

## REVIEW

# Blue Horizons: Assessing Geopolymers as Eco-Friendly Materials in the Context of the Transition to a Sustainable Blue Economy

Jihene Nouairi<sup>1,2,3\*</sup> , Slavka Andrejkovičová<sup>4</sup> , Angelo Camerlenghi<sup>1</sup> , Mounir Ghribi<sup>1,3</sup> 

<sup>1</sup> National Institute of Oceanography and Applied Geophysics—OGS, 34010 Trieste, Italy

<sup>2</sup> International Centre for Theoretical Physics—ICTP, 34151 Trieste, Italy

<sup>3</sup> EMUNI Centre of Excellence on Sustainable Blue Economy, Euro-Mediterranean University (EMUNI), 6000 Koper, Slovenia

<sup>4</sup> Geosciences Department, Geobiotec Research Unit, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

## ABSTRACT

Geopolymers, characterized by their sustainable composition, are increasingly recognized as viable alternatives in construction materials. This paper examines the prospects of geopolymers within the sustainable blue economy, as a context emphasizing blue growth in smart, inclusive and above all sustainable development in the marine and maritime sectors. A synthesis of existing knowledge, emphasizing geopolymers' potential contribution to sustainable practices within the blue economy is presented, delving into specific but innovative applications such as the use of alternative and non-conventional materials for marine infrastructures and offshore construction, and assessing the performance and the many advantages of geopolymers in challenging marine environments through a number of studies. Sustainability considerations and environmental impact are analysed, comparing geopolymers with conventional materials. The paper also identifies challenges related to the applications for marine infrastructures and offshore construction, proposing research directions and solutions. Finally, regulatory aspects are explored outlining current guidelines and advocating for a regulatory framework supportive of geopolymer integration in the Blue Economy sectors, and future trends

### \*CORRESPONDING AUTHOR:

Jihene Nouairi, National Institute of Oceanography and Applied Geophysics—OGS, 34010 Trieste, Italy; International Centre for Theoretical Physics—ICTP, 34151 Trieste, Italy; EMUNI Centre of Excellence on Sustainable Blue Economy, Euro-Mediterranean University (EMUNI), 6000 Koper, Slovenia; Email: [jnouairi@ogs.it](mailto:jnouairi@ogs.it)

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and innovations are discussed, providing insights into ongoing research. The aim of the present review is to inform researchers, practitioners and policymakers involved in the intersection of geopolymer materials, marine ecosystems and circular economy.

**Keywords:** Geopolymers; Eco-Friendly Materials; Marine Infrastructure; Offshore Construction; Environmental Impact; Sustainability; Blue Economy

## 1. Introduction

Used in marine and offshore environments, classic concrete is subjected to alternating wet-dry and thermal cycles. In these conditions, exposure to seawater results in complex deterioration mechanisms driven by aggressive species such as chloride  $\text{Cl}^-$ , sulfate  $\text{SO}_4^{2-}$ , and magnesium  $\text{Mg}^{2+}$  [1]. For Ordinary Portland Cement (OPC), these aggressive ions interact with the cement hydration phases, resulting in the formation of secondary products such as Friedel's salt, ettringite, brucite, and magnesium silicate hydrates [2]. When accelerated by environmental cycles, these compounds, precipitated and crystallized in the concrete pores, can result in the formation of cracks and corrosion [2]. For this reason, special concrete with high resistance to the marine environment has been extensively studied. For example, in recent years, studies have explored the use of geopolymers as high-anticorrosion concrete for marine structures [3,4].

Geopolymers, first discovered in the late eighties, are an innovative category of inorganic polymers derived from aluminosilicate precursors. They have drawn interest as low-impact construction materials [5]. Their synthesis consists on the activation of aluminosilicate materials through alkaline solutions. They are known for their high-strength and durability [6]. Known for their lower  $\text{CO}_2$  footprint during production and enhanced resistance to chemical degradation, geopolymers present a critical advancement in eco-friendly building practices [7].

As sustainability challenges intensify globally, the Blue Economy has emerged as a framework emphasizing the balanced exploitation and management of marine resources [8]. The incorporation of geopolymers in the framework of a Sustainable Blue Economy appears as a strategic necessity to meet the evolving needs of marine and maritime sectors, including infrastructure development, artificial reefs deployment and the transition to-

ward sustainable ports.

The main objective of this paper is to demonstrate the importance of geopolymers and their role in supporting the Blue Economy sector. The aim is to underscore their potential as resilient and low-impact construction materials especially in the marine environments.

## 2. Background and Basis of Geopolymers

As inorganic aluminosilicate binders, geopolymers develop extensive, covalently linked amorphous networks, resembling ceramic-like materials in structure and behaviour [5]. They are synthesized via an alkaline activation process, in which an aluminosilicate precursor reacts with a highly alkaline solution to produce a polymeric binder, resulting in a semi-crystalline amorphous material [9,10]. The term "geopolymer" reflects its chemical nature: "geo" denotes its origin from earth-derived minerals rich in silicon and aluminium, major constituents of the Earth's crust, while "polymer" highlights its three-dimensional network formed from aluminosilicate units [5]. The synthesis of geopolymers involves the mixing of a dry solid aluminosilicate with an alkaline solution and another reactant [3]. The most critical component is the source material, which must be rich in silicon and aluminium. The formation of geopolymers is influenced by variables such as the Si/Al ratio, the type of alkaline ion used, and the water/solids ratio, which have repercussions on the final properties of the materials [3,11]. Geopolymers exhibit optimal properties that make them attractive for various applications including marine construction materials. These properties include: high mechanical strengths [3,12-14], low thermal conductivity [15-18], high thermal stability [12,19,20], good resistance to high temperatures [19,21,22], low permeability [23-25], enhanced resistance to chemical degradation [26-30]. Geopolymer matrices have a predominant amorphous phase, but, depending

on the formulation and curing conditions, small quantities of crystalline zeolite-like phases may be present<sup>[31]</sup>. The primary amorphous phase in geopolymer systems is known as the N-A-S-H gel<sup>[32]</sup>. This phase refers to the characteristic chemical composition produced during the geopolymerization process<sup>[32]</sup>. Geopolymers are considered to be sustainable alternatives to Ordinary Portland Cement OPC. They are suitable for a broad spectrum of engineering applications such as fire and heat-resistant coatings<sup>[33,34]</sup>, adhesives<sup>[35]</sup> and new binders for concrete<sup>[36]</sup>.

In fact, compared to widely used construction materials, geopolymers offer significant environmental benefits. They are considered ecologically friendly substitutes for OPC, with lower CO<sub>2</sub> emissions during production and a reduced reliance on non-renewable natural resources<sup>[37,38]</sup>. Additionally, the use of geopolymers in construction materials showed robust mechanical properties, exceptional durability and a reduced overall environmental impact compared to traditional cement-based materials<sup>[37]</sup>. These benefits make geopolymers an optimal choice for sustainable construction practices aligning with global sustainability goals and the increasing demand for eco-friendly building materials.

### 3. Environmental Impact and Sustainability

Within the Sustainable Blue Economy framework, the evaluation of the environmental impact of geopolymers needs a comprehensive analysis particularly when compared with OPC. The production of cement is a major contributor to global CO<sub>2</sub> emissions as it is estimated to account for roughly 5–8% of total anthropogenic CO<sub>2</sub> emissions<sup>[3,19,23]</sup>. Each ton of OPC typically generates about 0.8–0.9 t of CO<sub>2</sub>, resulting primarily from the calcination of the limestone and the combustion of the fuel<sup>[8]</sup>. In addition, the emissions intensity has remained stable, although a modest upward pressure has occurred due to increases in the clinker to cement ratio in some regions<sup>[19]</sup>. To align with the “net zero” by 2050 scenarios, the cement industry must adopt deep decarbonization strategies targeting continual reductions in CO<sub>2</sub> emissions. In cement manufacturing, the significant share of emissions of ~50% result from material (clinker) processing, ~40% from fuel combustion

and a smaller portion from electricity usage and transport<sup>[7]</sup>.

According to Jwaida et al.<sup>[38]</sup>, the temperature required for the manufacturing, grinding and heating of raw materials in the making of OPC is very high (up to 1,450 °C and more). Beyond the direct release of carbon dioxide, the calcination of limestone also generates other greenhouse gases and trace amounts of harmful emissions, including sulfur dioxide (SO<sub>2</sub>) and nitrogen dioxide (NO<sub>2</sub>)<sup>[39]</sup>.

The escalating demand for concrete in infrastructure, housing and maritime construction has led to a daily increase in cement production, reaching around 4,100 million metric t worldwide in 2018. Alarming projections from the Global Cement Report<sup>[40]</sup>, suggest a further rise with anticipated production reaching 4.38 billion t in 2025 and 5 billion t in 2030. These projections raise concerns due to the considerable energy and raw material demands, reducing non-renewable fossil fuels and natural resources. Additionally, it is recognised that the 2050 emission reduction goals cannot be achieved without the adoption of specific strategies that include, for example, carbon capture utilisation and storage (CCUS) technologies (e.g., ECCESEL ERIC Annual Report 2021).

Studies have indicated that geopolymers formulated with aluminosilicate precursors, offer notable environmental benefits, such as:

#### 3.1. Reduced CO<sub>2</sub> Emissions

TAs reported in the literature, the production of one ton of geopolymer is estimated to generate only 0.15–0.20 t of carbon dioxide, which is significantly lower than the emissions associated with OPC production<sup>[5]</sup>. Therefore, substituting OPC with geopolymer binders can reduce embodied carbon by up to 70%, depending on the specific precursor materials and alkaline activators employed<sup>[41]</sup>.

#### 3.2. Reduced Reliance on Finite Natural Resources

In alignment with sustainability objectives, geopolymers exhibit a reduced reliance on finite resources such as limestone, a primary component in OPC<sup>[6]</sup>. Indeed, research studies showed that geopolymers are considered to serve as a sustainable approach for the beneficial reuse of industrial by-products, providing an environmentally re-

sponsible disposal pathway for materials such as ground granulated blast furnace slag (GGBS) [42,43], fly ash [44], bottom ash [45], rice husk ash [46–48], mine waste [18,49,50], glass waste [51], red mud [52], palm oil ash [47], petroleum sludge [47], polyethylene terephthalate waste [53] and many more industrial by-products.

### 3.3. Lower Energy Consumption during Synthesis

Over OPC, geopolymers offer significant energy efficiency advantages. The production of one ton of Portland cement requires approximately 4.7 GJ of energy, whereas geopolymers only need about 1–1.5 GJ. This translates into a reduction in energy consumption by up to 70–80% [5,54]. Additionally, the carbon footprint of geopolymers is noticeably lower, with emissions of 0.15–0.20 t of CO<sub>2</sub> per ton produced, compared to 0.8–0.9 t for OPC. This translates to a 60–70% decrease in carbon dioxide emissions [5] and presents geopolymers as a more sustainable alternative.

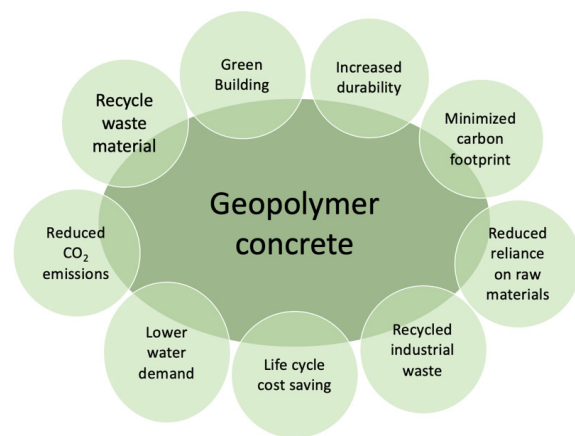
### 3.4. Lower Water Demand

During the early stages of the reaction process, geopolymer materials require a limited quantity of water [9]. As a result, most of this water can be removed without damaging the material's mechanical characteristics. Compared to traditional materials, Geopolymer concrete typically demands substantially lower water content contributing to saving water. This reduction in water demand is primarily due to the different chemical reactions included in the two processes [9]. While OPC requires a significant amount of water to hydrate and form calcium-silicate-hydrate (C-S-H) gel [55], geopolymers form through a polycondensation reaction of aluminosilicate materials, which naturally requires less water [9]. As a vital resource, the extensive use of water in the construction industry presents significant sustainability challenges. By reducing water usage, geopolymer concrete conserves this valuable resource and lowers the environmental impact associated with water extraction and consumption. When process water is recovered and reused, the total water demand becomes significantly lower than that of conventional cement-based materials [56]. The reduced water demand in geopolymer production also means less shrinkage and cracking in the

cured concrete leading to more durable and long-lasting structures [57]. In regions facing water scarcity, this feature of geopolymers can be a decisive factor, making geopolymer concrete a more viable and sustainable alternative to OPC. Construction projects can benefit from cost savings related to water procurement and management, as well as improved scheduling and reduced risks of delays due to water availability.

### 3.5. Diminished Overall Carbon Footprint

Lower energy consumption during the production phase and reduced reliance on virgin raw materials contribute to a general decrease in the carbon footprint of geopolymers [58]. A life cycle assessment (LCA) approach is often employed to quantify and compare environmental impacts considering factors such as energy and resource utilization. Studies showed that geopolymers have the potential to significantly lower greenhouse gas emissions and reduce non-renewable resource consumption when compared with other conventional construction materials [59]. This supports the proposition that geopolymers present a more sustainable alternative in the context of the sustainable blue economy, aligning with global efforts to mitigate environmental impact in the construction industry (Figure 1).



**Figure 1.** Environmental advantages of geopolymer concrete in construction.

Note: based on Shekarchi et al. [59], modified by the authors.

## 4. Application of Geopolymers in the Sustainable Blue Economy

The concept of Blue Economy has emerged recently

in the framework of the European Union<sup>[60]</sup> to cover all existing and emerging economic activities, across and within sectors, that rely on or are associated with marine and coastal environments. At the global level, the Organization for Economic Cooperation and Development (OECD) defines the Ocean Economy as the aggregation of economic activities derived from ocean-related industries, combined with the natural assets, goods, and ecosystem services supplied by marine environments<sup>[61]</sup>. OECD estimated in 2016 that the ocean-based industries contribute ~1.5 USD trillion to the global gross value added, and will contribute global occupation with ~40 million full-time equivalent jobs in the business as-usual scenario. The use of cements in construction of marine infrastructure, ports, coastal defence structures is not identified in either EC and OECD reports as a key specific sector of the blue/ocean economy.

However, marine construction and repair, port activity and management, coastal tourism, and research and innovation are key sectors in the blue/ocean economy where the use of cements is fundamental. The EC report states that ‘the blue economy is comprised of both marine- and terrestrial-based activities and is influenced by the land-sea (coastal) interface. This is the framework in which the use of geopolymers in replacement of Portland cements bears a potential to contribute significantly to a ‘sustainable’ blue economy.

Indeed, geopolymers, as sustainable alternative to traditional materials, have shown great potential in marine infrastructures and the blue economy. It has been demonstrated that their application in marine concrete protection coatings, makes them a viable option for safeguarding structures in harsh marine environments<sup>[42]</sup>. The same study demonstrated that, although strength development progressed more slowly under seawater-curing conditions, the geopolymer still exhibited outstanding resistance to corrosion.

The durability and self-compacting characteristics of geopolymer concrete make it a promising candidate for the repair and rehabilitation of existing marine concrete structures, offering enhanced mechanical performance and strength development<sup>[62,63]</sup>. Findings from pilot-scale studies and limited field applications suggest that geopolymers could enhance the durability of marine infrastructures while meeting sustainability and environmental perfor-

mance objectives. Therefore, integrating geopolymers in the Blue Economy fields and marine infrastructures offers an opportunity to promote environmental responsibility and to ensure the longevity and resilience of coastal and offshore constructions<sup>[5,6]</sup>.

## 5. Challenges and Opportunities

The integration of geopolymer concrete in marine construction presents both challenges and opportunities. Its successful implementation requires a comprehensive assessment of its durability over time. Although some studies<sup>[64]</sup> have shown that certain geopolymer formulations may undergo chemical degradation under harsh marine conditions and may undergo microstructural alterations and decline of mechanical performance. Such a response is not a generalised behaviour and depends largely on the initial formulations and exposure conditions. Indeed, the resistance of geopolymers to seawater exposure is strongly influenced by different parameters such as the precursor type, alkaline activator composition, Si/Al ratio, curing regime and exposure conditions. Studies reported that low polymerization or under-cured specimens may be more vulnerable to ionic penetration and leaching<sup>[65]</sup>. In contrast, properly designed geopolymer matrices have shown stable or enhanced mechanical properties during long-term seawater exposure<sup>[65]</sup>. Thus, the observed degradation phenomena should be attributed to the initial formulations and exposure conditions rather than the intrinsic limitations of the geopolymer materials. In addition, heterogeneity in raw material characteristics may affect the performance consistency of the geopolymers, requiring rigorous quality assurance protocols<sup>[6]</sup>.

Other challenges such as the cost of activators need to be addressed to enable widespread adoption and commercialization. Indeed, alkaline activators (NaOH, Na<sub>2</sub>SiO<sub>3</sub>) constitute a large share of geopolymer concrete costs, often representing roughly 40–60% of total material cost and contributing to geopolymer mixes being up to ~1.4× more expensive than OPC in some reports<sup>[66]</sup>.

Evidence from the literature suggests that alkaline activators may constitute over half of the cost of geopolymer concrete<sup>[66]</sup>. Some reviews have reported that total costs exceed those of OPC mainly due to the activators’

prices and supply variability<sup>[66]</sup>. Cost-reduction strategies using alternative activators and industrial by-products (fly ash, slag and more) can reduce this gap and, in some cases, bring geopolymer concrete costs closer to or below those of OPC<sup>[67]</sup>. Therefore, in regions with abundant precursors and optimized activator sourcing, geopolymer concrete could be economically competitive. However, a comprehensive technical and economic analysis is needed for broader implementation. The supply and transportation of these chemicals, especially to remote coastal areas, can significantly increase the production cost. Ensuring that activators and geopolymers materials comply with environmental standards is essential for their acceptance in the Blue Economy sector.

Another challenge is meeting regulatory requirements and obtaining certifications for geopolymer materials, which can add additional costs (more details are provided in Section 6).

Solutions to enhance the durability of geopolymers in harsh marine environments involve optimizing the formulation. This could be achieved by incorporating additives or modifying the synthesis process to decrease the risks of degradation<sup>[68]</sup>. To overcome these challenges, future research directions should include the development of novel binders and additives adapted to marine environments, as well as advanced testing methodologies to predict long-term performance. Also, collaborations between academia and research institutions, the productive sector (including industries and other stakeholders) and governance bodies (such as policy makers and authorities) are crucial. These collaborations are essential to drive innovations in activator formulations and use.

## 6. Regulatory and Policy Considerations

Although geopolymer concrete has been studied for the past 40 years, it has not yet achieved full commercialization<sup>[69]</sup>. Inconsistent properties and performance remain the main barrier to its commercialization. To make geopolymer concrete more economical, transportation costs for raw materials and the final product must be minimized. Additionally, enforcing a hybrid policy to reduce cement usage within the cement and concrete industry is recom-

mended. According to recent findings<sup>[69]</sup>, establishing design codes and regulatory standards is also essential as the first step towards the successful commercialization of geopolymer concrete.

On the other hand, the incorporation of geopolymers into marine constructions requires a careful examination of existing regulations and policies to ensure adherence to regulations. Given the relatively novel nature of these materials in comparison to traditional alternatives, at present, the regulatory landscape for geopolymers in marine applications may lack specificity. An integrated assessment of environmental, safety and performance standards is essential for the development policy recommendations. It is mandatory that geopolymers should be assessed in accordance with existing maritime regulations, considering their unique chemical properties and long-term behaviour in the marine environment<sup>[6]</sup>. Some recommendations for integrating geopolymers into Blue Economy fields from a policy perspective involve initiatives such as active engagement with regulatory bodies to establish clear guidelines that address the use of geopolymers in different marine scenarios. Also, it is mandatory to foster collaborations among industry stakeholders, policymakers and researchers to support and facilitate the incorporation of geopolymers into standardized practices. Inspired by successful regulatory frameworks for sustainable materials, regulatory framework should remain flexible to accommodate technological advancement and the smooth integration of geopolymers into the diverse Blue Economy sectors.

## 7. Future Trends and Innovations

Recent research efforts are expanding the application fields of geopolymers in the Sustainable Blue Economy and particularly in marine settings. The following discussion presents some of the key emerging trends and innovations.

### 7.1. Corrosion Resistance

Findings reported that geopolymer concrete exhibits enhanced resistance to corrosion making it well-suited for structures operating in severe marine environments<sup>[42]</sup>. It was reported that geopolymers subjected to seawater exposure experienced modifications in the Si/Al ratio within the

N-A-S-H gel network, which promoted the development of additional gel phases and resulted in a few micro-cracks<sup>[70]</sup>. These geopolymers demonstrated superior compressive strength relative to specimens exposed to alternating seawater immersion and cooling cycles. According to the same study<sup>[70]</sup>, alkaline ions present in seawater are responsible of this enhancement in strength by helping neutralize the negative charge on aluminium tetrahedra within the geopolymer matrix, thus facilitating the formation of N-A-S-H gel. In the same context, it was also reported that natural seawater exposure promoted the evolution degree of geopolymers. The enhanced gel formation contributed to an increase in the compressive strength of the geopolymer material<sup>[2]</sup>. Additional studies<sup>[64]</sup> have highlighted the capacity of geopolymers to improve the durability of marine infrastructures exposed to harsh conditions.

Emerging studies<sup>[71]</sup> have examined the durability of geopolymer concrete by assessing its resistance to sulfate deterioration. The conducted tests consisted on immersing specimens in a 5% sodium sulfate ( $\text{Na}_2\text{SO}_4$ ) solution. Mechanical and physical tests were performed after 12 weeks of immersion. The results showed no significant variations in compressive strength, mass or specimen length, confirming that the material has a strong resistance to sulfate attacks. These findings support the future incorporation of geopolymer concrete marine infrastructure projects such as ports, harbours and offshore installations.

From a mechanistic point of view, the corrosion resistance of geopolymer concrete in marine environments is governed by degradation pathways that are fundamentally distinct from those of OPC systems. In aluminosilicate-based geopolymers, chloride ingress occurs primarily through transport mechanisms governed by pore connectivity and the physicochemical stability of the N-A-S-H gel, rather than by chemical binding reactions with hydration products as observed in OPC matrices<sup>[6,47]</sup>. Chloride ions are largely immobilized through physical retention and ionic exchange within the aluminosilicate framework, particularly in dense, well-polymerized systems with optimized Si/Al ratios and refined pore structures<sup>[6]</sup>. Sulfate attack mechanisms significantly differ between the two systems: whereas sulfate ions in OPC react with portlandite and C-S-H phases to form expansive secondary products such as ettringite and gypsum leading to cracking and

loss of cohesion. In contrast, geopolymer matrices lack free calcium hydroxides ( $\text{Ca}(\text{OH})_2$ ) which limits expansive sulfate-driven reactions especially in low calcium systems<sup>[6,27]</sup>. In the presence of magnesium ions, POC systems undergo severe decalcification of C-S-H and formation of cementitious magnesium silicate hydrate (M-S-H) phases, resulting in substantial strength loss. In contrast, geopolymers primarily experience ionic exchange or partial gel reorganization, with degradation dependent strongly on calcium content, precursor chemistry and curing conditions<sup>[72,73]</sup>. These distinct reaction pathways provide a mechanistic explanation of the superior durability of geopolymer concrete reported under marine exposure while highlighting the critical role of mix design and curing protocols in controlling long-term performance.

## 7.2. Underwater Infrastructure

Underwater concrete is a specialized form of high-performance material developed for constructions submerged underwater such as bridges and dams. Compared to OPC, underwater concrete requires specific properties to ensure successful implementation in submerged conditions. Besides high strength, underwater concrete is required to exhibit strong resistance to washout, adequate workability and long-term durability. In recent years, multiple studies have demonstrated that geopolymer concrete presents mechanical strength and chemical resistance comparable to that of OPC. Despite these advancements, limited research has focused on the application of geopolymers in underwater construction.

The ability of geopolymer concrete to set and cure underwater offers a unique advantage in the construction and restoration of submerged structures<sup>[74]</sup>. Future innovations may focus on leveraging these characteristics for the development and maintenance of underwater infrastructures such as submerged tunnels, breakwaters, artificial reefs, marine and harbour foundations.

## 7.3. Lightweight Structures for Shipbuilding

The potential of geopolymer concrete in creating lightweight yet high-strength structures can revolutionize shipbuilding industry. In the future, there might be an increase in the use of geopolymer composites in ship con-

struction, contributing to fuel efficiency and overall sustainability in the maritime industry.

#### **7.4. Seawater-Based Geopolymers**

Future trends and innovations may focus on further studying geopolymers produced using seawater and/or sea sand as a component<sup>[75,76]</sup>. This would not only reduce the need for freshwater in the production process but also align with sustainable practices in the Blue Economy and SDG goals.

#### **7.5. Erosion-Resistant Coastal Protection Infrastructures**

The durability of geopolymer concrete makes it an excellent candidate for coastal protection structures. Indeed, it has been shown that geopolymers provide enhanced resistance and superior durability to deterioration caused by aggressive ions commonly present in marine and wastewater environments, including sulfates, chlorides and acidic species<sup>[77,78]</sup>. Studies have shown that metakaolin-based geopolymers retain a dense microstructure even after 30 days of exposure to a 5% acid solution, with weight loss remaining below 7%<sup>[79]</sup>. Also, it has been reported that seawater containing 4.4% sodium sulfate did not compromise the microstructure of fly-ash-based solutions for erosion-resistant revetments, breakwaters and seawalls, contributing to the resilience of coastal areas. In coastal protection applications, geopolymers have been employed in erosion-resistant materials, demonstrating their resilience in dynamic coastal environments<sup>[6]</sup>.

#### **7.6. Green Ports and Sustainable Maritime Infrastructures**

As sustainability becomes important to the Blue Economy, geopolymer concrete can play a crucial role in supporting green port projects and encouraging sustainable development in maritime infrastructures. With their lower carbon footprint, geopolymers are more environmentally friendly options than traditional concrete and other building materials, which fits into a larger scheme of sustainable and responsible development<sup>[80]</sup>. The use of geopolymers offers opportunities in developing lightweight and high-

strength materials for subsea applications, thus, creating innovative solutions for the offshore industry<sup>[62,81]</sup>.

#### **7.7. Recycled and Waste Materials Integration**

Using recycled and potentially hazardous waste materials in geopolymer concrete formulations is a significant technological advancement that reduces waste, advances circular economy goals and minimizes environmental and public health risk. The Blue Economy Report of 2021<sup>[60]</sup> indicates active participation from emerging sectors including ocean energy, which will have a major role in fulfilling the European Union's circular economy strategies and supporting the sustainable development of the maritime industry. Incorporating industrial by-products and recycled materials into geopolymer concrete meets the Blue Economy's goals by providing environmental protection and promoting sustainable economic development at the same time.

#### **7.8. Slag-Based Geopolymers**

In order to determine how well slag-based geopolymers can be used in marine and coastal applications, we need to perform a thorough investigation into their mechanical characteristics, especially those related to tensile resistance as these characteristics will control all aspects of crack formation, longevity and long-term integrity of the finished structure. While the compressive strength of the material is usually presented as the most important characteristic, it is more accurate to determine how well developed the tensile strength of the material is since it provides a more sensitive indicator of crack initiation and propagation under conditions of service, especially in the types of environments found in the oceans and seas<sup>[82]</sup>. Multiple experimental studies on boro-aluminosilicate slag-based geopolymers have shown that the performance of slag as a tensile material is significantly affected by the type of precursor used in formulating the material, the activator used to activate the precursor and specific curing conditions<sup>[83]</sup>. Unreinforced slag geopolymers were found to typically have a split-tensile strength between 2 and 6 MPa at the end of a 28-day curing period. The tensile strength of unreinforced slag geopolymers can be significantly enhanced with increasing amounts of both slag and improved gel po-

lymerization<sup>[83]</sup>. These findings indicate a clear correlation between slag reactivity, microstructure densification and tensile resistance.

With statistical optimization and reinforcement, tensile performance has improved through various methods of reinforcement. Studies applying the Taguchi method to slag-based aluminosilicate geopolymers reinforced with waste polymeric materials showed that optimized mix proportions and curing parameters can scientifically increase split tensile strength reaching values above 7 MPa<sup>[84]</sup>. In laboratory testing using a design of experiment DOE methodology, on slag-based boro-aluminosilicate geopolymers reinforced with steel fibres, tensile strengths close to 10 MPa were achieved at optimum test conditions<sup>[85]</sup>, thus confirming the increased strength in both the mix design and the benefits of fibre reinforcement.

## 8. Conclusion

Geopolymer concrete presents an opportunity to support the development of resilient and sustainable coastal marine infrastructure in the Blue Economy sector, while having a low carbon footprint; therefore, the use of geopolymer concrete in marine construction has gained increasing interest due to its ability to replace traditional concrete.

These sustainability benefits result from the reduced carbon emissions associated with the production of geopolymer concrete, as well as the reuse of industrial waste materials that would otherwise be disposed of. With respect to long-term durability of geopolymer foundations, additional research is needed. However, the results of multiple studies clearly demonstrate the potential of geopolymer concrete to provide an environmentally sustainable option for marine construction. Several of these studies indicate that the durability of geopolymer concrete solutions exposed to marine conditions will be determined by the specific formulations used to create the geopolymer concrete.

Variations in precursor mineralogy, alkaline activator chemistry, Si/Al ratios, curing conditions and exposure regimes lead to apparent differences ranging from strength enhancement to chemical degradation after seawater exposure.

These findings show the importance of assessing the durability of specific compositions rather than generalized performance assumptions for marine applications. In order for widespread implementation of geopolymer concrete, challenges such as the cost of activators and energy footprint need to be addressed. Improving the production process, conserving energy and reducing expenses will allow geopolymer concrete to become a major contributor to sustainable construction strategies within the Blue Economy sector. The use of geopolymer concrete in new marine infrastructure projects aligns with the Blue Economy principles that focus on responsible management of marine resources and support global sustainable development goals. Continued research, combined effort between material scientists, chemists, marine and coastal engineers, will enhance our ability to help develop environmentally friendly and resource efficient methods of construction within the Blue Economy Sector.

## Author Contributions

J.N.: conceptualization; methodology; investigation; data curation; writing—original draft; visualization. S.A.: review and editing; validation. A.C.: supervision; writing—review and editing. MG: supervision; funding acquisition; writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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This study is based on previously published data and literature, all of which are cited within the manuscript. No new data were generated.

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## Conflicts of Interest

The authors declare no conflict of interest.

## AI Use Statement

The authors used ChatGPT solely for grammar checking, sentence structure refinement, and improving the readability of the English text in this manuscript. The authors take full responsibility for all academic content, including all ideas, data, analyses, and conclusions presented herein. The use of AI was thoroughly reviewed and supervised by the authors.

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