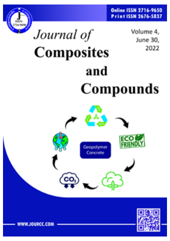

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The features of geopolymer concrete as a novel approach for utilization in green urban structures

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A B S T R A C T

Because of its unique qualities, concrete is the second most commonly utilized building material after water. However, there are significant downsides to the Portland cement manufacturing process, producing one ton of carbon dioxide per every ton of Portland cement. As a result, the usage of a Portland cement substitute appears to be required. On the other hand, the "waste-free" idea and the manufacturing of new materials with an environmental impact will be less important in future cities than the aims of sustainable development. To further develop environmentally friendly materials, it is vital to understand the environmental stimuli of novel materials as well as to assess the environmental effects of standard building materials. Geopolymers are ceramic-like materials with three-dimensional poly-compact structures that are made by chemically activating aluminum and silica-containing solids at low temperatures. Industrial wastes or by-products like coal combustion ash, smelting iron furnace slag, construction debris, or agricultural waste like rice husk ash can be utilized to make geopolymer concrete and construction. The present article reviews the studies on the use of geopolymer technology in sustainable materials to develop urban sustainability and reduce the emission of environmental pollutants with a life cycle assessment approach. 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

One of the most prevalent definitions of sustainable development is that current generations should not risk future generations' capacity to satisfy their requirements [1, 2]. Economic, environmental, and legal support, as well as social development, are the four pillars of long-term sustainability [3, 4]. 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 have predicted that 68% of the world's population will live in cities by 2050 [5]. As a result, while considering sustainable development, cities' expanding dominance and their direct and indirect consequences should be considered. Huge cities serve as hubs for large networks of vital infrastructure services. Therefore, urban infrastructure's flexibility and ro-

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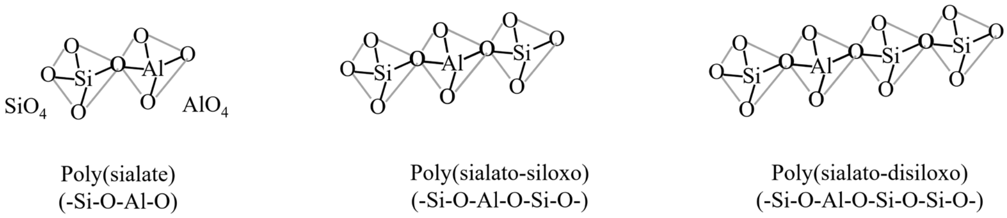

Fig. 1. Chemical structure of poly(sialate).

bustness are critical for long-term growth [6, 7]. In recent decades, sustainable urban and rural development has always been one of the main concerns of development in Iran and most developing countries [8].

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 [9-11]. 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 materials, energy, construction space, and the ecosystem in general. In the built environment design, sustainable architecture requires, leading to efficient energy and environmental conservation [12]. Factors affecting energy-related environmental difficulties resulting from technological innovation and behavioral trends should be taken into account in the development of sustainable cities [13-15]. Construction and demolition waste, manufacturing waste, and agricultural waste contribute to the total amount of waste created. Some of the most common classifications for these wastes include municipal solid waste, building and demolition debris, and industrial or agricultural by-products. On-site waste management is emphasized in sustainable architecture [16-19]. 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 [20, 21]. Today, green building design and construction are becoming more common in most nations. To protect the environment, a green building should have particular traits that help preserve resources (energy, land, water, and materials) and reduce pollution throughout its life cycle [22]. Environmentally friendly design and construction approaches must be used in modern green building design strategies despite cost constraints.

Smart grids, the creation of more efficient insulating materials, and lowering greenhouse gas (GHG) emissions were formerly the emphasis of green energy efficiency research. The notion of "zero waste" should be implemented gradually in green communities [23]. This strategy will undoubtedly contribute to long-term development and greenhouse gas reduction. This implies that the great majority of rubbish produced in the city or surrounding areas must be recyclable in order to create by-products that may be utilized for a variety of purposes, including buildings. Two factors to consider are the quality and pricing of these materials [24]. Due to the need for environmentally sustainable development of building materials and the lack of comprehensive review articles in this field, the purpose of this review article is to investigate the synthesis method and properties of geopolymers for sustainable development of green materials using by-products and waste. Also in this paper, based on studies, the environmental load of geopolymer concrete to reduce the effects of environmental pollution with a life cycle assessment and sustainable urban development approach is investigated.

2. Geopolymers

Geopolymer was initially introduced as a brand-new binder within the mineral chemical compound family by the eminent french chemist Davidovits [25]. He recommended the employment of the name poly(-sialate) for the chemical identification of geopolymers, which is additionally an associated abbreviation for the silico oxoaluminate chain. Fig.1.shows the various forms of poly(sialate).

2.1. Mechanism of setting and hardening of geopolymers

In contact with the alkaline solution, the aluminosilicate source dissolves, and the synthesis of Al and Si complexes begins. The concentration of the alkali solution, the alkali metal cation, the stirring speed, the dissolving time, the structure of the aluminosilicate source, and the chemical analysis all influence the quantity of dissolution. Among these factors, the source qualities of alumina silicate and the concentration of alkaline solution are more essential. When alumina-silicate particles dissolve from their surfaces, Al and Si complexes penetrate the gel phase, and germination occurs. As a result, the concentration of Al and Si complexes on the surface of aluminosilicate particles reduces, increasing Al and Si dissolution.

Dissolution time and stirring intensity are important considerations in the diffusion phase, because the greater the dissolution of Al and Si complexes from the breaking point of the kinetic barrier between the raw material and the gel particles, the longer the dissolution and stirring time. In addition, Al and Si complexes penetrate better than Si complexes that have been polymerized. As an outcome, densification of Al and Si complexes occurs as well as their dissolution and diffusion from the aluminosilicate source simultaneously. The densification phase is affected by temperature, pH, and cation size. Densification of alkali metal cations with bigger atomic sizes is accelerated by greater temperatures, higher pH, or higher concentrations of alkali solution. Dissolution and diffusion between the particle surface and the gel phase can occur during the hardening phase, even when there is no movement between the particles. Geopolymers, in a broad sense, are the products of geochemical processes that convert geomolecules [26-32].

In 2006, Sindhunata et al. [33] examined the microstructure of an air ash-based geopolymer matrix and found that its structure was approximately similar to that of 5 to 20 nm aluminosilicate nanoparticles, part of which is used to create pores and channels for nanoparticles. This is consistent with the report of Kriven et al. [34] on the potassium-poly (silate-siloxo) geopolymer . The aggregation of nanoparticles, or single particles, forms a geopolymer matrix, usually expressed as precipitated particles, and their dimensions are roughly similar to micelles composed of surfactant molecules. However, the temperature stability of geopolymer nanoparticles strongly supports the presence of supermolecules. In other words, this is in favor of the polymer model [35, 36].

Geopolymers, in a broader sense, are molecules that have been converted by geochemical processes. The word "geopolymer" was first used to apply to inorganic materials, but it has now been expanded to encompass organic elements. River straw and mud containing organic materi-

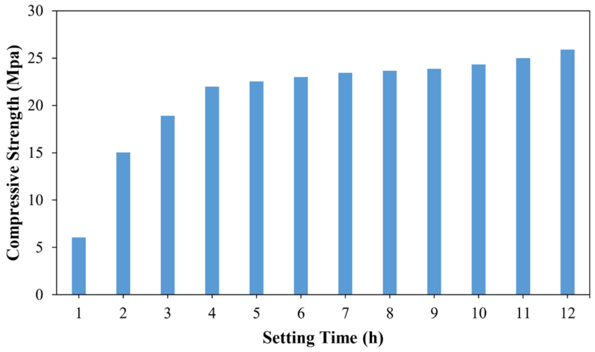

Fig. 2. Setting for cement made of Poly (sinlante - siloxo potassium) at room temperature.

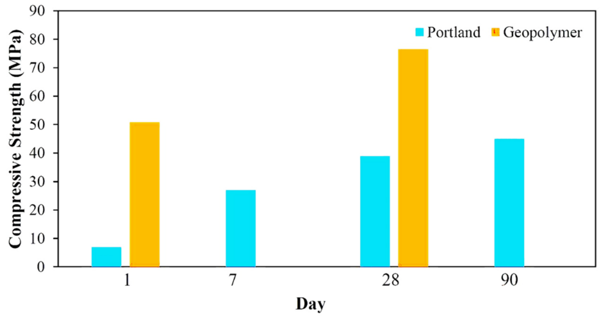

Fig. 3. Comparison of strengths of geopolymer and Portland concrete.

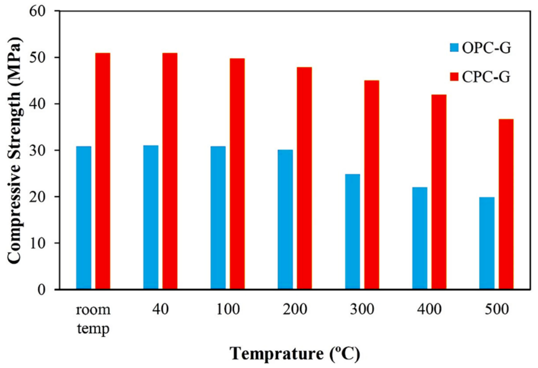

Fig. 4. Compressive strengths of Portland and geopolymer concretes at different temperatures.

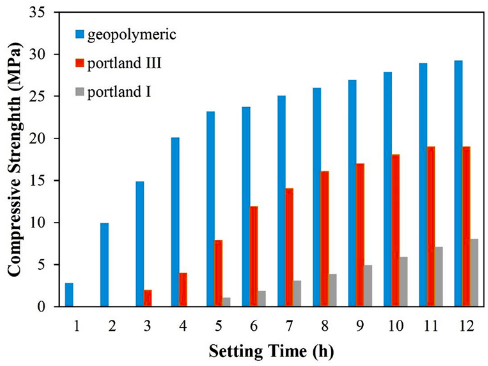

Fig. 5. Room temperature curing for Portland concretes types 1 and 3, and concretes made of geopolymer.

als (e.g., humic compounds) were employed by the ancient Egyptians to create construction components with great strength and durability. As a result, it's crucial to think about how inorganic and organic species interact during polymerization [37-39].

2.2. Applications and properties of geopolymers

As a precursor to geopolymer and polycondensation, any silica and alumina source that can be dissolved in an alkaline solution is employed. Metakaolin (MK) is a kind of geopolymer that is made by calcining kaolin at 750 degrees Celsius [40]. Shaw and Wangersa [41] examined 16 natural minerals containing Al-Si as a possible geopolymer source. Geopolymer concrete may be one of the best alternatives to conventional concrete due to its beneficial properties. Although geopolymer concrete is not yet widely accepted, the use of this type of concrete or its derivatives is rapidly increasing worldwide. The main application of this concrete is in the construction, maintenance of road pavement, and also in airport runways. A short-term objective is to employ geopolymer concrete in bridge building, particularly for prefabricated portions. But the most important advantage of concrete made of geopolymer compared to ordinary concrete is its high durability, so the use of this type of concrete in areas such as tanks, offshore structures, and all concrete parts that are exposed to corrosive conditions such as sulfate or chloride attack, are very suitable. However, there are drawbacks, such as manufacturing difficulties, workability, and geopolymer concrete's high sensitivity to sintering and processing temperatures. Despite the fact that geopolymer concrete offers various benefits over Portland cement concrete, including superior chemical performance, low energy consumption, low emissions, and little shrinkage, it cannot be utilized in all concrete structures. Due to the rising worldwide need for expansion and the necessity to use new materials, further studies on the use of geopolymer concrete in specialized constructions are required [37, 42-44]. Geopolymer materials for use in concrete construction may be made from a variety of wastes, including mine, power plant, municipal, and construction waste, as well as any other source of aluminosilicate that is generated in substantial numbers in any country today. It's also utilized as a fire retardant and an insulator. Some of these wastes (such as fly ash and smelting iron slag) are presently solely utilized as pozzolans in Portland cement manufacturing [45-47].

Other potential geopolymer applications include hazardous waste stabilization, surface coating, and landfill stabilization, construction of low permeability baseliners in landfills, water control structures, and thermal insulation. In the construction of urban constructions, geopolymer can be utilized instead of Portland cement [23].

At room temperature, geopolymer concrete hardens rapidly, reaching a compressive strength of 20 MPa after 4 hours and compressive strength of 70 to 100 MPa after 28 days or more (Figs. 2 and 3) [48].

Because their porosity is lower than that of cement or mortar, geopolymer cement have better mechanical qualities. A comparison of the strength of Portland cement with geopolymer cement is shown in Fig. 3 [49].

Their ultimate structure and physical attributes are due to several factors. For instance, particle size, water content, thermal history, alkali metal concentration, and degree of polymerization affect it. When heated to 1000° C, sulfates and alkaline condensation processes preserve their stability by forming very durable products from low-iron geopolymers. Fig. 4 shows a comparison of Portland concrete with a sample of geopolymer concrete at different temperatures, each of which was broken in twenty-eight days [50].

Geopolymers are harden quickly and have high initial strength, with an ultimate compressive strength of 100 MPa or more after 28 days. Geopolymers have a permeability of 10-9 cm/s, low alkali expansion, high acid resistance, and can withstand freeze-thaw melting cycles [51-54]. Davidovits [27] compared the compressive strengths of cured geopolymer concrete samples at room temperature and concrete samples constructed of Portland cement type one and type three, revealing that geopolymer concretes have great strength and very fast setting. Fig. 5 shows the results.

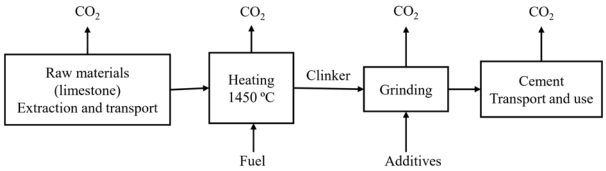

Fig. 6. CO_2 emissions during the cement production process.

Sulfate and chloride assaults are the two mechanisms that cause concrete to deteriorate. Geopolymer concretes are highly resistant to chemical attacks. According to studies, geopolymers have a lower calcium content than typical Portland cement, making them more sulfate resistant. Because the production of the chemicals that induce sulfate breakdown in regular Portland cement needs the presence of calcium. The adhesive phase of the geopolymer has a lower permeability than Portland cement. The fundamental advantage of low permeability is that it minimizes chloride permeability, which lowers the rate of chloride attack on reinforced concrete steel and extends its service life [55, 56].

Water is an essential component in geopolymerization since it helps the initial paste operate better but is not included in the final geopolymer structure. Water does not play a substantial part in the primary chemical processes of polymerization, unlike hydration reactions in ordinary concrete. It is excreted during the heat treatment and subsequent drying of geopolymer concrete, and this has a considerable impact on the mechanical and chemical characteristics of the material. Unlike geopolymer concrete, Portland cement reacts with water to form hydrated calcium silicate and calcium hydroxide, which is known as the hydration process [57, 58].

3. Current processes in cement production

The construction materials industry is the world's third-largest industrial CO_2 emitter, accounting for around 10% of total human CO_2 emissions, with concrete manufacturing accounting for the majority of these emissions. Cement production is responsible for over 85% of CO_2 emissions. Approximately 95% of this CO_2 is released during manufacturing, with approximately 5% released during raw material and end product transit. The environmental consequences of cement are widely recognized, and the emission of major pollutants has been confirmed 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 [59, 60].

Fig. 6 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 [61]. 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 [62].

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 [63, 64].

4. Methods

Life Cycle Assessment (LCA) is a technique for examining environmental consequences associated with all phases of a commercial product, processes, or service life cycle. For instance, in the case of a manufactured product, environmental consequences are examined from the extraction and processing of raw materials (cradle), throughout manufacturing, distribution, and use of the product, to the recycling or final disposal of the materials (grave) [65].

The life cycle evaluation process is divided into four stages [66, 67] :

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

The potential environmental implications of the environmental inputs and outputs indicated in the LCA are investigated through impact assessment. The LCA has been interpreted as a potential environmental impact by applying different models to environmental systems (such as global warming due to greenhouse gas emissions). There is a variety of "interpretation" methods, each with its own set of advantages and disadvantages [68]. A list of regularly used impact categories (and indicators) are as follows [69]:

- Abiotic Resource Depletion Potential (potential for destruction of non-living resources - ADP)
- Global Warming Potential (potential for global warming and greenhouse gas emissions - GWP)
- Acidification Potential
- Eutrophication Potential
- Human Toxicity Potential
- Ozone Depletion Potential

Evaluation can be done in the early phases of an environmental process called «midpoint evaluation» when analyzing environmental processes resulting from the consequences of a product life cycle. In the endpoint environmental mechanisms, these consequences cause damage to one of the three protected sectors (human health, resources, and ecosystem quality). Various approaches have been created to analyze environmental impacts, followed by several practical and comprehensive methodologies for quantifying the assessment of environmental consequences of the life cycle. The classification of impacts, environmental models, and characterization factors varies between these methodologies.

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 of Environmental Science, University of Leiden). The effects evaluation method is defined for the midpoint approach using the CML-IA method. There are two versions of this CML-IA method in SimaPro software: one with ten sets of effects; a nd an extended version containing other changes to the work category for different periods [70].

4.2. CED method

CED (Cumulative Energy Demand) is a single-purpose method that measures energy consumption cumulatively (directly and indirectly) [71].

4.3. The role of geopolymer composition on environmental effects

The environmental characteristics are heavily influenced by the raw materials utilized. There are significant differences 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), between main fluid raw materials with high consumption sources (such as NaOH solution, and silicate solution) as well as between secondary fluid raw materials and low-consumption sources (such as

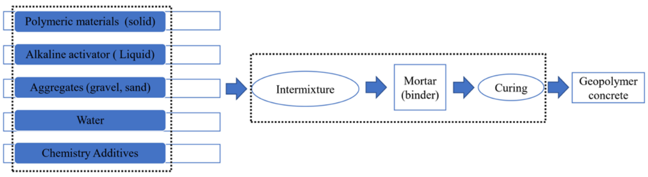

Fig. 7. System boundaries for comparing different geopolymer compositions.

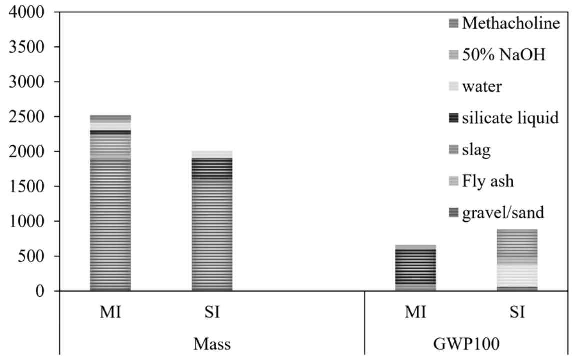

Fig. 8. Comparison of balanced mass and GWP results for two different geopolymer compositions (SI, MI).

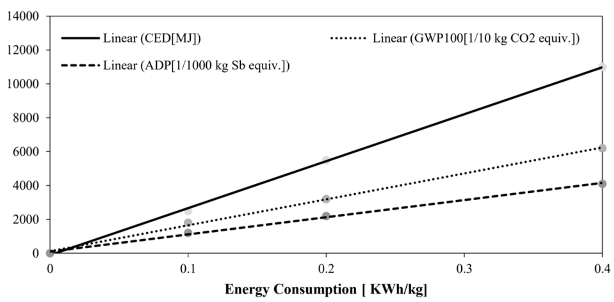

Fig. 9. Impact of heat treatment (electricity consumption) on the effects of environmental indicators (CED, GWP, and ADP).

water). The system boundaries for comparing the life cycle assessment of different geopolymer compounds (raw materials) are shown in Fig. 7 (the box on the right), which does not include transport processes [64, 72].

For example, the CML method is used to quantify and evaluate the impact in the paper by Guinée et al. [73], and the exponential energy demand (CED, [MJ]) is also considered. Table 1 shows the normalized indicator values related to each environmental impact obtained from the life cycle evaluation of one cubic meter of geopolymer concrete, using the CML method,.

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

Classes of effect	Amount (dimensionless)
ADP	1.31×10^{-11}
ADP (fossil fuels)	1.38×10^{-11}
GWP	1.27×10^{-11}
ODP	1.27×10^{-14}
HTP	9.8×10^{-11}
Freshwater aquatic ecotoxicity	7.07×10^{-11}
Marine aquatic ecotoxicity	2.27×10^{-9}
Terrestrial ecotoxicity	5.91×10^{-13}
Photochemical oxidation	3.57×10^{-12}
AP	8.63×10^{-12}
EP (non-livable)	5.69×10^{-12}

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 of the potential of global warming [38] 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. 8) [72].

For two distinct geopolymer compositions, a comparison of the mass ratio of raw materials (Fig 9, left) to the share of environmental impacts using the GWP 100 index (Figure 9, right) illustrates the following significant results [74]:

- Sand, despite its high mass, contributes only slightly to the GWP.
- Slag (only mixed in MI mixing, Fig. 7 contributes significantly to GWP.
- 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.

To the extent practicable, silicate and sodium hydroxide solutions should be avoided, or these components should be substituted with a more ecologically friendly activator. This is also true for metakaolin, which must be replaced or combined with other materials in order to reduce the environmental pollution load.

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

The major stages of the geopolymer production process (Fig. 7, the box on the left) are as follows [72]:

- Combining elements
- Thermal treatment

Excess compaction (using a vibrating table) during molding is not considered in the life cycle of geopolymer production, 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) [61].

Heat treatment, on the other hand, has the potential to alter the geopolymer's environmental properties significantly. It is important to note that not all geopolymer compounds need to be heated. Without heat treatment, slag-rich geopolymer compounds achieve the desired technical properties in a matter of hours or days at room temperature [75, 76].

To increase the polymerization process, the mixtures with a high percentage of fly ash (or other slow-reacting raw materials) must be heated. Temperatures are usually in the range of 20 to 80 degrees Celsius on average. In the precast concrete industry, the process of heat treatment in the same temperature range is despread, which accelerates the improvement of concrete member strength. Energy consumption for making the products 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) [68]. Energy consumption and environmental indicators have a simple linear relationship (Fig. 9).

5. Geopolymer concrete versus ordinary concrete

Geopolymers offer a lot of potential for producing green concrete and other low-carbon building materials. In order to estimate this potential accurately, the environmental consequences of geopolymers should be examined by considering the impacts of by-products utilized in life cycle assessment (LCA) studies [77].

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. Most types of geopolymer concrete have a lower global warming effect than conventional concrete, according to research thus far [78, 79].

6. Conclusions and future insights

Sustainable development in the construction industry and concrete should be given a lot of attention, according to the Islamic Republic of Iran's vision document, which states that Iran is a developed country with the region's first economic, scientific, and technological position.

On the other hand, urban industrialization is a vital component of long-term economic development. One of the issues in sustainable development is the interference of industrialization and environmental damage that leads to the transmission of environmental pollutants to water, soil, and air in the suburbs. Therefore, in this review article, with the life cycle assessment approach, the studies conducted in 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. In addition to the advantages of Portland cement concrete, geopolymer concrete has advantages such as superior mechanical properties and high durability against chemical attacks compared to conventional concrete, which reduces the consumption of natural resources and environmental damage. All of these contributes to the long-term growth and conservation of natural resources for future generations. The following are suggested based on studies collected to reduce the environmental pollution burden of concrete production:

1. The use of geopolymer cement as a suitable alternative to Portland cement in the construction industry
2. The combination of different aluminosilicate materials to reduce the consumption of sodium silicate (as a factor in increasing greenhouse gases and CO_2 production), in the mixing of geopolymer concrete (such as the combination of metakaolin and fly ash to increase SI / AL).
3. Sodium silicate synthesis method from agricultural waste should be used to reduce energy consumption and environmental pollution load of geopolymer concrete.

Despite the advantages of geopolymer cement over Portland cement, more research is needed to develop technology and expand the potential of geopolymer systems in commercial applications to reduce environmental impact.

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