Environmental Benefits of Geopolymers

Subjects: Economics

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The global concerns about environmental sustainability have roused interest in innovative green technologies, including those related to geopolymer production. Geopolymers are aluminosilicate synthetic materials obtained from a reactive powder of silicon and aluminium (i.e., precursor) mixed with an activating alkaline solution (i.e., activator), whose process is commonly named the alkali activation process. Moreover, their structure makes them very versatile thanks to some features, namely chemical attacks and fire resistance, thus suitable in different sectors, particularly in the building and restoration ones.

Keywords: sustainability ; geopolymers ; volcanic ash ; circular economy ; environmental and resource economics

1. Introduction

Concerns about sustainability mainly relate to the environmental consequences of anthropogenic activities on future generations [1], among which is the over-exploitation of natural resources [2]. In this perspective, recovering value from waste is acknowledged to minimise the use of non-renewable materials [3][4]. By supporting the conservation of natural resources while reducing disposal problems, waste material recycling is a socially valuable activity that benefits both the environment and the economy [3]. Indeed, recycling is the main component of the circular economy, namely “an economic system based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production, distribution and consumption processes with the aim to accomplish sustainable development” [5]. In addition, the circular economy helps to improve the economic and social conditions of people and territories, creating new job opportunities, decreasing the dependence on external resources and promoting sustainable and inclusive development, especially benefitting lagging countries [6]. Recycling is also one of the pillars of both sustainability economics, which focuses on the efficient use of scarce resources and non-wastefulness [7], and environmental sustainability [8].

In the last few years, sustainability issues have gained momentum in the construction industry [9][10], with particular attention on the materials used [9][11][12]. From the point of view of recycling policies and environmental sustainability initiatives, inorganic polymers can play a relevant role, enabling the reuse of wastes in a wide range of potential applications [11][13][14][15][16]. Specifically, the use of these materials in the construction sector is of particular interest as they can be a sustainable alternative for cement and concrete [17][18][19][20], whose production requires an intensive consumption of non-renewable raw materials (i.e., limestone, clay or its natural mixture, marl) and constitutes one of the major causes of global CO_2 emissions (e.g., [21][22][23][24][25]). In this sense, in the literature [26], there are several studies on the reuse of industrial and artificial wastes (e.g., [27][28][29][30][31][32]) or biomass ashes from agricultural farming wastes [33]. Moreover, there is a substantial number of papers on the technical properties of volcanic ash geopolymers [34][35][36][37][38][39][40][41] and an increasing interest in regional sustainability initiatives [42][43][44][45][46][47][48][49].

Considering the environmental benefits of volcanic ash geopolymer as a case study and limiting the analysis of CO_2 emission due to the production process only to activators (i.e., sodium silicate and sodium hydroxide), which represent the most polluting components in the production of geopolymers [11][21][50][51], there is a decrease in CO2 emissions of approximately 78% compared to that of the cement industry. In this sense, assuming a social cost for carbon dioxide of USD 51 (about EUR 48.4, at the exchange rate of 10 October 2023, as set by the Biden administration in the USA in February 2021) per ton, the net social cost per kg of geopolymer would fall by about 0.019 EUR/kg in respect to cement materials.

2. Sustainability of Geopolymers and Applications

The global concerns about environmental sustainability have roused interest in innovative green technologies, including those related to geopolymer production [10][52]. Geopolymer technology traces back to the pioneering research in 1957 by Victor Glukhovsky, who investigated the possibility of preparing low-calcium or even calcium-free cementitious materials (initially called “soil cements”), using clays and alkaline metal solutions [53]. However, the term geopolymer was first used by Davidovits to describe synthetic alkali aluminosilicate materials, hitherto broadly termed “inorganic polymers” [54]. Geopolymers are, indeed, aluminosilicate synthetic materials obtained from a reactive powder of silicon and aluminium (i.e., precursor) mixed with an activating alkaline solution (i.e., activator), whose process is commonly named the alkali activation process [55]. Moreover, their structure makes them very versatile thanks to some features, namely chemical attacks and fire resistance, thus suitable in different sectors, particularly in the building and restoration ones [56][57].

The growing interest in geopolymers is due to their production process, which is less polluting than that of traditional alternatives. Indeed, the production of clinker needed for the Ordinary Portland Cement production (OPC) requires thermal treatments at high temperatures of around 1400 °C [58], thereby consuming large amounts of natural raw materials and energy, and releasing a massive amount of CO_2 into the atmosphere [59]. Moreover, the activation of clinker-based materials and thus their application need a substantial amount of water that directly causes an additional burden on the already scarce natural resource. Therefore, it is not surprising that the cement industry is among the top CO_2 emitters in the world, responsible for about 5–8% of global anthropogenic CO_2 emissions [60]. In this scenario, Miller et al. [61] show that in 2012 concrete production was responsible for 9% of global industrial water withdrawals (approximately 1.7% of total global water withdrawal). Furthermore, the global demand for OPC is set to increase further by 2050, especially in developing countries [62], where water stress is expected to be a more serious problem [45].

In contrast, geopolymer production requires a lower temperature, or generally, the process is at room temperature [63], implying less energy and water consumption, reducing CO_2 emissions and turning waste streams into “green” cement [4][23][64][65][66]. In reference to the production process, empirical studies have shown that geopolymer concrete mixes indicate a potential for up to a 40% reduction in overall energy consumption [67] and up to 80% reduction in CO_2 emissions [50] compared to OPC. Additionally, if the raw materials are available locally, the production of geopolymers can take place in situ, also reducing the emissions (and the related social costs) from transport [68].

Further environmental benefits concern the production of waste-based geopolymers, to the extent that both the extraction of non-renewable raw materials from (existing or new) quarries and the disposal of waste itself (with the related costs and landfill space saved) are avoided [28]. Indeed, the use of waste materials as precursor is a good example of waste management as it gives them a new life and prevents the possible contamination of the environment that might have resulted from their improper disposal.

What has been said so far also concerns the geopolymer considered here as a case study, the one based on the use of volcanic ash whose disposal in Italy is strongly regulated. In fact, volcanic ash is classified by law as a special municipal waste, to be disposed of in highly specialised landfill implants, with significant costs for the local community that are damped on to citizens in the form of higher local taxes. Recently, to lighten the heavy financial burden on the eastern Sicilian municipalities involved in a prolonged eruptive activity of Mt. Etna, the central government has allowed the reuse of volcanic ash “to replace raw materials within production cycles, using processes or methods that do not harm the environment or endanger human health” (Law no. 108 on 29 July 2021). Furthermore, the use of volcanic ash, readily and freely available in areas surrounding eruptive volcanos such as Mt. Etna, can help alleviate the problem of the lack of enough natural materials that is expected to affect the market of cement worldwide. In fact, while it is expected that the global consumption of concretes will grow considerably in the future, the production of industrial wastes (e.g., fly ash and slag) to be used as precursor materials is likely to decrease, due to the worldwide adoption of stricter environmental regulations of polluting industrial activities.

The research focus is currently on minimizing the use of alkali activators (e.g., sodium silicate and sodium hydroxide), which are the least ecological part of the entire production process, being highly corrosive and the highest contributors of embodied energy and carbon emissions [51].

Because of the above environmental benefits, the use of recycling-based geopolymers in the construction sector is set as a priority in the recent European political agenda. The worsening of the global environmental crisis has prompted the European Commission to develop a long-term strategy to promote sustainability. Accordingly, the European Green Deal includes a roadmap to mitigate the negative environmental impact of the construction sector, with the aim of reducing greenhouse gas emissions by up to 60% by 2050 and conserving natural resources. Among the key actions are investments in “greener” cementitious binders and the promotion of the use of recycled materials and industrial by-products as secondary raw materials.

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