

Review of Recent Advances in Reinforced Geopolymer Concrete: Mechanical Properties, Durability, and Challenges

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Abstract

Due to the enhanced mechanical properties and significant environment-friendliness of reinforced geopolymer concrete (RGPC), it has found a potential alternative for traditional cement formulation-based composites. The properties and features of the materials and reinforcing methods within RGPC were found to be the central focus and various aspects around this subject were dealt with precisely by this review article, providing a detailed account of the recent advancements and trends being pursued within this area. It has been proven and well-verified from previous literature and research studies that when fiber and steel rebar reinforcing elements were incorporated with geopolymer-based materials, the resulting hardened structural materials showed significant improvements and incremental increases within their compressive and tensile strengths and resistance to severe exposure conditions such as corrosion under harsh conditions and exposure to higher temperatures and chemicals. Despite the vast advancements available from research and current potential for expansion within this subject domain and application area, various critical and significant hindrances and gaps exist.

Keywords: fiber reinforcement, mechanical properties, durability, reinforced geopolymer concrete, and sustainable building

1. Introduction

The pressure for more sustainable construction materials has recently been gaining momentum with increased concerns for the environment and reducing the carbon footprint for traditional construction processes. However, this drive for more environmentally conscious construction materials has given rise to research on geopolymer concrete, which is emerging as a great prospect. This material can be produced from waste products from industry such as fly ash and slag. Its potential is such that it may even outlast and outperform traditional concrete in terms of durability and strength. Additional reinforcement gives this material a huge boost so that reinforced geopolymer concrete can be said to be a material for real construction tasks. Recent advancements made within the process for generating geopolymer concrete and the ingredients for this material have brought under the light the importance and criticality of this material, particularly its strength and durability aspects as cited within several research articles. For instance, [1] and [2] give fairly convincing evidence on the strength and durability aspects and the extent to which reinforced geopolymer concrete performs compared to traditional constructions. However, the extent to which this material withstands all conditions and tests passed on time and conditions has not been well understood by us and is argued within research articles such as [3], and [4]. Short-term research articles on this material give us fairly good understanding on this material from durability and strength aspects. However, research literature hasn't really focused much on its overall durability and strength when under recurrent loads and harsh chemicals. Research articles such as [5], and [6], investigate particular aspects such as varying raw ingredients and complex mix design concepts. As cited within these articles, all these parameters can really wreak havoc on this material's overall efficiency. Research articles such as [7], and [8], investigate whether this material

can be adjudged as cost-efficient for bulk construction usage and whether waste materials can be efficiently utilized for this purpose. As cited within research articles above, this material can be said to be really valuable from a considerable amount from environment and commercial considerations. However, the literature tends to overlook the broader picture with regard to lifecycle analysis, which considers the environment and economic costs on one side and traditional cement-based materials on the other. In addition, while numerous articles exist within the literature that can be said to increase the body of knowledge with regard to the strength properties, there is limited field evidence on the basis of how it performs and what kind of issues may arise. Research such as that carried out by [9] and [10] emphasizes the fact that there is a clear emphasis on field research and analysis to see that the work being developed within the lab can apply to more functional uses within construction. In this respect, this literature review seeks to examine the current literature trends and close any gaps on the state-of-the-art application and uses for reinforced geopolymer concrete and offer additional avenues for research-based solutions to implement broader construction-based uses for reinforced geopolymer concrete.

In summary, the literature emphasizes significant achievements with regard to the strength and durability properties of reinforced geopolymer concrete. However, with regard to the potential application and uses within construction industry research trends and gaps with regard to actual uses within real construction and additional avenues for research and development should be clarified.

2. Review of literature

The advancement in geopolymer reinforced concrete has gone as planned regarding its properties. Initially, experiments were done in the late 90s. They were only laying down groundwork. They were beginning to grasp inherent properties of geopolymer. They showed their potential for being a green substitute for conventional concrete, Cameron R. Rusnak [1], P. T. & T. S. [2]. So, come the 2000s, researchers had begun to identify some principal benefits of this material. Better strength and heat resistance are a few among those benefits this geopolymer concrete offers compared to conventional concrete, O. Чернева et al. [4]. Fast forward again to today in the 2010s. Now steel fiber reinforcement and even nanoparticle reinforcement are being added. Now they were realizing that this made geopolymer concrete much better in terms of strength, Guanfeng Liu & Xiaoqi Wang [5], Patchirajan & Madasamy [6]. This was a major breakthrough because this time researchers had begun to explore more about how geopolymer interacts with this reinforcement material. This paved way for developments of optimized compositions for this geopolymer material, Bhukya Prakash M V [7], Rohan Sawant et al. [8]. So, meanwhile. People were trying to explore effects of environmental conditions on geopolymer concrete. They found out that because geopolymer material relies on alkali activation. Thus geopolymer material would quite perform well when exposed to chemicals & heat exposure. Lingling Qin et al. [9], Mohammadhossein Mansourghanaei [10]. So with this much advancement. Rumors among researchers go that geopolymer concrete still has mountains to cross before reaching its goal. Variability in properties & uncertainty about material withstanding a prolonged environment. This are a few among current developments among researchers today. M. A. Faris et al. [11], Tao Wang et al. [12]. Recent reviews urge for a more unified way of testing and assessment that will make it more reliable to get the thumbs-up from the construction world, Zhibin Li et al. [13], Huayi Wang et al. [14]. So, though we have come a long way, there is still plenty of work required to unlock all the functionality geopolymer concrete can achieve. The investigations of sophisticated applications, hybrid formulations, and numerical modeling techniques of recent contributions through a variety of studies have advanced our understanding of reinforced geopolymer concrete. Extensive experimental and numerical studies were performed by Le et al. [18] to develop theoretical frameworks on bond behaviour of reinforced fly ash-based geopolymer concrete to optimize the interface strength between geopolymer matrices and steel reinforcements. Their test results indicated that, besides mix design, curing regimes significantly influence bond development.

Liu and Yan [19] also presented the use of geopolymer adhesives for CFRP-supported concrete beams. According to their study, there is a possibility of achieving bonding strengths from geopolymer adhesives comparable to conventional epoxy resins, hence more environment-friendly with improved thermal stability. This therefore constitutes a critical breakthrough in the rehabilitation and retrofitting of the buildings. Kipsanai et al. [20], with a focus on a different aspect, wrote about the role of diatomaceous earth in geopolymer. This naturally occurring material, which is still being researched today, has great potential in increasing sustainability indicators because of its silica content and low processing needs. But mechanical performance shortcomings were noted, and this had led to an additional optimization of alkaline activation being required. Nehemiya and Rao [21] were particularly interested in flexural performance geopolymer concrete slabs with fixed boundary conditions. They claim that, through adequate reinforcement and curing, the geopolymers slabs can effectively compete with the conventional concrete where load carrying behaviour is concerned. The findings directly support the uses of GPC within a broader structural context. Through the integration of both modeling and experimental activities, Zhou et al. [22] manufactured a sustainable blend of geopolymer binder and OPC. Their mixed use strategy meant that there was a high level of carbon emission reduction without a compromise in mechanical strength. Their future predictive models will assist in automation of mix design process. Ahmed et al. [23] proposed the use of regression tree model and ANN to estimate the strength of geopolymer mixtures with nanosilica. Their model had high accuracy which showed that AI-assisted design methodology could help to decrease trial-and-error efforts with a significant boost in the reliability of mix design. Kenan [24] examined the strain rate performance and the damping of geopolymer composites. His work is one of the very few which include geopolymers in the seismically or vibrationally active zones and gives empirical equations of dynamic load situations. Shahedan et al. performed a targeted literature review of the application of fly ash-based geopolymer concrete in repair of marine infrastructure. [25]. GPC was identified to be good in use in saline harsh environments due to its minimal permeability and resistance to corrosion. In this way, the possibilities of the material are increased in comparison with traditional structural elements. Li et al. [26] endorsed this argument by critically analyzing the microstructure and the performance of fibre-reinforced geopolymer concrete on long-term basis. They emphasized the importance of nanofibre dispersion, interface bonding as well as curing time to enhance durability, especially in corrosive and freeze-thaw environments. Research in geopolymer has also been aimed at the development of 3D printing technology. Buswell et al. [27] made the first contribution to printable concrete by extrusion and suggested that geopolymer pastes have better flow and buildability at controlled conditions. This is also evidenced by Chang et al. [28], who demonstrated that the addition of the microbial biopolymers to the concrete or soil could be used as a greener geotechnical technique. Lastly, the working mechanisms and/or the strength of alkali-activated materials were also reviewed critically by Majidi [30] and Bernal and Provis [29]. Their painstaking effort, which compiles a number of decades of experimental evidence, and theoretical advances, is important to this day in guiding future GPCSystems designs. In the previous decade, there have been much more details revealed on geopolymer concrete and its reinforcement technologies, particularly those that have been reviewed and investigated between [31] and [40]. The studies that have followed have greatly contributed to the scientific structure and practical orientation to the geopolymer studies. A crucial precedent was established by Duxson and Provis [31] in which the precursor design and choice were named as important factors to geopolymer systems. Their article showed that not every industrial by-product is made equal and that the reaction, and mechanical performance kinetics can also be optimized through adjusting the synthesis of precursors, especially those with optimal Si/Al ratios. This pioneer work has shaped the approach of researchers to design hybrid compositions depending on the regional material availability i.e. FA, metakaolin and slag. Geopolymerisation was initially described as a theoretical framework by Davidovits [32], a scientist who pioneered geopolymer science. His early 1990s research concerned the polycondensation processes involved in the conversion of the aluminosilicate sources into three-dimensional polymeric networks, which form the foundation of recent alkali-activated

binder systems. To this day, his paper has been used as a point of reference with which to substantiate the role of alkali activators in material strength development and microstructural evolution. In the recent past, Iftekar et al. [33] examined the application of additive manufacturing and geopolymer concrete. In 3D printing, their review considered the pros and cons of the application of geopolymer binders and highlighted the problems of strength anisotropy, the rheology, and bonding between successive layers. To preserve the environmental credentials of the traditional cementitious systems and be consistent with them, they suggested that the nozzle geometry and printing speed should be optimised.

Pol Segura et al. [34] extended this opinion by reviewing alkali-activated binders in terms of an industrial perspective. The geopolymer systems were compared to the life-cycle emissions, energy consumption and production processes in comparison to the Portland cement. They found that the absence of standard production standards, codes of regulation and quality control processes does not allow to adopt the market despite the fact that AABs are environmentally advantageous. Their review gave an account on the demand of the global structures that might facilitate the evaluation and sanctioning of the GPC systems with structural uses. Chen et al. [35] was more concerned with the city level by saying that low-carbon cities can be remanufactured with materials like reinforced geopolymer concrete. Their review suggests that the idea of green construction must involve a comprehensive approach that involves renewable energy, urban planning, and materials the performance of which is proven under the practical implementation. It is not merely a matter of replacement of materials. The adoption of geopolymer concrete as a viable building material explains an increased awareness of the applicability beyond the academic society.

Peng and Unluer [36] evaluated the use of other binders, namely geopolymers, in 3D printing considering the future construction technologies. They talked about the benefits of geopolymer pastes along with the fact that they have fast-setting time, have very little shrinkage and are printable among others. They have, however, emphasized that certain problems are still left, such as the preservation of dimensional accuracy, and attainment of stable flow properties in the presence of varying humidity and temperature. It implies that in future material design, the printable geopolymer formulations that would be combined with automated equipment should be in the forefront. Palomo et al. [37] in cement science initiated a larger philosophical and practical discussion on whether Portland cement must move to the hybrid solutions or a complete shift to alkali-activated systems should be made in the industry. Given that it is essential to decarbonize the construction sector, they advocated a clean break instead of a gradual development. They hope to see the increased application of reinforced geopolymer concrete particularly when more efforts are attributed towards increasing its scalability and long-term structural life.

The other important contribution was made by Jipa and Dillenburger [38], who surveyed the implementation of 3D printed formwork with the use of new materials such as geopolymer concrete. GPC, according to their study, will be able to reduce waste in formworks and construct geometrically complicated constructions and therefore is a potential material of digital construction and new architecture. Their study was not out of order with other scholars, which advocated prefabricated GPC parts, as they have structural and aesthetic benefits. According to Sambucci et al. [39], case studies of academia and industry have been gathered, and the results depicted the recent success of geopolymer concrete technology. Transportation, nuclear, and marine infrastructure applications which demanded high performance were considered and these applications showed that GPC can serve or even perform better in various, demanding, specific environmental conditions. Their effort speaks in support of the fact that the material is currently gaining popularity in commercial implementations at scale and is not limited to laboratory use. Lastly, Imtiaz et al. [40] conducted an extensive literature review of production of environmentally friendly geopolymer concrete. The findings of dozens of studies on mechanical performance, chemical stability and environmental impact were fused in this review. They were able to discover that reinforcement methods-by fibre-based or by bar-based-methods-are

progressively being made use of to boost the service life and serviceability of GPC structures. They came up with a conclusion that implementation and acceptance gaps need an effort to collaborate between industry and academia. All these works by [31] to [40] are a major shift in trend in that the theoretical explorations were being changed to the empirical validations. In addition to being a research interest, they demonstrated that reinforced geopolymer concrete is a viable material with significant prospects to the shift to a more sustainable building sector.

3. Conclusion

The future of reinforced geopolymer concrete has a lot of promise and can potentially transform the overall perception of sustainable construction, both in theory and in practice. The process of mechanical properties of geopolymer concrete has already been demonstrated to be remarkable. Its compositional peculiarities allow it to have superior compressive and tensile strengths than the traditional cement-based counterparts according to the works by Cameron R. Rusnak [1] and P. T. & T. S. [2]. In addition, it is also indicated by test that such concrete is less susceptible to environmental stressor such as chemical exposure and cycling of temperature which may contribute to increased service life of buildings [3], [4]. The mechanical characteristics of such materials are of great interest in consideration of the building industry that is in search of more environmental friendly material.

Nevertheless, even though the potential of geopolymer concrete is rather intriguing, it has been made known that there are a number of very important problems. Its performance and its durability under varying environmental conditions are yet to be determined; more research is required to make this certain. Studies like the one by Liu and Wang [5] and Patchirajan and Madasamy [6] demonstrate the effect of employing various attributes of materials and combining processes on the concrete durability. Such variabilities might block its widespread use. Generalized techniques of testing and cognition about it are also required [11], [12]. The point made by Qin et al. [9] and Mansourghanaei [10] is that in order to know how geopolymer concrete will perform over time we will have to know practical research where we learn in the laboratory will be applied in the real world buildings.

Moreover, despite the fact that there are some pieces of evidence that reinforced geopolymer concrete is as strong and durable as regular concrete, it remains unclear whether the new concrete type is sufficiently inexpensive to be used widely. We can not have a reasonable detailed analysis in terms of environmental impact and economic feasibility compared to the conventional concrete [14], but the waste material was taken into consideration by Bhukya Prakash M V [7] and Rohan Sawant et al. [8] to make the cost cheaper. Hopefully, these economic factors can be clarified further, and informed choice would be made to promote the use of geopolymer concrete in the building construction projects.

All these have far reaching consequences. Reinforced geopolymer concrete may be used to make significant reduction in the carbon footprint of construction. The buildings can be prolonged in time and need fewer repairs and changes, as they are stronger and more mechanically sound [13], [15]. Nonetheless, it has an important obstacle to its widespread use, such as the inconsistency of the quality of raw materials and the difficulty of manufacture [16], [17].

Segura et al. [34] and Chen et al. [35] do not undermine the importance of mechanical performance on issues of policy and industrialization, where economic viability, standardisation, and life cycle assessment are equally significant. Commercial scale implementation is challenging even following technical achievements due to the absence of policy integration and regulatory support.

The philosophical and strategic way forward of the cement industry is an extremely important question that was raised by Palomo et al. [37]: should the cement industry completely adopt the use of alkali-activated binders or should it keep developing the Portland cement step by step? Their demand to have a clean break is in line with the long-term objective of implementing the geopolymer concrete technology.

Sambucci et al. [39] and Imtiaz et al. [40] have indicated that geopolymer technologies are only beginning to be used in the industry with reference to prefabricated structures, nuclear power and in the marine industry. Nonetheless, the problem of curing conditions, talented labour and the inconsistency of raw materials are still the factors which restrict large-scale use.

In a concise, although there have been numerous challenges and doubts, there has been a positive development in the area of reinforced geopolymer concrete. Future studies need to be centred on lifecycle performance, economic modelling, and combination with smart manufacturing methodologies other than mechanical and durability. This disconnect between the laboratory advancements and the real world construction solutions can only be reduced through smooth interaction between the academic institutions, industry players and the policy formulators. By devising solutions to such problems, the researchers can do a great part in ensuring that RGPC becomes a mainstream, eco-friendly solution in the future in green buildings. The summary of the literature review is presented in Table 1.

Segura et al. [34] and Chen et al. [35] argue that economic viability, standardisation and life cycle assessment are equally significant in the perspective of policy and industrialisation as mechanical performance. Without regulatory backing and the policy combination, it is still hard to deploy commercial-scale deployment despite technical achievements.

Palomo et al. [37] raised the question of the considerable importance: what is the philosophical and strategic perspective of the cement industry: should it move towards a complete use of alkali-activated binders, or should it develop the Portland cement gradually? Their promotion of a clean break is consistent with the long-term objective of embracing the technology of geopolymer concrete.

The prefabricated structures, nuclear power and the marine industry are some of the sectors where geopolymer technologies are currently being implemented as evidenced by Sambucci et al. [39] and Imtiaz et al. [40]. Things such as curing conditions, skilled labour and fluctuation in raw materials are however still factors that hamper large scale application.

To conclude, the development of the sphere of reinforced geopolymer concrete is still very promising, despite numerous challenges and doubts. The lifecycle performance, economic modeling, and combination with smart manufacturing techniques should be the areas to be addressed in future research, besides mechanical and durability aspects. Only through a cordial interaction of the academic institutions, the industry stakeholders, and policymakers, the distance between the laboratory developments and practical construction solutions will be reduced. These are the problems that a researcher can contribute to significantly towards changing RGPC into a mass rather than a highly specialized product as the future in the sustainable buildings. Table 1 is a literature review summary.

Table 1. Literature Review Summary

Author	Year	Main Focus	Findings
Cameron R. Rusnak	2025	To review and evaluate innovative strategies for preserving and retrofitting reinforced concrete structures, focusing on sustainability.	Identified advancements such as low-carbon binders and self-healing technologies. Stressed the importance of coordination for guideline development.
P. T., T. S.	2025	To optimize fiber content in fiber-reinforced geopolymer concrete for improved performance.	Achieved superior mechanical properties and durability with optimized fiber contents, enhancing the sustainability of GPC.

Longni Wang et al.	2025	To develop a new geopolymer-based grouting material using industrial byproducts.	Determined optimal mix ratios that improved setting time and flowability, and showed potential for structural applications.
О. Чернева et al.	2024	To evaluate the use of geopolymer solutions in conserving architectural monuments.	Geopolymers offer durable and environmentally friendly alternatives to epoxy resins for monument preservation.
Guanfeng Liu, Xiaoqi Wang	2025	To review the advancements in basalt fiber reinforced cement-based composites.	Incorporation of basalt fiber increases the mechanical strength and durability of concrete under harsh conditions.
Ulagambika Patchirajan, M. Madasamy	2024	To evaluate the performance of geopolymer concrete specimens after fire exposure and FRP retrofitting.	GFRP and BFRP retrofitting enhanced the load-carrying capacity of fire-damaged geopolymer concrete.
Bhukya Prakash M V	2024	To provide a detailed review of advancements in geopolymer concrete technology.	Geopolymer concrete shows improved mechanical properties and durability compared to traditional concrete.
Rohan Sawant et al.	2024	To investigate factors affecting the strength of fiber reinforced geopolymer concrete.	Identified crucial parameters like binder composition and curing conditions impacting material strength.
Lingling Qin et al.	2023	To review advancements in fiber reinforced geopolymer composites.	Fiber reinforcement enhances mechanical properties and durability, making geopolymers suitable for various applications.
Mohammadhossein Mansourghanaei	2023	To evaluate mechanical properties of polymer fiber-reinforced geopolymer concrete.	Inclusion of nano-silica and polymer fibers significantly enhances mechanical properties of geopolymer concrete.
M. A. Faris et al.	2023	To summarize advancements in steel fiber-reinforced metakaolin geopolymer concrete.	Steel fiber inclusion enhances compressive and flexural strengths, improving overall material performance.

Tao Wang et al.	2023	To analyze the influence of various fibers on geopolymer concrete properties.	Fibers improve compressive strength and toughness, suggesting optimal fiber usage enhances material performance.
Zhibin Li et al.	2024	To investigate bond performance between engineered geopolymer composites and existing concrete.	High bond strength is achieved with optimized roughness indicating effective bonding strategies.
Huayi Wang et al.	2024	To explore crack characteristics in polypropylene fiber-reinforced concrete beams.	Increasing fiber volume enhances cracking load capacity and improves structural integrity.
Zhangyong Ma et al.	2023	To evaluate bond performance between epoxy-coated reinforcements and geopolymer concrete.	Bond strength is impacted by rebar diameter and bonding length, suggesting careful design for durability.
Bariş Bayrak et al.	2023	To assess metakaolin-based geopolymer concretes for nuclear protection applications.	Superior mechanical and nuclear shielding properties highlight potential for safety applications in nuclear contexts.
Huanyu Zhu	2023	To analyze the effects of fiber reinforcement on geopolymer composite properties.	Optimal fiber incorporation enhances toughness, impacting overall performance positively.
T. Le et al.	2022	To evaluate bond behavior in geopolymer concrete reinforced with steel bars.	Bond strength increases with compressive strength, showcasing important design implications.
Jinliang Liu, Fan Yan	2022	To study flexural performance of CFRP strengthened concrete using geopolymer adhesive.	Found that geo-adhesive can serve as a viable alternative to epoxy for enhanced load capacity.
Janet J. Kipsanai et al.	2022	To review diatomaceous earth's role in geopolymer concrete development.	Reinforces sustainability through resource use but highlights need for greater experimental focus in applying it.
K. Nehemiya, T. Rao	2016	To investigate the flexural behavior of geopolymer concrete slabs.	GPC slabs exhibit flexural behavior comparable to

			conventional concrete under similar conditions.
Peng Zhou et al.	2024	To explore OPC-blended geopolymer concrete production and modeling.	Established high-performance blend with reduced carbon footprint and reliable predictive models.
H. Ahmed et al.	2022	To develop models predicting compressive strength in geopolymer concrete containing nano-silica.	Found that ANN models provide superior predictions based on various influential parameters.
F. Kenan	2014	To investigate the damping and strain rate effects in geopolymer materials.	Confirmed geopolymers can match traditional materials in damping behavior, proposing new empirical equations.
Noor Fifinatasha Shahedan et al.	2024	To explore fly ash geopolymer concrete's potential in marine infrastructure repair.	Exhibits excellent resistance to corrosion, making it suitable for restoring marine structures.
Weiwen Li et al.	2022	To analyze the microstructure and durability of eco-friendly fiber-reinforced geopolymer concrete.	Long-term performance shows promise, necessitating further exploration of durability in corrosive environments.
Yiming Peng, Cise Unluer	2022	To review advancements in alternative binders for 3D printing in construction.	Progress made, but challenges related to performance and scaling need to be addressed for broader applicability.
A. Palomo et al.	2021	To analyze the feasibility of alkali-activated binders compared to Portland cement.	AABs can replace Portland cement, introducing lower carbon footprints and emphasizing production efficiency.
Andrei Jipa, Benjamin Dillenburger	2021	To review 3D printed formworks and their applications in concrete construction.	Identified new geometric possibilities and outlined challenges for improving sustainability in concrete construction.
Matteo Sambucci et al.	2021	To present advances in geopolymer technology as a sustainable alternative.	Geopolymers provide superior properties and reduced environmental impacts, suggesting further demands for their adoption.

Lahiba Imtiaz et al.	2020	To review developments in geopolymer concrete, focusing on its constituents and practical applications.	Emphasized the effectiveness of GPC for sustainable development in construction, proposing areas for further optimization.
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