VT + MK	Qtz, Feld, Hem, Plas	Mechanical activation	Na_2SiO_3	—	Ambient	14	25	[93]
Mo+MK	Cal, Gro, And, Alm, Qtz	—	NaOH—Na_2SiO_3	—	Ambient	3	46	[94]
BT+GGBFS	Kln, Dio, Musc, Qtz, Cor	Thermal	NaOH—Na_2SiO_3	1.22	Ambient	3	56	[95]
BT	Ca–Al–Si, Cal, Can, Dia, Goe, Hem, Qtz	Thermal	K_2SiO_3	—	60	3	40	[96]
PS+FA	Fap, Dol, Cal, Qtz	—	NaOH—Na_2SiO_3	3.50	83.33	14.50	62	[97]
PS+MK	Fap, Dol, Cal, Qtz	—	NaOH—Na_2SiO_3	3.46	83.33	14.50	53	[97]
PS+MK	Fap, Dol, Cal, Qtz	Alkali fusion	NaOH—Na_2SiO_3	—	60	28	40	[98]
PW	Heu, Qtz, Cal, Gyp, Pal, Fap	Thermal	NaOH—Na_2SiO_3	—	Ambient	28	10	[99]

Table 3. *Cont.*

Waste	Mineralogical Composition	Waste Activation	Activator	Si/Al	Curing (°C)	Curing (Days)	Compressive Strength (MPa)	Ref.
PWR	Qtz, Dol, Mont, Fap	Thermal	NaOH—Na_2SiO_3	3.78	Ambient	28	25	[100]
PS+MK	Fap, Dol, Cal, Pal, Qtz	—	NaOH—Na_2SiO_3, KOH	2.08	60	28	46.86	[101]

Waste Acronyms: CT = copper tailings; FA = fly ash; AS = aluminum sludge; GT = gold tailings; GGBFS = ground-granulated blast furnace slag; IT = iron tailings; MK = metakaolin; slag = blast furnace slag; TT = tungsten tailings; WG = waste glass; BW = brick waste; VT = vanadium tailings; Mo = molybdenum tailings; BT = bauxite tailings; PS = phosphate sludge; PW = phosphate washing waste; PWR = phosphate waste rocks. Mineralogical Composition Acronyms: Qtz = quartz; Alb = Albite; San = Sanidine; Gyp = Gypsum; Musc = Muscovite; Pyr = Pyrite; Alu = Alunite; Goe = Goethite; Dol = Dolomite; Cal = Calcite; Verm = Vermiculite; Feld = Feldspar; Plag = Plagioclase; Hem = Hematite; Bir = Birnessite; Sod = Sodian; Ant = Antigorite; Amp = Amphibolite; Chl = Chlorite; LS = lime sludge; Na-Al-Si = sodium.

The recent European legislation on the management of WEEE (waste electrical and electronic equipment) and its subsequent transposition in the various Member States has sought to fill the regulatory gap concerning such waste by introducing a specific plan for their management, which involves the pathway of the waste from "birth" to its "final destination", which might not necessarily be a landfill but possibly another destination. All this is to produce the least possible waste and recover the necessary materials. An analysis of the European and national reference standards for the management of WEEE revealed the need to clarify everything generically defined as "extractive waste" to re-evaluate and possibly redefine it as "non-waste". The technologies of recovery are currently highly evolved and today it is possible to re-evaluate the potential of waste from outdated industrial activities and rehabilitate this sector from an environmental point of view. In fact, in the case of old storage facilities, now closed or abandoned, the levels of waste can sometimes be quite high. Incentives to promote recycling/recovery initiatives for such waste should come from the local authorities where landfills are located and who live with this problem daily; in turn, the EU and the Member States should provide more financial support for the research and development of partially available recovery technologies and require additional research efforts, for instance through the European Partnership, which could also provide funding for a pilot project in this field.

To do so, it is essential to know the physical and chemical characteristics of the waste in order to target the best reprocessing activities or programs of environmental protection, but there is still no European database on the location and physical and chemical characteristics of WEEE. The first step is the inventory of closed and/or abandoned storage facilities that could hurt human health or the environment that each Member State made by May 2012, albeit with different levels of detail: in some cases, probably due to lack of information on individual storage facilities, it was drawn up based on data attributable to closed or abandoned mine sites but not to individual storage facilities. In other cases, the individual storage facilities were indicated but were limited to simple cataloguing. In other cases, the inventory was carried out by classifying each storage facility according to the risk it poses, as required by the EU.

In any case, the inventory is the first continuously updated guiding tool that sensitizes to appropriate investigations where the hazardous characteristics of structures may pose risks to human health and/or the environment and which, at the same time, represents a first level of knowledge on the characteristics of the WEEE inventoried and possibly recoverable. Today, no country can ignore the recycling potential of waste produced by the perennial exploitation of raw materials and WEEE should no longer be considered as such but as deposits from which to recover secondary raw materials; in fact, they can represent a threat, if abandoned without any measures to reduce their environmental risk, but also an opportunity, if considered as new sources to be exploited. This latter view of waste is a challenge for the future.

4.3. Sewage Sludge

Sewage sludge is the product of purification treatments in which the pollutants removed from wastewater are concentrated, i.e., a liquid suspension, more or less rich in solids of an organic and inorganic nature, with a dry matter percentage of approximately 20%. Thus, it originates from purification processes and proper wastewater management.

According to data from ISPRA Urban Waste 2020 Report [18], in 2018, urban wastewater treatment activities generated more than 3.1 million tons of sludge, which should be added to approximately 800 thousand tons from industrial wastewater treatment. Lombardy is the region with the largest amount produced, over 445 thousand tons (14.2% of the national total), followed immediately by Emilia Romagna, with 387 thousand tons (12.4%) (Figure 3).

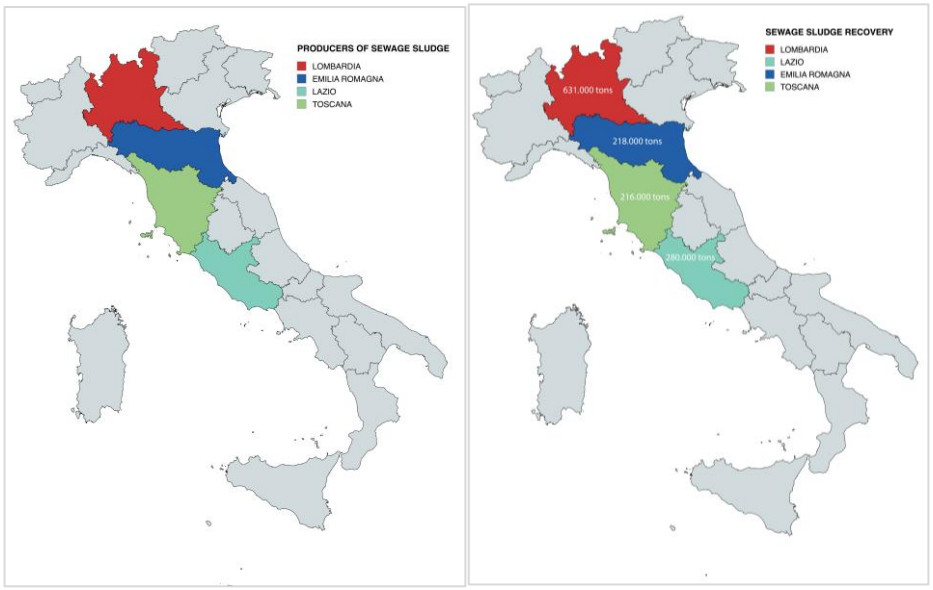


Figure 3. Producers and recovery of sewage sludge in Italy [18].

In terms of management, the tons of sludge from urban wastewater treatment managed in 2018 were just over 2.9 million. As a mode of management, landfilling (56.3% of the managed) prevails over recovery (40%), showing a wide range of the valorization of sewage sludge. The same data show that about 70% of certified recovery is of type R3, i.e., the recycling/recovery of organic substances not used as solvents (including composting operations and other biological transformations). Today, more than 1.6 million tons of sludge end up in landfills each year, which, on the contrary, could be transformed into new materials or energy (especially with anaerobic digestion). At the regional level, again Lombardy is the region where the largest amounts of sludge are recovered (631 thousand tons). This is an amount that exceeds the total amount recovered by all the other regions (amounting to 536 thousand tons), for a total of 1167 thousand tons. Latium, on the contrary, with only 280 thousand tons recovered, is the region where the quantities disposed of are the highest, followed by Emilia Romagna (218 thousand) and Tuscany (216 thousand).

Over the past ten years, several methods for effectively recycling this waste into products with added value have been described [102–107]. Normally, sewage sludge is used as a biofertilizer in agriculture; however, because heavy metals are present in sewage sludge, its use in agriculture is limited [108]. One method for treating it is to burn sewage sludge as the main fuel or via co-combustion [107,109,110]. As a by-product of the incineration process, sewage sludge ashes are left behind, despite the method's over-70% reduction in waste weight [111]. In general, the origin of the waste and the type and amount of chemicals employed during the sludge conditioning process can have a

significant impact on the features and specific composition of ashes [112]. It mostly consists of oxides, like SiO_2, CaO, and Al_2O_3, thus representing a good aluminosilicate source for GPs. Fly ash, metakaolin, powdered granulated blast furnace slag, slag-based cement, and other precursors have all been used in the development or preparation of sewage-sludge-ash-based GPs thus far [111–114]. Over the years, sewage sludge ash has shown to be an effective tool in the production of GPs. Employing equal parts of ground-granulated blast-furnace slag and sewage sludge ash, Zhao et al. [111] synthesized one- and two-part GPs. They did this by employing sodium hydroxide and sodium silicate as alkaline activators.

According to the findings, the one-part geopolymer's compressive strength was 20% less than that of the conventional two-part GPs. The conventional two-part geopolymer had a maximum compressive strength of 48.5 MPa, but the one-part geopolymer had a compressive strength of 37.8 MPa, which was 20% less. In comparison to the two-part geopolymer, the one-part geopolymer demonstrated 20% more porosity and a less compact structure. The study also showed that the heavy metals in the sewage sludge ash were consolidated by the one- and two-part GPs that were created.

By substituting 20% of sewage sludge ash for metakaolin, Istuque et al. [112] discovered that the sewage sludge ash incorporation produced GPs with the same compressive strength as those based on metakaolin. Nevertheless, the inclusion of ash from sewage sludge revealed that the geopolymeric gel was more stable. Santos et al. [113] created a geopolymer using Portland cement based on slag and sewage sludge ash. After 28 days of curing, the produced GPs had the greatest compressive strength of 50 MPa.

When sewage sludge ash and rice husk were combined in a 60:40 ratio, Nimwinya et al. produced GPs with a maximum compressive strength of 24 MPa at a curing temperature of 60 °C [114]. The feasibility of employing sewage sludge as an aluminosilicate feedstock to create a geopolymer cement was investigated in this work since there have not been many studies done where sewage sludge ash is utilized as the only precursor in the development of GPs.

Starting from these assumptions, and to avoid emergencies shortly, Italy should increase the number of water purification plants and provide an efficient sludge recovery system.

The various regions could be asked to plan sewage sludge management within their territory by prioritizing agricultural use and then considering alternative fates for sludge unsuitable for this use.

4.4. Biomass Ash

The use of biomass energy has become increasingly important as the share of renewable energy sources in the world's total energy production has increased. Burning biomass, mainly wood (bark, sawdust, leaves, wood chips, cellulose, sludge, etc.), is a strategy to achieve a higher percentage of coal-free energy sources. However, burning biomass produces a large amount of ash as a by-product of the combustion process, accumulating in landfills and increasing the cost of electricity. It should be mentioned that because these ashes include a significant amount of silica and alumina, they can be employed as fertilizers in agriculture, applied to soil, and utilized in cementitious materials. However, these pollutants are generally put in landfills or disposed of wrongly. For government entities, this material raises a serious environmental issue.

In Italy, electricity production through biomass combustion is a fast-growing trend that many private individuals and companies have convincingly chosen in recent years. Today, the use of biomass accounts for just over 5% of total national energy needs. However, their potential is very high, especially in uses related to domestic heating. Development is continuously increasing, and in Italy, we can already count 2700 active biogas and biomass plants, with a total energy production exceeding 19,562,000 MWh. The largest number of

plants is located in the north, more precisely in Lombardia, Veneto, and Emilia Romagna (Figure 4).

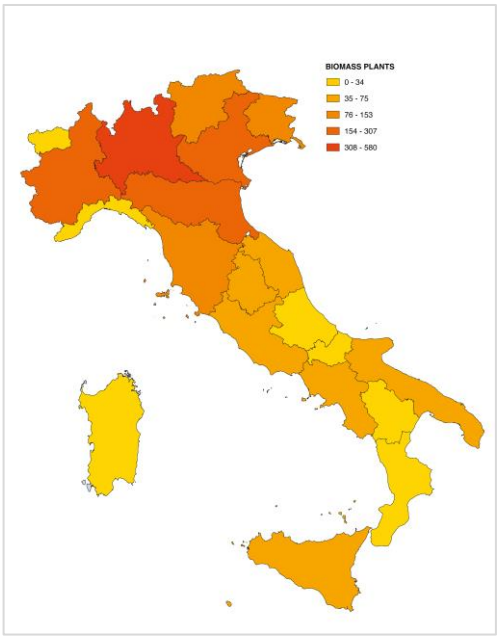


Figure 4. Biomass plant in Italy.

Ashes from biomass combustion processes are classified as "special non-hazardous waste" under Italian Legislative Decree 152/2006 (Part IV). This regulation establishes several possibilities for the recovery of "ashes from the combustion of biomass and related materials" with simplified procedures that concern, in particular, the production of cement mixes or the production of compost and fertilizers. Direct spreading, on the other hand, was not foreseen in the regulations. Ashes are, in any case, waste, and spreading them on the ground would mean illegally disposing of waste. It is, therefore, necessary to qualify ash as a "by-product", thus opening new possibilities for its use.

Thus, developing innovative techniques for recycling fly ash is a crucial and urgent problem. One of the most economical, efficient, and innovative ways to valorize accumulated fly ash is to produce geopolymer materials through the alkaline activation process.

Fly ash is the inorganic fraction that remains at the end of the biomass combustion process, and it is characterized by most of the minerals present in the original biomass [115]. An ideal wood combustion process produces 6–10% ash.

The physical and chemical structure of ash is influenced by the kind of raw material burnt, where it comes from, how wood is processed, and the technologies used in the combustion process [116]. The diameter of more than 80% of fly ash particles is smaller than 1 μm.

For hay, chipboard, native wood, and urban waste wood, the average fly ash particle diameter is smaller than 0.25 μm [117]. Fast-growing woody or herbaceous plants, which have short growth seasons and are simple to seed, represent the majority of biomass [118,119].

The application of geopolymer products made from biowaste materials is highlighted by the current scientific research. Comparing these items to traditional building materials, they show better strength, durability, and fire resistance [120]. The advantages can be further increased by using the ability to change the composition of the geopolymer to achieve certain features [121]. The synthesis and application of biomass-fly-ash-based GPs is summarized in Table 4.

Table 4. The synthesis of GPs from biomass waste and their application fields.

Fly Ash Source	Aluminosilicate Source	Application	Ref
Paper waste	Metakaolin.	Wastewater treatment.	[122]
Paper waste	Metakaolin.	Board and wall panels.	[123]
Co-generation plant (BA)	Metakaolin.	Filtration and separation.	[124]
Kraft pulp mill (BFA)	Metakaolin.	Construction and masonry.	[125]
Wood biomass (BA)	Metakaolin.	Reducing the cost of the geopolymer.	[126]
Mixed waste from Hauts-de-France (BFA)	Metakaolin and shooting range soil (SRS).	Immobilization of heavy metal.	[127]
Wood biomass (BWA)	Fly ash.	Economic and environmental benefits.	[128]
Mix of pine pruning, forest residues	Metakaolin.	Building materials, bricks.	[129]
Olive and forest pruning (FBA)	Metakaolin; aluminum industry slangs (AIS).	Partial substitutes for metakaolin and Portland cement.	[130]
Burder eucalyptus biomass	Metakaolin; aluminum; construction and demolition waste.	Applications in building, replacing conventional mortars.	[131]
Wood biomass	Metakaolin.	pH regulators for biogas reactors or wastewater treatment.	[132]

In order to produce safe concrete for future use, biomass fly ash must be immobilized [133]. Because GPs can immobilize heavy metals, they are considered very important for environmental protection. Their large surface area development and ion exchange capacities are intimately related to this capacity [134]. Within the geopolymer structure, metals such as cadmium, copper, lead, chromium, zinc, and others can become immobilized. It has been discovered that high concentrations of chromium or zinc have a detrimental effect on bending and compressive strength [135]. The excellent immobilization of hazardous heavy metals (including Cr, Mo, Pb, Sb, Se, and Zn) present in biomass fly ash was demonstrated in a recent study. This was accomplished by applying the accelerated carbonation/geopolymerization process. The results of the study show that processes of geopolymerization and carbonation stabilization are capable of efficiently capturing a wide variety of elements, such as As, Cr, Mo, Pb, Sb, Se, and Zn.

The effectiveness of this process is significantly influenced by the composition of the metakaolin [127]. Prefabricated construction components, transport structures, and materials with excellent adhesion to steel, aggregates, and numerous other materials can all be prepared with GPs [136,137]. The bonding strength of GPs has been demonstrated by Songpiriyakij et al. [138]. By varying the amounts of the original binder reagents and alkaline content, twelve different mix proportions of GPs were produced. The compressive and bonding strengths of these combinations were then assessed. The round bar and geopolymer system exhibited somewhat higher bonding strengths (ranging from 1.05 to 1.12 times) compared to the control concrete. For distorted bars, the bonding strengths ranged from 1.03 to 1.60 times greater, indicating a significant increase. The bonding strength and compressive strength ratios were also included in the study. Comparing geopolymer to commercial repair materials, the bonding strengths of the former were found to be 1.24–1.81 times higher than those of the latter. Additionally, geopolymer concrete mixed with biomass fly ash can be used as a filler joint for reinforced concrete structures, an additive for ceramics, chemically resistant exterior and interior cladding, chemically resistant items for industry, and a composite item for handling hazardous materials (heavy metals, radioactive substances, etc.) [139,140]. The differences in particle sizes, morphology, content, and reactivity across various fly ash samples provide difficulties when using biomass fly ash for GPs, thus making the development of a standard realization protocol complex [141,142]. The composition of the feedstock used in the boiler and the production circumstances have a significant impact on the particle differences in biomass fly ash. It has been noted that even when employing fly ash from different sources that appear to have

a comparable composition, as well as different batches of fly ash from the same source, the resultant mechanical strengths of the GPs vary considerably [143,144]. An extensive and current investigation on the synthesis of GPs using biomass fly ash was carried out by Sharko et al. [145]. The study made use of six different fly ashes that came from six different biomass thermal power facilities in the Czech Republic.

The study's methodology involved the sole synthesis of GPs utilizing biomass fly ash as a precursor material by the researchers. The geopolymer matrices were examined using a scanning electron microscope (see Figure 5).

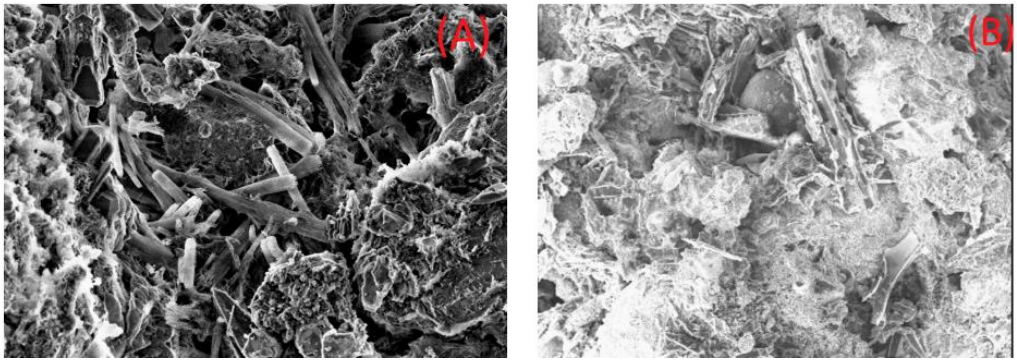


Figure 5. Scanning electron microscope images of geopolymer matrices prepared by the biomass fly ash of (**A**) Loucovice and (**B**) Cesky Krumlov [145].

The performance of these GPs was then evaluated through a mechanical durability test. Furthermore, a comparison was conducted between the mechanical test results of ordinary concrete and geopolymer concrete containing metakaolin (Figure 5). Because different forms of biomass fly ash have distinct chemical compositions, there is significant variety in their flexural and compressive strength, as well as their impact toughness. The investigation showed that the biomass fly ash from various thermal power plants has an impact on the physical characteristics of geopolymer constructions, as well as their durability performance.

Understanding the effects of various synthesis parameters on the final geopolymer's features is crucial to guarantee the development of a consistent geopolymer product from a raw material source with variable physicochemical qualities. This knowledge will make it possible to precisely modify these parameters for the particular product, which will open up possible commercial uses in sectors like construction [146]. Reactive silicon compounds are the main factor that determines the chemical composition of fly ash [147,148]. The main component of the internal structure of the geopolymerization products that are produced when fly ash is alkalinized is silicon [149]. Under extremely alkaline conditions, the reactive silicates in the fly ash dissolve, and Si-O-Al polymer bonds are formed (Figure 5). Consequently, large amounts of aluminosilicate gel develop when reactive silicon compounds are present, increasing the possibility that the resulting geopolymer material will be very strong [150,151]. The following are the primary qualities of fly ash that are thought to be appropriate for creating geopolymer materials with excellent mechanical properties: a maximum of 5% unburned material, 10% iron oxide, and 10% calcium oxide should be present in the fly ash [25]. The reactive silicon content should be between forty and fifty percent. Eighty to ninety percent of the particles should be less than 45 μm in size [143–151].

4.5. Municipal Waste Incineration Fly Ash

In Italy, waste incineration is a minority disposal method, but it is within the average range of European countries. Of a total of 54 plants (Figure 6), 40 are in operation (2022);

the vast majority are located in northern regions and Tuscany. Over the years, the percentage of municipal waste sent to incineration has increased from 2.5 million tonnes (2001) to 5.5 million tonnes (2012): most (about 70%) Italian waste is incinerated in plants in the north. In 2019, 1.4 million tonnes of incineration by-products were produced in Italy: 73 percent "bottom ash and non-hazardous waste"; 14 percent "hazardous waste from flue gas abatement processes"; and the remainder "fly ash, bottom ash, and hazardous waste".

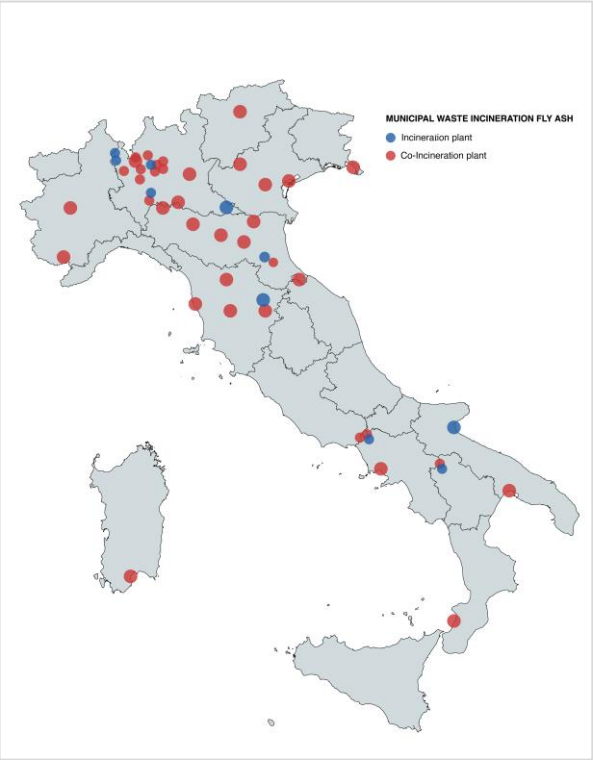


Figure 6. Municipal waste incineration fly ash in Italy [20].

An increasing amount of municipal solid waste (MSW) is produced annually as urbanization progresses and people's quality of life improves. Around 3.5 million tons of MSW are produced daily in metropolitan areas worldwide; the World Bank estimates that this amount will rise to 6.1 million tons by 2025 [152]. In 2017, the US, Australia, and the EU generated 482, 558, and 742 kg of MSW per person, respectively [153]. Global municipal solid waste production is predicted to reach 3.4 billion tons per year by 2050 [154]. Because of its low levels of pollutants, waste incineration bottom ash is commonly used as a secondary raw material in the construction sector [155,156]. On the other hand, due to its high levels of potentially harmful substances and other impurities, municipal solid waste incineration fly ash (MSWI FA) is categorized as hazardous waste in many nations, including Italy [157–160]. In addition to chlorinated compounds, the main constituents of MSWI FA include CaO, SiO_2, Al_2O_3, Na_2O, K_2O, and Fe_2O_3 [161]. MSWI FA has high concentrations of heavy metals, including Zn, Pb, Cu, Cr, As, Cd, and Ni, in both bulk and leachate forms. Furthermore, dioxins, furans, polycyclic aromatic hydrocarbons, and sulphates are present in MSWI FA [162]. According to Zheng and Wang (2016) [163], the disposal of MSWI FA must meet the specifications for a stable product structure and a low volume addition rate. Two of the main obstacles that must be addressed in the treatment and disposal of MSWI FA are the immobilization of heavy metals and the elimination of dioxins.

Reactive silica-aluminate materials and MSWI FA were used as geopolymer precursors in several studies. The performance of the geopolymer is closely correlated with the physicochemical characteristics of the raw material. According to recent studies, raw materials containing Si, Al, and Ca significantly affect the characteristics of GPs. Because there is little SiO_2 or Al_2O_3 present in the raw material, the interaction between oligomeric SiO_3^{2-} and Ca^{2+} produces a calcium silicate hydrate when just MSWI-FA is present. C-A-S-H or N-A-S-H gels may then be formed by reacting dissolved Ca^{2+} or Na^{+} with $Al(OH)^{4-}$ and $SiO_2(OH)_2^{2-}$ or $SiO(OH)^{3-}$ [164]. In order to prepare an alkali activator, Lee and van Deventer [165] synthesized GPs using MSWI FA as a raw material in combination with NaOH and Na_2SiO_3. To improve the mechanical properties (a compressive strength of around 20 MPa), the specimens are first cured at 90 °C for 24 h, and then they are cured at room temperature for 90 days. In the condensed tetrahedral silica-aluminate network, the higher concentration of rice husk ash enhances the degree of condensation and the existence of Si-O-Si links. The hydraulic binder's high compressive strength is a result of the Si-O-Si bond's superior strength over the Si-O-Al and Al-O-Al bonds [166,167]. By combining MSWI FA with rice husk ash, a source of reactive silica, and potassium hydroxide solution, an alkali activator [168], created a geopolymer. When too much rice husk ash is applied, though, this tendency is reversed. On the one hand, too much soluble silica (which is said to happen at Si/Al molar ratios greater than two) prevents dissolved silica and alumina from recombining, which lowers the geopolymer's skeletal density [28]. Alternatively, an excessive amount of unreacted rice husk ash as a porous filler reduces strength [169,170] in GPs developed using Class C fly ash and MSWI FA as raw materials, with added nano-Si_3O_2 and nano-γ-Al_2O_3. It was discovered that the nanoparticles had a more effective modifying impact on the geopolymer materials. This is because the nanoparticles' large specific surface area speeds up the geopolymer's microscopic reaction rate [171]. Conversely, the nanoparticles occupy the pores, increasing the structural density of the geopolymer system. For a given quantity of aluminate addition, a rise in Na^{+} will encourage an increase in compressive strength. An intermediate dose of Na^{+} yields the geopolymer treatment with the maximum compressive strength. The big holes in the microstructure change into a huge number of mesopores and micropores once Na^{+} is added. As the density of the material increases, so does the compressive strength. However, after adding a certain amount of Na^{+}, the material's compressive strength would decrease as more is applied. From the standpoint of the pore structure, the reduction in compressive strength cannot be explained. The composition of fly ash produced by various waste incineration procedures varies significantly [172], which eventually impacts the geopolymer's compressive parameters. To synthesize a geopolymer [173], combined fly ash and slag fines (GBFS) were mixed with MSWI FA, which is obtained via a grate furnace and fluidized bed incineration. In addition, the impact of MSWI FA on the characteristics of the GPs generated by two distinct incineration methods was examined. At 20%, 30%, and 40% additions of MSWI FA generated by the fluidized bed, the geopolymer's compressive strengths were 36.67, 33.11, and 28.69 MPa, respectively. By pretreating the fly ash with water, the geopolymer's compressive strength was further improved, increasing by 1.6–4.9 MPa. Research has indicated that the fluidized bed method yields superior MSWI FA for geopolymer production compared to the grate furnace. The primary cause is due to the fluidized bed fly ash containing significantly more Al, Si, and Fe oxides than grate-firing fly ash [174,175]. Moreover, the large amount of calcium compounds and chloride salts existing in grate-firing fly ash have negative effects on the compressive strength of the alkali-activated bricks [173].

The performance of the geopolymer is closely correlated with the chemical–physical characteristics of the raw material. According to recent studies, raw materials containing Si,

Al, and Ca significantly affect the characteristics of GPs. Table 5 shows the compressive strength values of GPs compared to experimental conditions.

Table 5. Comparison between mechanical properties and experimental conditions of GPs.

Aluminosilicate	Activator	Liquid/Solid	Curing		Compressive Strength (MPa)	Ref.
			Parameters	Days		
MSWI FA 100%	NaOH 15 M, Na_2SiO_3 3 M solutions; Si/Al molar ratio is 2.0	0.25	Room Temp.	7	21.04	[176]
MSWI FA 50%, CFA 50%	Molar ratio ($NaOH/Na_2SiO_3$) = 1 NaOH 4.45M	0.3	Step 1: 60°C—6 h Step 2: room temp.	7	10.51	[177]
MSWI FA 15%, CFA 85%	NaOH 8M	0.37	Ambient temp. and RH	28	15.69	[178]
MSWI FA 5.5%, SF 9.2%, GBFS 39.9%, Sand 14.4%, Fiber 1.1%	NaOH 3.0%, Na_2SiO_3 13.6%	0.5	Step 1: 80 °C—2 h Step 2: room temp.	28	73.57	[179]
Water-washed MSWI FA 100%	NaOH (10 M) and Na_2SiO_3 (0.8M) solutions	0.21	Ambient temp. and RH	130	25.94	[179]
CFA 88.5%, MSWI FA 10.5%, nano-SiO_2 1.5%	Na_2SiO_3 43.5, adjust with naOH to 1.5 M.	0.3	Ambient temp. and RH	28	57.19	[170]
MSWI FA 60%, NSFA 40%	NaOH (10 M)	0.5	20 °C RH 60%	28	27.36	[171]
MSWI FA 30%, RM 70%	Na_2SiO_3, solution with 7.91% Na_2O, 23.72% SiO_2	0.5	Ambient temp. and RH	28	9.95 MPa	[180, 181]
CFA 21.3%, MSWI BA 5.3%, Sand 73%	NaOH 13%, Na_2SiO_4 13%	0.65	Step 1: 60°—48 h Step 2: 60°—50% RH	28	53.0	[182]
MSWI FA 90% Metakaolin 10%	NaOH 9.04%, Na_2SiO_4 16.91%	0.65	20 °C—RH 90%	90	20.51	[183]
MSWI FA 40% Metakaolin 60%	NaOH 9.2%, Na_2SiO_4 34%	0.85	20° C—RH > 60%	28	40	[184]

In addition to the technical issue, the synthesis and use of MSWI FA-based polymers are also extremely pertinent to managerial and economic concerns. In order to provide more cost-effective and efficient management practices, we investigated the optimization of the synthesis process and created better reaction equipment via characterizing raw materials and GPs using a variety of spectroscopic techniques; the interactions between MSWI FA and binder or other chosen wastes were also further examined. This revealed the mechanism of the solidification/stabilization of hazardous compounds in MSWI FA via alkali activation processes. Additionally, this helps to establish a theoretical foundation for MSWI FA treatment and resource recovery in the future. To solve the current issues with MSWI FA pretreatment, the following research goals should be addressed: (1) create less-expensive photocatalytic materials and stabilizers; (2) research and develop larger, more-energy-efficient mechanochemical and electrochemical equipment for treating MSWI FA in large quantities; and (3) investigate integrated wastewater treatment technologies to manage a range of contaminants that may be present in the wastewater from water-washed MSWI FA, including heavy metals, dioxins, and Cl^-.

The following industrial applications have been reported using GPs made from different clay minerals: biomedical materials, porous thermal insulation, protective coatings, sustainable building materials, and three-dimensional printing materials. In order to opti-

mize their qualities and process parameters, MSWI FA-based GPs may be applied in the aforementioned sectors. The testing index of mechanical characteristics has to be further expanded by consulting research on various concrete materials (such as splitting tensile strength, flexural strength, axial compressive strength, and static compressive modulus of elasticity).

Furthermore, it is necessary to evaluate the GPs' resilience to various environments, including dry, alternating moisture, high temperatures, alkaline, acidic, and alternating freeze–thaw. Future studies should concentrate on the combination of geopolymer synthesis methods and raw material pretreatment methods to attain superior mechanical qualities for construction materials while achieving the thorough control of various pollutants. To create a thorough evaluation system, it is required to integrate toxicity evaluation tests, cost–benefit analyses (CBAs), and lifecycle assessments (LCAs) to examine the cost, energy consumption, and environmental effects of various technologies. Through technological investigation and the extension of applications, MSWI FA synthetic geopolymer technology could advance.

4.6. Non-Metallic Fractions of Electronic Waste

The extraordinary demand and short lifecycles of electronic items can be linked to the rapidly expanding solid waste stream known as electronic trash, or e-waste [185]. According to a United Nations estimate, the annual creation of e-waste has reached over 44 million metric tonnes (Mt), or roughly 4500 Eiffel Towers, and is predicted to soon exceed 52 Mt [186]. The amount of e-waste generated globally in 2019 was approximately 54 Mt, or 7 kg per person [187], a startling 21% increase from six years prior [185]. Global e-waste production is now predicted to rise by 75 Mt by 2030 [188]. With about 25 Mt, Asia leads the globe in e-waste creation, followed by the United States (approximately 13 Mt), the European Union (approximately 12 Mt), Africa (approximately 3 Mt), and Oceania (approximately 1 Mt) [189].

In Italy, as of 2017, there exists an estimated annual waste production per person of 10 to 15 kg (see Figure 7).

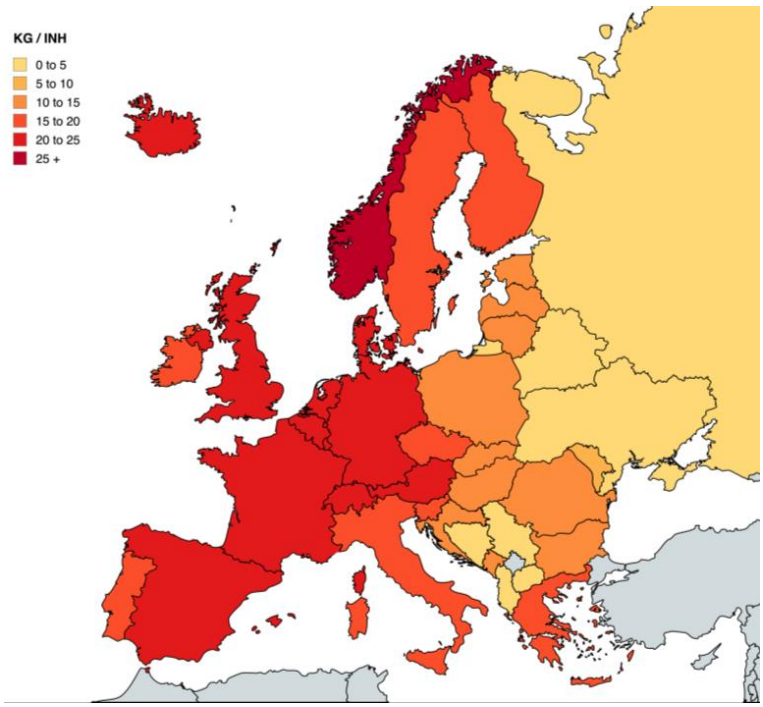


Figure 7. Generation of waste electrical and electronic equipment in the EU [190].

There are several methods on the market for handling mechanically regenerated (or separated) e-waste, including acid baths, incineration, and landfilling; however, each of these methods has several disadvantages. By dissolving lead and/or copper with extremely concentrated acid, acid bathing is used to recover gold and silver from e-waste; nevertheless, hazardous acid waste contaminates the surrounding waterbodies [191]. Because of the substantial reduction in trash volume and the independent use of the energy produced, incineration is considered fairly favorable. The long-distance transport of poisonous gases and fine particulate matter from burning e-waste hurts human health and the ecosystem [192]. Lastly, landfilling is the most economical method of getting rid of e-waste, especially in nations like the United States, with many open areas [193]. Nevertheless, gases from the waste may leak into the nearby soil and atmosphere. Furthermore, the breakdown of garbage releases carbon dioxide (CO_2), which contributes to climate change. Biological techniques (bioleaching, biosorption, bioaccumulation, biotransformation, biomineralization, and microbial-based chemisorption) and chemical techniques (pyrolysis) are among the other recycling approaches that have been studied recently [191], but they are either in the research and development stage or are not very effective.

According to the discussion above, handling e-waste is a major issue globally because of its dangerous contents and rising production rates. The disposal of e-waste has serious environmental risks, such as contaminating water and soil, releasing greenhouse gases, and destroying ecosystems. Even while recycling programs have become more popular, little is known about sustainable disposal methods for e-waste's non-metallic fractions (NMFs). However, geopolymerization seems to provide a chance to recycle and repurpose NMFs into environmentally friendly building materials. It is crucial to critically assess how well e-waste fractions work with the manufacturing of GPs.

Plastics, metals, glass, PCBs, rubber, adhesives, insulating materials, wire insulation, cables, and wires are all included in e-waste. Glass, metals, and plastics are the most common e-waste fractions among those listed. Essentially, the components of e-waste may be roughly separated into two categories: non-metallic fractions (NMFs) and metallic fractions (MFs). Over 40% of all e-waste is from NMFs. According to the literature now under publication, glass (LCD) and plastic (cathode ray tube, or CRT) are two NMFs that work well with GPs.

While e-waste glass (e-glass) can be utilized as a precursor or as an aggregate in the manufacturing of GPs, e-waste plastic (e-plastic) can be used as an aggregate. Because of their exceptional intrinsic qualities (such as low water absorption, high silica content, low thermal conductivity, and incombustible nature), e-glass and e-plastic are excellent substitutes for natural aggregates in geopolymeric composites. Because of its high silica and alumina content, e-glass may also be used as a source material for aluminosilicate in the synthesis of GPs.

Remarkably, the inclusion of e-plastic had a positive impact on compressive strength, which the authors believe is unlikely given that e-plastic has a lower density and specific gravity than natural aggregates. The fine granularity of e-plastic (in contrast to natural aggregates) and the presence of glass fibers or other components of e-waste, which results in the densified microstructure of the resultant GPs, might be the cause of this tendency. This should be confirmed by experimental research, though, as it is only a theory. It would be biased to suggest that e-waste is a suitable substitute for natural fine aggregates given the range of findings shown in Figure 8. However, if a significant strength drop is noted, a little decrease or increase in compressive strength offers some optimism that high-level e-waste integration can at least produce concretes with strengths appropriate for non-structural uses. Given the conservative nature of the construction industry, the authors think that these GPs should be studied in a variety of settings, including varying alkali activator

concentrations, ratios, and types, as well as curing regimes, aluminosilicate materials, etc. This will enable stakeholders to evaluate the GPs' suitability for practical uses.

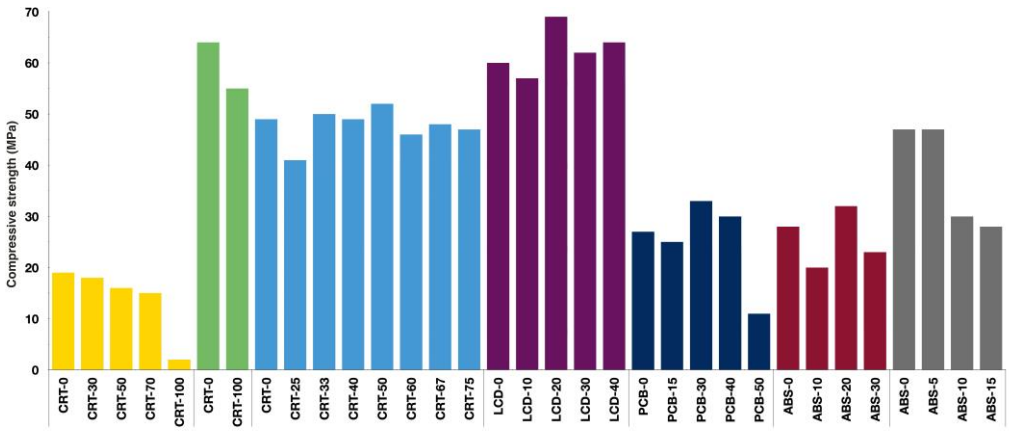


Figure 8. Compressive strength of geopolymer materials prepared with different types of e-glass and e-plastic (PCB: Printed circuit boards. ABS: Asbestos-based plastic. (asbestos-based plastic as coarse aggregate). Specimen description: type of aggregate–percentage incorporation level, e.g., CRT-100% e.g., 100% of aggregate with cathode ray tube substitution). Data acquired from Refs. [194–200].

Previous research has shown that the geopolymer matrix's structure effectively immobilizes heavy metals and has a greater fixing capability than cementitious composites, making it one of the best options for immobilizing heavy metals in e-waste (e.g., [201,202]). Only three studies have examined the leaching behavior of AAMs [203] and GPs integrated into e-glass [195,196]. The research above confirmed that GPs had a beneficial effect on lowering the leaching of heavy metals in CRT glass. Different cations (such as hazardous cations and alkali metal ions in e-waste) might act as counterions to balance the negative charges of $[AlO_4]$-units in the geopolymer network because of the tunable composition and amorphous structure of GPs. The interaction between $[AlO_4]$-units and counterions facilitates physical immobilization by preventing poisonous or dangerous cations from escaping by electrostatic attraction. Furthermore, the diffusion of hazardous compounds from the encapsulation network's core to its surface can be inhibited by using high-temperature curing to transform the solidified hazardous substances into components of a stable ceramic phase [204]. Depending on the kind of heavy metal, immobilization was achieved by chemical bonding and physical encapsulation. Since lead (Pb) is the main heavy element found in e-waste, the authors think that lead can be physically sequestered by the gelling product made of geopolymer. Future research needs, however, to confirm how geopolymerization immobilizes certain heavy elements found in e-waste.

Even though using e-waste in the manufacturing of GPs seems like a good strategy, it will still be difficult to market these composites and apply them to other possibilities. This is a result of the construction industry's continued conservative approach to change. Thus, more research is needed in the following areas to promote the widespread incorporation of e-waste in the manufacturing of GPs:

1. To fully evaluate their potential, the properties of e-waste-based GPs should be investigated under various circumstances, including varying e-waste fractions, curing regimes, precursors, aggregates (size and gradation), fibers, etc. Addressing divergent viewpoints over the effectiveness of these items will also result from this.
2. To identify their suitable uses in the building sector, the GPs transformed by e-waste should be grouped according to their performance.
3. Another step that might raise manufacturing costs and embodied energy is reprocessing e-waste components to the size of the available geopolymer reagents. To determine

if GPs truly provide sustainable e-waste disposal, a thorough lifecycle evaluation and lifecycle cost analysis of e-waste-incorporated GPs should be carried out.

4. Except for possible economic, social, regulatory, and policymaking implications, this study briefly focuses on the technological viability of the environmental advantages of GPs derived from e-waste. In order to reveal the potential and hidden constraints of this disposal method, future research should concentrate on evaluating these factors.

Investigating the hotspot, as mentioned in earlier research topics, would aid in confirming that geopolymerization is an appropriate e-waste management approach. This will not only encourage the commercial use of e-waste-based GPs but may also open up possibilities for the production of additional value-added products from e-waste.

4.7. Waste-Derived Activators for GPs and AAMs

Reducing AAM manufacturing costs while preserving their high performance and environmental friendliness is crucial to advancing their commercial viability. One important component in AAMs that has received huge attention lately is the alkaline activator. Due to their high cost, caustic and dangerous nature, and lack of environmental friendliness, alkaline activator solutions are frequently cited as one of the main practical drawbacks of AAMs [205]. AAM activation often requires high concentrations of sodium silicates. As a result, these activators have relatively high embodied energy, carbon footprints, and costs [206]. Therefore, an urgent need is to create affordable and sustainable activators that can significantly increase the likelihood of employing AAMs. One of the most important challenges of scientific research in the AAM and GP fields concerns the synthesis of alternative activating solutions that are more affordable, ecological, and user-friendly [207].

The development of substitute solutions based on a mix of alkalis and waste-derived silica has been encouraged in order to move closer to more environmentally friendly alkaline activators. These waste materials consist of fly ash [208], silica fume [209], bottom ash [210], rice husk ash (RHA) [211,212], waste glass (WG) [207], microsilica [205], green olivine nano-silica [213], and precipitated silica [214]. An alkaline silicate activator similar to the commercial one made mostly from commercial sodium silicate can be produced by dissolving silica from these sources in an alkaline hydroxide solution. Furthermore, depending on the extraction technique, the environmental impact of the substitute activators suggested a potential 50% decrease in CO_2 emissions when compared to commercial sodium silicate [215–218]. The production of alternative sodium silicate would be advantageous for the formulation of AAMs, as well as several other uses, such as drilling fluids [219–221], heat-resistant binders [222,223], fractured oilfields [224], and coal mine fire prevention and extinction [225–227].

In Italy, most SiO_2-rich wastes are derived from glass. According to the Consortium for the Recovery of Glass (CoReVe), the glass recycling rate reached 80.8% in 2022, an increase of +4.2% compared to the previous year. This result allowed our country to exceed, for the fourth consecutive year, the EU target of 75% set for 2030, but also the quota of 2.5 million tonnes of glass collected per year on average.

Different silica extraction techniques have been developed to create sodium silicate activators from a variety of silica resources, as shown in Table 6. Metakaolin, fly ash, slag, red mud, calcined kaolin sludge, water treatment sludge, and fluid catalytic cracking catalysts were the primary activators that were employed.

Table 6. Summary of different extraction methods to produce sodium silicate activator from various silica sources.

Silica Characteristics of Raw Material				Extraction Conditions				
Silica Source	**SiO_2 (%) [a]**	**LOI (%)**	**Average Particle Size (µm)**	**Alkaline Source**	**Molarity of Alkaline Solution (mol/L)**	**Temperature (°C)**	**Duration**	**Ref.**
RHA and WG	83.05 and 68.70	0.55	<90	NaOH pellets	NR [b]	100	2 h	[228]
RHA	90.5	3.8	6.82	NaOH pellets	1.0, 2.0, 3.2, 4.9, and 6.5	Room temp., 60, 80, 90 and 100	1, 3, 5, 7, and 15 h	[225]
RHA	93.49	NR	NR	NaOH pellets	NR	80	2 h	[229]
RHA	NR	NR	<45 µm	NaOH granules	8, 10, and 12	Room temp.	40 min	[220]
RHA	97.3	NR	9.87	NaOH	NR	100	1 h	[224]
RHA and silica fume	68 [c]–95.51	<2	9.2 and 64.1	NaOH	NR	Room temp.	10 min	[217]
RHA	91.5	6 [d]	25 and 32	NaOH	2, 4 and 6	Room temp.	15 min	[230]
RHA	90.91	5.10	4.6	NaOH	NR	Room temp.	24 h	[231]
RHA	~94	2.8–3.5	36.9–39.5	NaOH	NR	Room temp.	NR	[232]
RHA	89.51	6.95	20.4	NaOH	NR	Room temp. and 90	30 min	[233]
RHA	85.58	6.99	20.3 and 62.3	NaOH	NR	100	5–240 min	[234]
WG	82.52	0.41	<38 and 38–125	NaOh pellets	NR	550	NR	[235,236]
WG	69.9–71.4	NR	<45, 45–90 and >125	NaOH and $NaOH/Na_2CO_3$	4	22 and 80	10 min and 2, 4, and 6 h	[237]
RHA	56.22	40.42	8	$NaAlO_2$	N/A	Room temp.	N/A	[238]
RHA	88.49	2.48	11.1	$NaAlO_2$	N/A	Room temp.	N/A	[239]
RHA and microsilica	88.46 and 94.25	9.22 and 2.31	23, 30, 172 and 199	NaOH	0.1, 1 and 10	Room temp.	4 h	[213]
WG	72.37	NR	<90	NaOH flakes	10	120	4 h and 24 h	[240]
WG	71.51	0.27	12	NaOH	NR	150, 250, 330 and 450	1, 2, and 4 h	[215]
Nanosilica	NR	NR	NR	NaOH and KOH	NR	NR	NR	[241]
Inceneration bottom ash	58.8	2.7	>125	NaOH	NR	20, 75 and 90	24, 48, and 72 h	[218]
Silica, quartz	99.9 and 98.6	NR	0.14 and 90	KOH pellets	NR	Room temp.	NR	[242]

[a] Total SiO_2 (amorphous and crystalline). [b] Not reported. [c] This value represents the amorphous silica in the final RHA. [d] This value represents the residual carbon as indicated by the XRD analysis. [c] In this study, RHA was used as a source of silica and a binder to produce one-part mix GPs.

Other researchers used a low-temperature synthesis method, which included dissolving the silica-rich source in an alkaline solution at temperatures ranging from 20 to 100 °C [210,217]. To improve the dissolving efficiency at a temperature as low as 20 °C, a lengthy processing period of up to 72 h was needed. In order to maximize the processing time and the temperature in the creation of sodium silicate powder, Vinai and Soutsos [207] used a thermochemical technique. In this procedure, a silica-rich source and NaOH were mixed at temperatures between 150 and 450 °C. The research results showed that obtaining sodium silicate powder appropriate for one-part AAM casting required heating the combination for an hour at 150 °C. According to another research [218], WG may be heat-treated with NaOH at 150 °C to produce solid sodium silicate with a conversion efficiency of around 70% in the form of Na_2SiO_3. In most of these investigations, the silicates have been extracted from the various silica-rich by-products using NaOH. However, several researchers extracted the silicate using alternative alkaline solutions, such as KOH [214,243] and $NaOH/Na_2CO_3$ [244]. When creating one-part AAM mixes, Hajimohammadi and van Deventer [245] and Sturm et al. [246] utilized RHA as both the binder and the activator source.

Since the extraction process has a significant impact on the quality and characteristics of the synthesized activator, further research should be done on the methodical approach to

appropriately designing the extraction process for any kind of silica-rich material. To allow for commercial application, it is necessary to fully comprehend the durability (different chemical assaults and time-dependent features) of AAMs triggered by alternate activators. Additionally, more investigation into the temporal rheological behaviour is advised as it might offer insight into the structural accumulation and reaction process of "geopolymerization." Thus, it is important to thoroughly examine how the alternate activator's composition affects the geopolymerization reaction. Additionally, it is essential to conduct a study on how non-traditional activators affect greenhouse gas emissions and how they affect the economy.

5. A Look Beyond Italy: European and UK Perspectives on Regulatory Frameworks

Although Italy has a strong regulatory and research base for the development and implementation of GPs and AAMs, an analysis extended to the European context highlights a broader and more coordinated commitment to low-carbon building materials, both at the national and supranational levels. This convergence is driven by common objectives promoted by the European Green Deal, the Circular Economy Action Plan, and the "Fit for 55" package, which aim to significantly reduce the carbon footprint of the construction sector through material innovation and resource efficiency.

In the Netherlands, the "Transition Agenda for the Circular Economy in Construction" actively promotes the large-scale replacement of traditional cement with recycled, secondary, and low-emission binders, including alkaline-activated systems. Instruments such as mandatory circular procurement criteria, lifecycle-based "material passports" and performance-oriented public tenders have incentivized both the public and industrial sectors to adopt circular material flows [247]. The "Concrete Agreement" (Betonakkoord) complements these actions by setting verifiable targets for the reduction of CO_2 emissions, the use of recycled aggregates and industrial by-products, and the promotion of joint research between institutions, universities, and companies.

The path of support for alkaline-activated materials in Germany has been built with a strategic vision and continuity thanks to programs like FONA (Forschung für Nachhaltige Entwicklung—Research for Sustainable Development), which has encouraged the development of interdisciplinary projects aimed at converting industrial residues into useful resources, promoting environmentally friendly alternatives to traditional cement, and encouraging production models based on the circular economy [248]. One of the most promising outcomes is the drafting of DIN 18998, which is presently being finalized and intends to facilitate the entry of clinker-free alternative binders, including geopolymers, into the construction market by regulating and certifying their use.

In France, the regulatory landscape is strongly influenced by the RE2020 environmental regulation, which obliges the inclusion of LCA criteria in the performance assessment of buildings. This regulation has given a strong impetus to the adoption of innovative low-emission binders, finding applications mainly in prefabricated components, energy-efficient building envelopes, and social housing pilot projects [249]. In parallel, public–private collaborative initiatives, such as the E+C- (Énergie + Carbone -) program, have further encouraged the testing of geopolymer-based concretes within sustainable building demonstration projects [249].

Spain has also emerged as one of the most active countries in research and innovation on geopolymers and alkaline-activated materials, thanks to its participation in several EU-funded European programs. Prominent projects, such as ReSHEALience, supported under Horizon 2020 and Horizon Europe, have focused on the design and validation of highly durable AAMs designed to withstand extreme environments, such as marine structures,

coastal defense works, and critical infrastructures [250]. These initiatives have led to the development of validated technical guidelines and reliable prediction models to assess the durability and sustainability of such materials over the long term, even under severe exposure conditions.

Thanks to strict environmental laws and demanding public procurement standards, sustainability has emerged as a key component of building strategies in Scandinavian nations, especially Sweden and Denmark. The requirement to disclose the carbon footprint of every new construction in Sweden is known as Boverket (the regulation on climate declarations for buildings), and it encourages the comparative assessment of low-emission materials in tenders [251]. The market introduction of geopolymers and alkaline-activated materials is encouraged in Denmark, where municipal-scale studies have been started and public tenders establish maximum CO_2 emission criteria as an eligibility requirement.

In the United Kingdom (UK) there are numerous proposals and amendments to reduce environmental impacts in construction. Part Z is a proposed amendment to the UK building regulations that aims to integrate lifecycle analyses (LCAs) and assessments of the carbon embodied in buildings. The aim is to set clear standards for measuring carbon emissions throughout the lifecycle of a building, including the building materials used [252].

To support the transition to more sustainable technologies, the British Standards Institution (BSI) introduced the BSI Flex 350 guide, which provides practical guidance on the use of alternative binders to Portland cement for the production of low-emission concrete. This tool is a concrete support for engineers, designers, and builders committed to reducing environmental impacts in the construction sector [253].

A further important step in this direction is the Future Homes Standard, legislation expected in 2025 that will set more stringent energy efficiency and emissions reduction requirements for new homes in England. The intention is to ensure that new buildings are highly energy efficient, thus contributing to the progressive decarbonization of the building industry [254].

The adoption of alternative cement binders is not a stand-alone initiative of individual nations, but rather a component of a larger political and scientific strategy to decarbonize the building industry, as demonstrated by these concerted efforts throughout Europe and the UK. Incorporating these experiences into the Italian context could boost national innovation pathways, make it easier to meet European carbon neutrality goals, and hasten the widespread adoption of circular economy-based construction methods.

The strategies and programs implemented at the national level in Europe and the UK to promote the development of geopolymers (GPs) and alkaline-activated materials (AAMs) are compared in Table 7, which also highlights the range of research projects and policy tools that are in line with low-emission building objectives.

Table 7. Comparative policy and research frameworks on GPs/AAMs in Europe and the UK.

Country	Key Policy/Programme	Focus Area	Reference
The Netherlands	Transition Agenda for Circular Construction; Betonakkoord	Circular procurement; CO_2 reduction targets; recycled materials.	[247]
Germany	FONA Programme; DIN 18998 (in progress)	Waste valorization; AAM standardization; sustainable cements.	[248]
France	RE2020; E+C- program	LCA-based regulation; prefabricated low-carbon elements.	[249]
Spain	Horizon projects: ReSHEALience	Durability in extreme environments; infrastructure applications.	[250]
Sweden	Klimatdeklaration Law	Carbon declarations for new buildings; public procurement incentives.	[251]
Denmark	Municipal carbon-based procurement initiatives	Eligibility thresholds for CO_2 in public tenders.	[251]
United Kingdom	Part Z; BSI Flex 350; Future Homes Standard	Lifecycle carbon assessment; low-carbon standards; sustainable materials.	[252–254]

6. Conclusions and Future Remarks

In recent years, Italy, like the rest of the EU, has become increasingly attentive to environmental issues and the development of sustainable materials and technologies. The development of AAMs and GPs from industrial by-products could open up interesting economic and environmental scenarios.

Geopolymers and AAMs are innovative and sustainable ceramic materials developed recently, with outstanding workability, high strength, and resistance to heat, acids, corrosion, and wear. Solid wastes can be used in GPs at a higher level of reuse according to the waste management hierarchy. Nevertheless, given their complexity and diversity, there are still several obstacles to the widespread use of solid wastes in GPs, which have yet to be thoroughly investigated.

The feature knowledge of GPs and AAMs is the major focus of contemporary solid waste research, which is mostly used in geopolymer cement. Few studies have examined the deeper applications of solid-waste-based GPs, even though many works use solid waste for GPs. Competitive advantages include low-temperature curing, low-cost energy consumption, resource recovery, the ease of preparation, and large-scale production when using inexpensive silico-aluminum-rich solid wastes and alkali activators to create GPs for adsorbents, catalysts, and other high-value applications. The alkali–silicon reaction and high-temperature maintenance issues with geopolymers, however, will also create obstacles in engineering building. Thus, the following recommendations are indispensable to develop and employ AAMs and GPs prepared from solid wastes:

- The collection, separation, and characterization of the aluminosilicate waste most suitable for alkaline activation is a key step to support the development of geopolymers. In this sense, the creation of a structured database for the classification of different wastes could offer an important operational and cognitive tool.
- Deepening the mechanisms of geopolymerization is essential to build a solid theoretical basis to guide the choice of precursors and the optimization of the Si/Al ratio, both in the case of single waste and in mixed streams.
- Understanding the relationship between waste characteristics and the final properties of geopolymers makes it possible to modulate material performance by acting on composition, reactivity, and critical process parameters (such as liquid/solid ratios, mixing modes, and curing conditions).

- Studying chemo-rheological behavior and reaction kinetics as a function of curing time and temperature is crucial to refine formulations and make production scalable, including 3D printing.
- The development of synthesis methods for alternative alkaline activators, obtained under mild conditions, could significantly reduce both costs and environmental impacts.
- Comprehensive LCA studies capable of realistically assessing the ecological footprint of alkaline-activated materials produced from different waste combinations are needed.
- Identifying new application frontiers, beyond conventional use as an alternative to Portland cement, represents a strategic opportunity to expand the impact of geopolymers and alkaline-activated materials.
- Areas such as water treatment, environmental catalysis, or regenerative medicine offer concrete scenarios where their unique properties can be exploited, accelerating their adoption on an industrial scale and enhancing their relevance in high-tech contexts.

In this journey, the role of institutions will be crucial. It is necessary to foster an ecosystem in which research and industry can hold a dialogue in a structured manner, supported by incentive policies and a shared vision oriented towards the development of truly sustainable technologies, in both environmental and economic terms.

Italy has already taken significant steps in this direction, promoting policies and investments aimed at supporting circular innovation. However, a cultural challenge remains: that of overcoming the still-too-deeply rooted perception of an antagonism between geopolymers and traditional cement. Rather than replacing them, these new materials can integrate with conventional binders, contributing synergistically to the ecological transition of the building sector.

Looking to the future, the development of geopolymers and AAMs appears not only desirable, but concretely feasible. With the right support, these technologies can evolve from a niche solution to a pillar of a new sustainable, resilient, and circular economy-oriented construction industry.

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