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REVIEW PAPER

A review of the features of geopolymer cementitious composites for use in green construction and sustainable urban development

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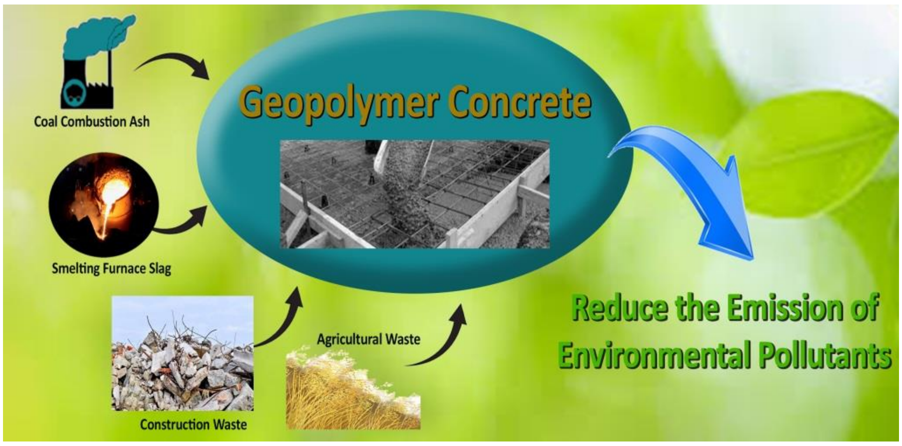
Highlights

- Investigation of physical and chemical properties of geopolymer cement as a substitute for common Portland cement in the construction industry.
- Investigation of an environmental load of geopolymer cement to reduce the environmental pollution of concrete production industry with a life cycle assessment approach.
- In the direction of sustainable urban development, the study of geopolymer concrete production as green and sustainable materials.

Graphical Abstract



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Abstract

Concrete is the second most widely used material in the construction industry after water due to its special properties. But the Portland cement production process also has major drawbacks, with one ton of Portland cement producing almost one ton of carbon dioxide. Hence the need to use an alternative to Portland cement seems necessary. On the other hand, the principle of "waste-free" and the production of new materials with environmental impact less than the priorities will be the goals of sustainable development in future cities. To further develop environmentally friendly materials, it is necessary to know about the environmental stimuli of new materials as well as to evaluate the environmental effects of conventional materials in construction. In recent years, geopolymer has emerged as a sustainable, environmentally friendly material and an alternative to Portland cement. Geopolymers are ceramic-like materials with three-dimensional poly-compact structures formed by the chemical activation of solids containing aluminum and silica at relatively low temperatures. For the production of geopolymer concrete and use in construction, waste or by-products from industries can be used, such as coal combustion ash, smelting furnace slag, construction waste**,** or agricultural waste such as rice paddy. The present paper summarizes the studies on the use of geopolymer technology in sustainable materials for sustainable urban development in order to reduce the emission of environmental pollutants and evaluate the life cycle. Findings and results of studies show that geopolymer concretes have higher mechanical, chemical**,** and energy consumption properties than conventional concrete and offer significant environmental benefits.

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1. Introduction

Sustainable development is a concept that has different definitions, one of the most common of which states that today's generation should not jeopardize the ability of future generations to meet their needs (Habert et al., 2011). The four pillars of sustainable development are economic, environmental, and legal support as well as social development (Dickens et al., 2019). It has been shown that natural resource constraints and human priorities determine land capacity to support people. Cities today consume three-quarters of the world's energy and are also responsible for 75 percent of global pollution. In addition, the United Nations predicts that 68% of the world's population will live in cities by 2050. Therefore, when discussing sustainable development, we need to consider the growing dominance of cities and determine its direct and side effects. Large cities are nodes that connect large networks of important infrastructure services. Therefore, theflexibility and strength of urban infrastructure are essential for sustainable development (Branscomb, 2006). In recent decades, sustainable urban and rural development has always been one of the main concerns of development in Iran and most developing countries (Mohammadi Ashnani et al., 2018).

Different approaches, known as development strategies, have been tried in many developing countries to promote economic and social development, particularly in metropolitan areas. Development, industrialization, and industry formation in the surrounding areas are key strategies. One of the most critical elements of such industries' environmental effects is that they are sometimes irreversible and permanent harm (Amininejad et al., 2018). The use of waste from these industries as sustainable materials or recycled materials in the sustainable architecture of housing and rural structures is one solution for reducing environmental pollution from such industries while also creating sustainable development in the city and surrounding villages. The sustainable design aims to reduce buildings' negative environmental consequences while also boosting productivity and reducing waste in materials, energy, construction space, and the ecosystem in general. In the built environment design, sustainable architecture requires leading to efficient energy and environmental conservation (Bakharev et al., 1999). Factors affecting energy-related environmental difficulties resulting from technological innovation and behavioral trends should be taken into account in the development of sustainable cities (Yasnolob et al., 2018). Construction and demolition waste, manufacturing waste, and agricultural waste contribute to the total amount of waste created. Municipal solid trash, construction and demolition debris, and industrial or agricultural by-products are some of the most common classifications for these commodities. On-site waste management is emphasized in sustainable architecture (Bielek, 2016). This means the vast majority of waste generated in industrial and agriculture near rural areas must be recyclable to manufacture by-products that can be used for many purposes, including construction.

The pricing and quality of these materials are two factors that should be examined. Sustainable materials are defined as renewable materials that positively influence employment and contribute to economic activities based on economics, environment, and energy. Materials produced from recycled, reused, or harmless materials at the end of their life cycle are examples of sustainable building materials (Sagbansua and Balo, 2017). Green building design and construction are becoming increasingly prevalent in most countries today. A green building should have distinct qualities that assist save resources (energy, land, water, and materials) and reducing pollution throughout its life cycle to safeguard the environment (Luhar et al., 2020). Modern green building design strategies must use environmentally friendly design and construction techniques facing economic barriers.

Previously, research on green energy efficiency-focused on smart grids, the development of more effective insulating materials, and reducing greenhouse gas (GHG) emissions. Green communities should gradually adopt the concept of "zero waste." This method will surely aid long-term development and the reduction of greenhouse gas emissions. This means that the vast majority of garbage generated in the city or neighboring areas must be recyclable to generate by-products that can be used in various applications, including construction. The quality and cost of these materials are two issues to consider. The primary aim of this review article is to glance into the properties of geopolymers in terms of sustainable development and use of by-products and waste to produce concrete (green) and sustainable building materials for use in urban buildings and reduce pollution effects using life cycle assessment approach.

2. Geopolymers

Geopolymers are amorphous three-dimensional aluminosilicate materials with ceramic properties produced and hardened at ambient temperature. In highly alkaline conditions, polymerization occurs despite the alkali hydroxide and silicate solution, when the reactive aluminosilicates dissolve rapidly, and the quadrilateral units [SiO4] and [AlO4] are released. Quadrilateral units alternate with other allogomers by splitting oxygen atoms and forming amorphous geopolymers. Positive ions such as potassium or sodium in framework cavities balance the negative charge (Esparham et al., 2021). In a broader sense, geopolymers represent the conversion of molecules through geochemical processes. The term geopolymer, as originally coined, refers primarily to inorganic (inorganic) materials, but can be developed to include materials with organic content. The ancient Egyptians are known to have used river straw and mud containing organic matter (eg humic substances) to produce building components with remarkable strength and durability. Therefore, it is important to consider the interaction between inorganic and organic species during polymerization (Esparham and Moradikhou, 2021c).

2.1. Applications and properties of geopolymers

Any silica and alumina source that can be dissolved in an alkaline solution is being used as a precursor to geopolymer and polycondensation. Metakaolin (MK), which is produced by calcining kaolin at 750 °C, is frequently used to make geopolymers (Esparham et al., 2020a). Shaw and Wangersa investigated 16 natural minerals Al-Si as potential source materials for geopolymer production (Xu and Van Deventer, 2000). A wide range of wastes, including mines, power plants, municipal, construction, and any other source of aluminosilicate that is produced in large quantities in every country today, can be used to generate geopolymer materials for use in concrete construction, road paving, building components, and resistant coatings. Also used for fire protection and insulation. Some of these wastes (e.g., fly ash, smelting iron slag) are now used only as pozzolans in the production of Portland cement (Esparham and Moradikhou, 2021a).

Other potential applications of geopolymers include: stabilization of hazardous wastes, surface coating and stabilization of landfills, construction of low permeability baseliners in landfills, water control structures and construction of bulk mines in the mining sector, thermal insulation as well as cement Geopolymer can be used as an alternative to Portland cement in urban structures such as BWWA Queensland Airport runway and Curtin University, Australia (Figs. 1 and 2). Geopolymerization due to rapid setting and initial strength of the dough may be considered in excavation, embankment, and filling operations (Esparham et al., 2020b). Geopolymers harden rapidly and have high initial strength, while the final 28-day compressive strength may reach or exceed 100 MPa. Their porosity can be less than that of cement or mortars, and therefore superior mechanical properties are obtained. Their final structure and physical properties depend on several parameters such as water content, particle size, thermal history, alkali metal content, and degree of formation. Geopolymers show similar permeability to Portland cement, 9-10 cm/s, low alkali expansion, low shrinkage, excellent resistance to acids, sulfates, corrosion, as well as freeze-thaw melting cycles (Esparham et al., 2020c; Hosseini et al., 2020; Moradikhou et al., 2019).

An important aspect during geopolymerization is water, which facilitates the performance of the initial paste but is not included in the resulting geopolymer structure. . Unlike hydration reactions in conventional concrete, water does not play a significant role in the main chemical reactions of polymerization. It is excreted during heat treatment and subsequent drying, which has a significant effect on the mechanical and chemical properties of geopolymer concrete. In conventional concrete, unlike geopolymer concrete, Portland cement mixes with water to produce hydrated calcium silicate and calcium hydroxide, which is called the hydration process. (Esparham, 2020).

Fig. 1. BWWA Queensland Airport Australia (The largest modern geopolymer concrete project with no Portland cement).

Fig. 2. Curtin University of Australia.

3. The process in cement production

The building materials sector is the world's third-largest industrial CO_2 generator, accounting for roughly 10% of total human CO_2 emissions, the majority of which are related to concrete manufacturing. Cement manufacture accounts for around 85 percent of CO_2 emissions. Approximately 95 percent of this CO_2 is emitted during production, with only 5 percent released during raw material and final product transportation. The environmental consequences of cement are widely recognized, and the emission of major pollutants has validated them from three different sources. These three sources are as follows:

1. Releases caused by high-temperature heating of raw materials to generate clinker.
2. Releases caused by fuel combustion in the cement kiln.
3. Releases caused by energy utilized to operate the cement plant (Nabi Javid and Esparham, 2021; Van den Heede and De Belie, 2012).

Fig. 3 depicts a simplified cement manufacturing process with CO_2 emissions. Cement raw materials are high in calcium carbonate and can be derived from limestone, gypsum, or shale deposits. The calcination process may include drilling, blasting, and crushing depending on where you are. The calcination process, which accounts for approximately 50% of cement CO_2 emissions, necessitates the combustion of calcium carbonate, producing calcium oxide and carbon dioxide. As a corollary, while it is feasible to reduce environmental emissions related to fuel and energy use, the nature of the calcination process limits the potential reduction of cement's environmental consequences (Suhr et al., 2015).

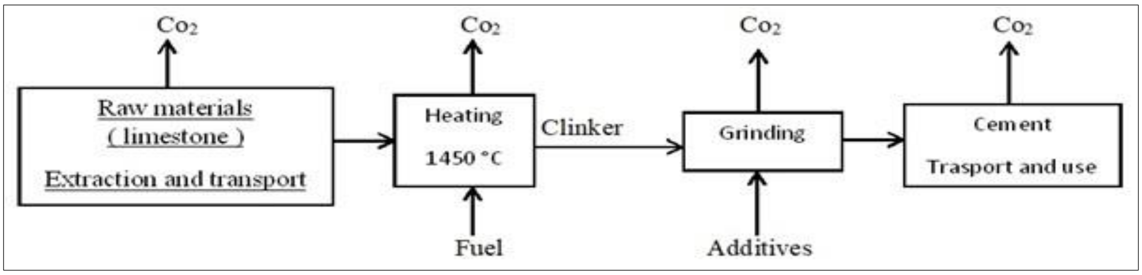

Fig. 3. The simple process of cement production shows CO_2 emissions (Nabi Javid and Esparham, 2021).

4. Life cycle assessment (methodology)

Life Cycle Assessment (LCA) is a technique for assessing all of a product's inputs and outputs (data and outputs), process or service (life cycle inventory), waste assessment, human health and ecological impact (impact assessment), and interpretation of evaluation results (life cycle interpretation) over through the entire life cycle of the product or process under consideration. The life cycle evaluation process is divided into four stages (Chevalier et al., 2011):

- Defining the goals and boundaries of the system
- Preparing a life cycle list
- Evaluate the effects
- Interpretation of results

Impact assessment assesses the potential environmental impacts of the environmental inputs and outputs defined in the LCI. Applying different models to environmental mechanisms (such as global warming due to greenhouse gas emissions), the LCI has been interpreted as a potential environmental impact. There are different methods for "interpretation" with different strengths and weaknesses (Dreyer et al., 2003). The following is a list of commonly used impact categories (and indicators):

- Abiotic Resource Depletion (potential for destruction of non-living resources - ADP)
- Global Warming Potential (global warming potential and greenhouse gas emissions - GWP)
- Acidification Potential (potential for acidification _AP)
- Eutrophication (Eutrophication Potential - EP)
- Human Toxicity - (Human toxicity potential - HTP)
- Ozon Depletion (potential for ozone depletion - ODP)

In the process of evaluating environmental processes resulting from the effects of a product's life cycle, evaluation can be done in the early stages of an environmental process called mediation or attitude (midpoint) evaluation. Subsequently, these effects cause damage to one of the three protected sectors (human health, resources, and ecosystem quality) in the (endpoint) environmental mechanisms. In order to assess the environmental impacts, various methods have been developed, followed by several practical and comprehensive methods in quantifying the assessment of environmental impacts of the life cycle. The difference between these methods is the classification of effects, environmental models, and characterization factors.

4.1. CML method

In 2001, a team of scientists led by the CML developed a set of workarounds and descriptive methods for evaluating the effects of the potential for global warming or greenhouse gas emissions (Center for Environmental Science, University of Leiden). The effects evaluation method is defined using the CML-IA method for the midpoint approach. There are two versions of this CML-IA method in SimaPro software: one with ten sets of effects; And an extended version containing other changes to the work category for different periods.

4.2. CED method

A single-purpose method that measures the energy consumption cumulatively (directly and indirectly).

5. The role of geopolymer composition on environmental effects

In a comparative LCA, the process of producing one cubic meter of geopolymer concrete and ordinary concrete with almost the same compressive strength of 33 MPa can be found that geopolymer concrete has a much smaller share in the potential of global warming (Esparham and Moradikhou, 2021b) and greenhouse gas emissions. GWP of geopolymer concrete is almost 70% lower than Portland cement concrete and in terms of cumulative energy consumption (CED), Portland cement concrete is approximately 21% higher than geopolymer concrete (Fig. 4), (Weil et al., 2009).

The environmental characteristics are heavily influenced by the raw materials utilized. Between main solid raw materials with high consumption sources (such as metakaolin) and secondary solid raw materials with low consumption sources (such as fly ash) as well as between main fluid raw materials with high consumption sources (such as NaOH solution, silicate solution) and There are significant differences between secondary fluid raw materials and low-consumption sources (such as water). The system's boundaries for comparing the life cycle assessment of different geopolymer compounds (raw materials) are shown in Fig. 5, which does not include transport processes (Nabi Javid and Esparham, 2021).

For example, the CML method is used to quantify and evaluate the impact in this paper, and the exponential energy demand (CED, [MJ]) is also considered. Table 1 shows the results obtained from the life cycle evaluation results of one cubic meter of geopolymer concrete, using the CML method (Guinée et al., 2001), also in Table 1, the results obtained to compare each of the effects Environmental degradation has been normalized with each other. The CML method consists of several environmental components with related indicators. Two important environmental indicators are analyzed:

- global warming and greenhouse gas emission potential GWP, ([kg CO_2 equivalent]).
- Potential for degradation of non-living sources of ADP, ([kg antimony equivalent]).

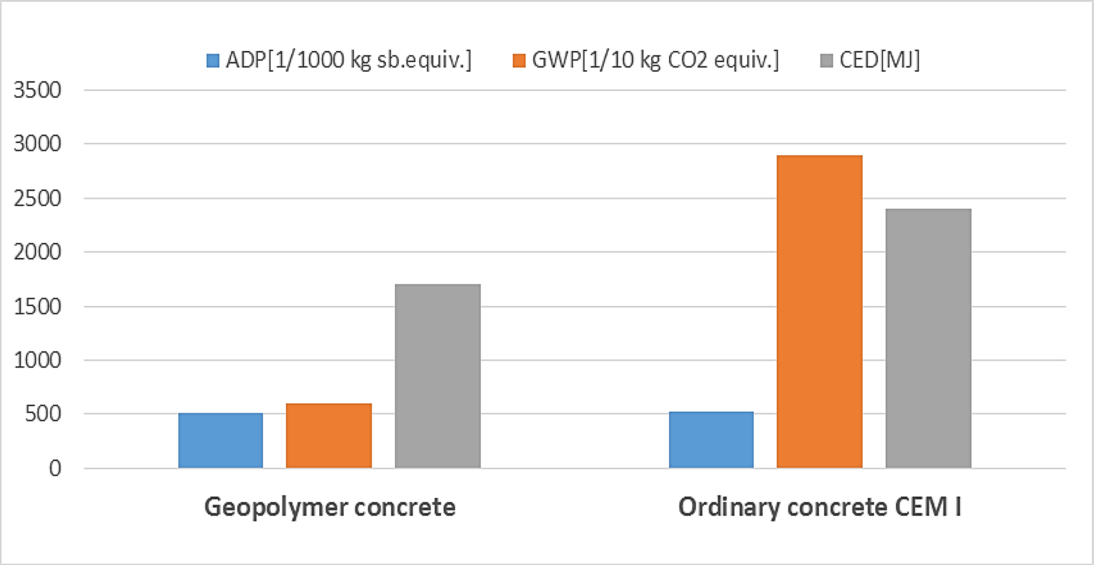

Fig. 4. LCA results for geopolymer concrete and ordinary concrete.

Table 1. Results of life cycle evaluation of the normalization stage of production of one cubic meter of geopolymer concrete using CML method.

Amount (no dimension)	Classes of effect
1.31×10^{-11}	Abiotic Resource Depletion Potential
1.38×10^{-11}	Abiotic Resource Depletion Potential (fossil fuels)
1.27×10^{-11}	global warming (GWP)
1.27×10^{-14}	Ozone Depletion Potential (ODP)
9.08×10^{-11}	Human toxicity
7.07×10^{-11}	Freshwater aquatic ecotoxicity
2.27×10^{-9}	Marine aquatic ecotoxicity
5.91×10^{-13}	Terrestrial ecotoxicity
3.57×10^{-12}	Photochemical oxidation
8.63×10^{-12}	Acidification
5.69×10^{-12}	Eutrophication (non-livable)

Comparison of the mass ratio of raw materials (Fig. 6a) to the share of environmental effects with the GWP 100 index (Fig. 6b) for two different geopolymer compositions expresses the following important aspect (Habert et al., 2011):

- Sand, despite its high mass, contributes only slightly to the GWP (global warming potential of greenhouse gas emissions).
- Slag (only mixed in MI mixing) contributes significantly to GWP (Fig. 6).
- Water supply has little effect on GWP.
- The silicate solution contributes significantly to the GWP and affects the environmental profile in both mixtures.
- Balanced use of NaOH solution (50%) in both mixtures significantly affects GWP.
- Balanced use of metakaolin (only in SI mixing) significantly affects GWP.

The use of silicate and sodium hydroxide solutions should be minimized as much as possible, or these materials should be replaced with a more environmentally friendly activator. This is also truly the case for metakaolin, which must be replaced with alternatives in reducing environmental concerns.

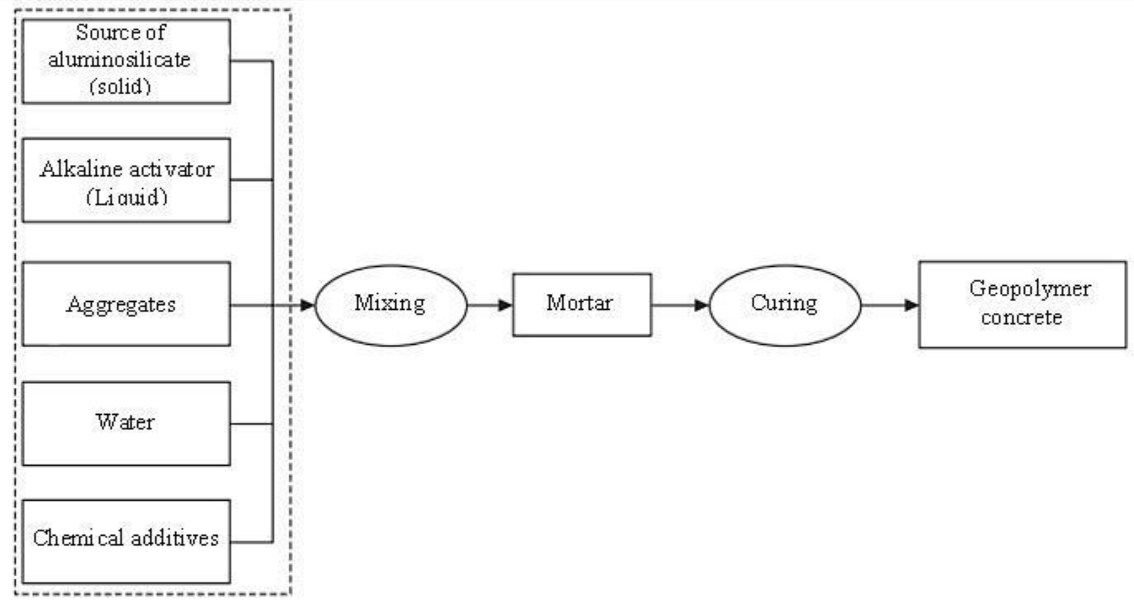

Fig. 5. System boundaries for comparing different geopolymer compositions (Weil et al., 2009).

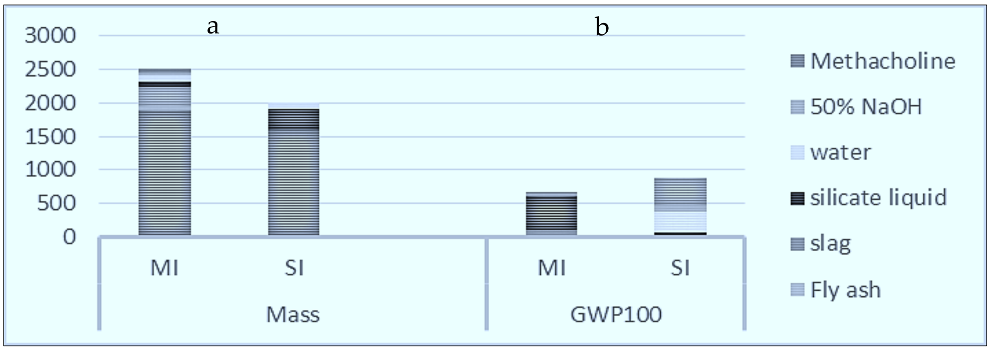

Fig. 6. Comparison of balanced mass and GWP results (global warming potential and greenhouse gas emissions) for two different geopolymer compositions (SI, MI).

6. The role of the geopolymer production process on environmental effects

The major stages of the geopolymer production process (Fig. 7) are as follows (Weil et al., 2009):

- Combining elements
- Thermal treatment

Excess compaction (using a vibrating table) during molding is not considered in the life cycle of geopolymer production, but its contribution to environmental impact is otherwise negligible. This is also true for the mixing process, which is accountable for less than 1% of the environmental impact (geopolymer production).

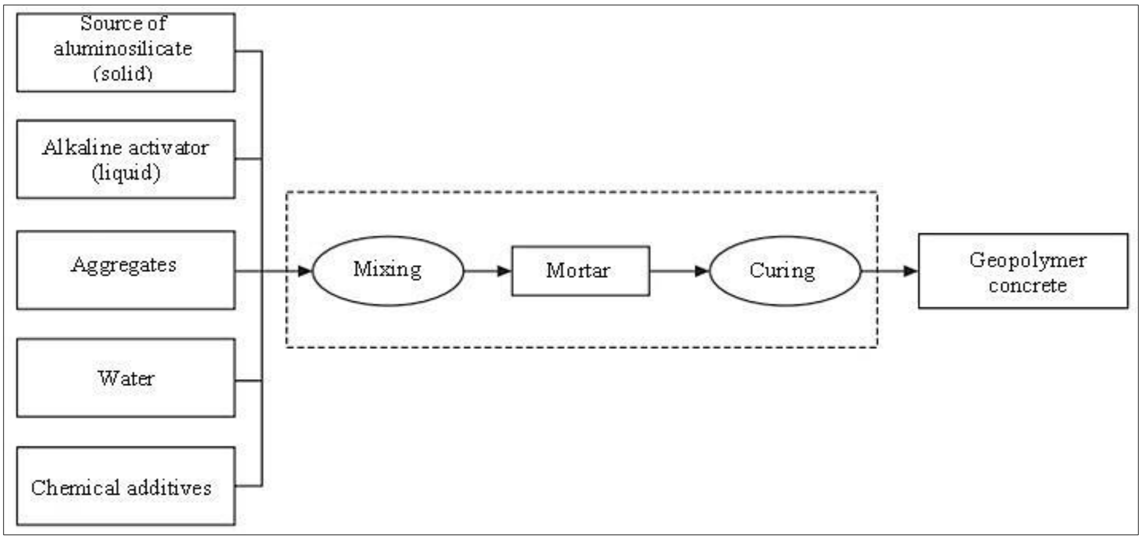

Fig. 7. System boundaries for recognizing production-related process.

The heat treatment process, on the other arm, has the potential to alter the geopolymer's environmental properties significantlyto significantly alter the geopolymer's environmental properties. It's worth noting that not all geopolymer compounds require heat treatment. Slag-rich geopolymer compounds achieve the desired technical properties in a matter of hours or days at room temperature without any heat treatment (Duxson et al., 2007b).

To increase the polymerization process, mixtures with a high percentage of fly ash (or other slow-reacting raw materials) must be heated. Temperatures usually range from 20 to 80 °C on average. In the precast concrete industry, the process of heat treatment in the same temperature range is widespread, which accelerates the improvement of concrete member strength .Energy consumption for product production in companies that manufacture prefabricated concrete parts ranges from 20 to 500 kWh per cubic meter, or approximately 0.01 to 0.2 kWh per kg. Fig. 8 depicts the effects of energy consumption on the environmental indicators of CED, GWP, and ADP, assuming an electrical enclosure (100 kW). Energy consumption and environmental indicators have a simple linear relationship. Furthermore, the energy consumption range for heat treatment is depicted (dotted line, Fig. 8).

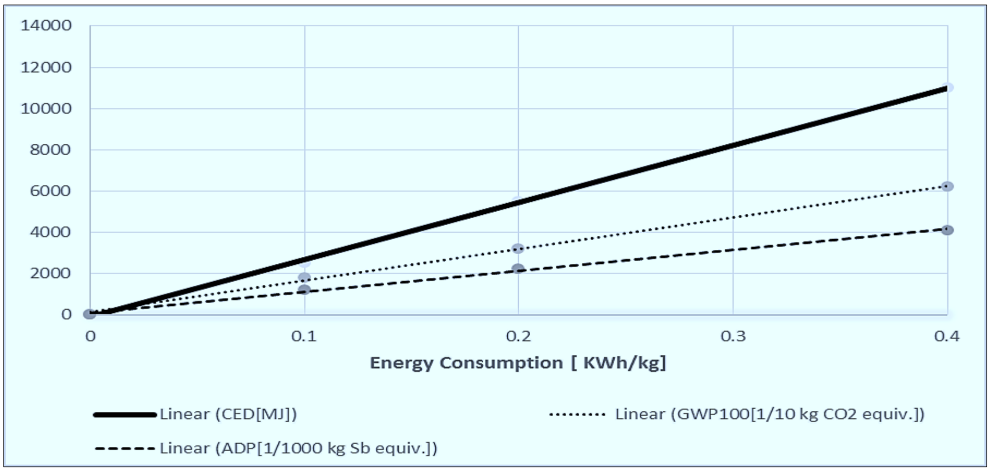

Fig. 8. Impact of heat treatment (electricity consumption) on the effects of environmental indicators (CED (Cumulative Energy Demand), GWP (global warming potential), ADP (Abiotic Resource Depletion Potential).

7. Geopolymer concrete versus ordinary concrete

Geopolymers have a high potential for producing green concrete and low-carbon construction materials. The environmental implications of geopolymers should be considered by considering the effects of by-products (or by-products) used in life cycle assessment (LCA) studies in order to measure this potential properly. Changes in the durability of reinforced cement and geopolymer concrete due to differences in carbonation performance should be scientifically investigated. The lifespan of any system can be more closely examined using a durability model that takes environmental variables into account. To date, research has shown that most types of standard geopolymer concrete have a lower global warming effect than conventional concrete (Damineli et al., 2010; Duxson et al., 2007a)

8. Conclusion

Sustainable cities of the future must meet human needs while maintaining a high standard of living. Whenever we focus on the future of sustainability, it is easy to understand how the concept of "waste-free" and the creation of new materials with increasingly negative environmental consequences become essential. On the other hand, the industrialization of cities is a vital component. It is considered long-term economic development. Interference from industrialization and environmental damage is one of the main concerns in sustainable development. For instance, production processes and industrial wastes such as cement, steel, coal mines, or agricultural wastes (bagasse, rice, lime ...) cause the release of environmental pollutants into the water, soil, and air of the surrounding areas. Cities To further develop environmentally friendly materials, the material designer needs knowledge of the environmental stimuli of new materials and awareness of the environmental effects of conventional materials in construction.

Therefore, in this review article, with the life cycle assessment approach, the studies conducted in the field of using geopolymer technology to convert raw materials or various wastes into green and sustainable materials, as well as in the direction of sustainable urban development are briefly reviewed. Unlike Portland cement, according to research, the geopolymer production method uses processed natural minerals, wastes, and industrial by-products to produce bonding agents. On the other hand, geopolymer concrete reduces environmental emissions and energy consumption and has much more favorable chemical and physical properties than ordinary concrete (Portland cement).

As a result, geopolymer materials can be used as green and sustainable materials for use in green buildings of future cities. It should be noted that according to the articles and studies performed to evaluate the life cycle of geopolymer concrete, normalization can be used to compare the effects of environmental degradation. Still, normalization according to ISO standards in assessing the environmental impact of the life cycle is optional. Geopolymeric materials can be employed as a viable alternative to typical materials in buildings that demand high durability and chemical performance due to their favorable physical and chemical qualities (such as structures subject to severe sulfate or chloride attacks). The following list is recommended based on the studies collected in this article in order to reduce further the burden of environmental pollution and energy consumption in the building industry, as well as the creation of sustainable materials:

- To minimize energy consumption and environmental pollution of geopolymer concrete, the synthesis method of sodium silicate from agricultural waste should be adopted.
- Combining a variety of aluminosilicate materials to minimize the use of sodium silicate in the mixing scheme (e.g., increasing the SI / AL ratio by combining metakaolin and fly ash).
- Use the normalization step to compare the environmental impact assessment category findings.
- In buildings and structures, use geopolymer cement as a viable alternative to Portland cement (especially those that require good chemical stability and physical properties).
- Indigenous sources of alumina silicate can be used in any area.

Despite the advantages of geopolymer materials over conventional materials, more research is needed to improve the technology and commercialization of geopolymer systems to reduce environmental impacts in future sustainable cities.

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