Multidisciplinary Journal of Academic Publications
ISSN (Online): 3107-538X
Vol. 01, Issue 02, November – December 2025

PERFORMANCE ASSESSMENT OF GEOPOLYMER CONCRETE AS AN ECO-FRIENDLY SUBSTITUTE FOR ORDINARY PORTLAND CEMENT CONCRETE

Tarendra singh marko[1], Sachin Sironiya[2], Chetan Gurjar[3], Rajesh chouhan[4]

Research Scholar, Department of Civil Engineering, Vikram University, Ujjain, (M.P.)[1]

Assistant professor, Department of Civil Engineering, Vikram University, Ujjain, (M.P.)[2]

Assistant professor, Department of Civil Engineering, Vikram University, Ujjain, (M.P.)[3]

Assistant professor, Department of Civil Engineering, Vikram University, Ujjain, (M.P.)[4]

Mail Id: sachinsironiya22@gmail.com

ABSTRACT

Ordinary Portland Cement (OPC) production contributes to nearly 8% of global CO_2 emissions, forcing the global construction industry under the climate change pressure. One of the most promising sustainable alternatives is geopolymer concrete (GPC), which is made by activating industrial by-products including fly ash, ground granulated blast furnace slag (GGBS) and metakaolin as aluminosilicate precursors using alkaline solutions. This review paper provides a meta-analysis of the published literature comparison between the mechanical, durability, micro-structural, and environmental performance of geopolymer concrete vis-a-vis conventional OPC concrete. This paper synthesises findings from over three decades of global research to assess the development of compressive and tensile strength, flexural behaviour, resistance to acid and sulphate attack, fire resistance, shrinkage and workability characteristics. The review also looks at how activator type and concentration, curing conditions, precursor composition and water-to-binder ratio influence the final GPC properties. In conclusion, when reviewed collectively the evidence shows that geopolymer concrete is comparable, if not superior, to OPC concrete in most performance metrics relevant to engineering application across a broad range of contexts, whilst achieving reductions in carbon emissions of 40–80 %. The paper highlights research gaps that should be filled and outlines a vision for large-scale deployment, standardisation and life-cycle cost impact in order to position geopolymer concrete as an alternative, practical and sustainable construction material for the twenty-first century.

Keywords: *Geopolymer Concrete[1], Ordinary Portland Cement[2], Fly Ash, Alkali Activation[3], Sustainable Construction[4], Compressive Strength[5], Carbon Emission Reduction[6].*

1. INTRODUCTION

1.1 BACKGROUND AND GLOBAL CONTEXT

Concrete is the most used construction material in the world for over 70 years, and more than 10 billion tonnes of concrete is produced every year. It is the most widely used construction material for infrastructure, housing and industry but it is the environmental cost of its primary binder, Ordinary Portland Cement (OPC), which is to be questioned heavily. Manufacture of cement produces about 0.83 tonnes of CO_2 per tonne of cement due to the calcination of limestone and combustion of fossil fuels necessary for clinker production, collectively accounting for around 8% of global anthropogenic greenhouse gas emissions [1]. With the pace of urbanisation in developing countries now peaked and global infrastructure demands only likely to increase, the environmental cost of cement-based construction will loom large in the decades to come. Here, the challenge is to identify, validate and deploy alternative binders with similar load bearing performance with lower carbon intensity. Geopolymer concrete, coded by Davidovits in 1978 through a study of the covalently bonded polymeric framework from aluminosilicates, is recognised as a scientifically sound and industrially scalable alternative to this opportunity[2]. Geopolymer concrete has cementitious properties through a fundamentally different chemical pathway, (i.e. polycondensation instead of hydration), which does not require the carbon-intensive production of clinker present in conventional cement, by replacing it with industrial by-products like fly ash, GGBS or metakaolin that are activated by alkaline solutions as sodium hydroxide and sodium silicate.

1.2 SIGNIFICANCE OF GEOPOLYMER CONCRETE RESEARCH

The increased research in geopolymer concrete indicates that it will change the way concrete is made. Research conducted across multiple climate zones, building types, and mixture combinations have shown that geopolymer concrete can achieve compressive strengths from 20 MPa to over 80 MPa based on activator concentration, precursor type and curing regimen [3]. In addition to its mechanical strength properties, GPC has a high resistance to not only elevated temperatures, but also to acidic environments and chloride-induced corrosion, which makes GPC especially appealing for use in potentially aggressive exposure conditions in marine, industrial and tunnelling applications [4]. Economically, the dependency on industrial waste by-products yields a win-win situation with waste valorisation and reduced cost of raw materials for geopolymer concrete. Fly ashes, produced in large volumes in fossil fuel energy supply plants, and ground granulated blast furnace slag (GGBS), a by-product in iron production, are expensive industrial wastes now landfilled and disposed of with credit. The use of these materials in geopolymer concrete not only diverts the materials from landfills, and turns them into value-added construction ingredients [5]. In addition, life-cycle environmental performance of GPC (carbon footprint, embodied energy and global warming potential) provides a firm basis for continued benefits over OPC concrete and justifies large-scale utilisation of GPC [6].

1.3 OBJECTIVE AND SCOPE OF THE REVIEW

This review paper primarily aims to systematically meta-analyze the literature on the performance of geopolymer concrete as a greener alternative to OPC concrete. The review covers mechanical properties (compressive strength, tensile strength, and flexural strength) durability properties (fire, acid, sulphate, and chloride resistance) characterisation of microstructural properties, fresh state properties, environmental and life-cycle performance and effects of various mix design variables. The review is based on peer-reviewed journal articles, proceedings papers, and technical reports published between 1990 and 2024 with a focus on comparative studies and meta-analytical studies. The review brings these pieces of evidence together, with a goal of providing the necessary foundation for researchers, engineers and policy makers to aid in the mainstreaming of geopolymer concrete into the construction and standardisation processes.

2. LITERATURE SURVEY

Geopolymer concrete literature dates back over 40 years of scientific research, starting with Davidovits foundational book on geopolymeric binders and now covering a very broad and various multidisciplinary research field. The initial steps of the research were directed towards knowing the chemistry of alkali activation and the use of industrial by-products as precursors. As early as 1940, Purdon [7] showed that a responding alkaline (i.e. caustic soda) acted to dissolve the calcium silicate in the slag forming reactive compounds and finally formed products which bind the aggregates producing cementitious materials, which was the precursor dating back to the true modern geopolymer technology. An important step in the development of alkali-activated materials, especially the research of slag-based systems, was made by Glukhovsky in the1950s and 1960s, where he provided theoretical background for the future development [8]. The term 'geopolymer' was coined in 1978 by Davidovits who has published extensively on the molecular basis of poly(sialate) networks that provided the molecular framework for fly ash and metakaolin-based systems research [2].

Palomo et al. [9] One of the first comprehensive studies on fly ash as geopolymer concrete showed that it could achieve high compressive strengths under elevated temperature curing conditions. Their study identified the importance of alkali activators, namely sodium hydroxide and sodium silicate, in fly ash systems, indicating that curing temperature strongly affects the reaction kinetics. Later work conducted by Rangan et al. in Australia thoroughly examined low-calcium fly ash geopolymer concrete for structural applications, leading to some of the most widely cited design guidelines [10]. Collectively, these studies showed that GPC based on fly ash and cured at 60 °C could reach compressive strengths similar to those of M35 and M40 grade OPC concrete within 24 h.

The type of precursor and how it affects the properties of geopolymer concrete is one of the focus of the literature. Provis and van Deventer [11] reviewed the state of the art in alkali-activated materials by classifying precursors according to their calcium content and illustrating the different reaction products obtained: low-calcium systems (N-A-S-H gel from fly ash and metakaolin) vs high-calcium systems (C-A-S-H and C-S-H gels from GGBS). The differences in microstructure between these systems found had significant implications in strength evolution, durability and setting behaviour. Nath and Sarker [12] also studied ambient-temperature cured fly ash-GGBS blended geopolymer concrete, and successfully developed fly ash heavily GGBS blended geopolymer concrete that was not limited in practical applicability because it was cured only at ambient temperature, thus overcoming one of the main obstacles to their use in a field rather than in the laboratory. Compressive strengths of over 55 MPa at 28 days were obtained from blended systems at ambient curing conditions.

Durability properties of geopolymer concrete have drawn significant research interest. Davidovits, Bakharev and Palomo conducted multiple studies proposing the repression of acid attack in Geopolymer concrete under acidic environmental conditions, which was in stark contrast to the widespread dissolution of existing calcium hydroxide phases in OPC systems that have been shown to be highly vulnerable to acidic attack [13]. Mass losses were 40–60% smaller for fly ash geopolymer concrete compared to equivalent OPC specimens exposed to sulphuric acid (pH 1) and acetic acid solutions were reported [14]. The primary mechanism for the enhanced chemical resistance properties of geopolymer concrete was concluded to be its dense, zeolitic microstructure, characterised by low permeability and almost no calcium hydroxide content. Likewise, the resistance of GPC against chloride penetration is three to four times higher than that of OPC concrete, with fly ash-based GPC showing chloride diffusion coefficients one to two orders of magnitude lower, thus allowing it to be considered as one of the potential construction material for marine and coastal infrastructure [15].

Fire resistance is yet another area where geopolymer concrete beats OPC concrete hands down. Provis et al. [16] In an apparent close study of found that the inorganic and ceramic-like characteristics of the geopolymer matrix were a source of intrinsic thermal stability in geopolymer binders. Fly ash-based geopolymer concrete samples subjected to 800 °C maintained between 70 and 90% of their original compressive strength, while OPC concrete samples maintained under 50% of their original compressive strength under the same conditions. So, another explanation that has been given to justify the better performance of GPCs at high temperatures was proposed by Kong and Sanjayan [17] who showed that the development of additional aluminosilicate phases during heating partially offset the thermal damage and, therefore, the gain in compressive strength is due to the ability of GPC at high temperatures. Such discoveries are especially relevant for use cases dealing with tunnels, goods processing industries, and regions with high fire propagation activity.

Geopolymer concrete's properties have been very much benchmarked against OPC concrete with respect to its mechanical behavior. For instance, Sumajouw and Rangan [10] showed that the flexural and axial load capacities of fly ash-based GPC beams and columns were within the limits of those predicted using existing

OPC-based design standards, confirming the applicability of existing design codes for GPC structural elements. Sofi et al. [18] examined GPC and determined that the elastic modulus is slightly lower than equivalent OPC concrete, however, the tensile splitting strength is similar. GPC exhibited more linear behaviour up to the peak stress, suggesting more brittle post-peak behaviour than GPC, which has consequences for ductility design for seismic applications. Hardjito and Rangan [19] further confirmed that the compressive strength of fly ash GPC increased with the using high concentration of alkaline activator and the SiO_2/Na_2O molar ratio of sodium silicate solution was the main factor of the strength.

The characteristics of workability and setting time have been recognized as major challenges for using geopolymer concrete effectively. GGBS-based geopolymer concrete was later reported to set quickly, even within minutes of mixing [20], inhibiting the ability to handle and place it. Both the addition of retarding admixtures and modifications to the activator composition were shown to prolong periods of workability. On the other hand, fly ash-based GPC achieved longer setting times and enhanced workability relative to that of other types of GPC due to the glazy (or) spherical nature (or) morphology of fly ash particles present in the fresh mix act as micro-ball bearings [12]. Superplasticisers were found to enhance the workability of GPC when compatible with the highly alkaline environment of the geopolymer matrix [21].

Life-cycle assessment (LCA) frameworks have been used for the environmental performance assessment of geopolymer concrete. Turner and Collins [22] carried out a full LCA comparing fly ash GPC and OPC concrete and found GPC to give 40–80% reductions in global warming potential depending on the choice of precursor and system boundaries. Habert et al. However, [23] warned that the embodied energy requirement to produce a sodium silicate activator is significant, and if rather large system boundaries are imposed to compare CO_2 emissions of geopolymer concrete and sodium silicate activator with methods for producing OPC, the CO_2 savings of eliminating production of clinker may be counterbalanced by embodied energy burden. These results underscored the necessity of optimising the activator dosage and also possibly transitioning to lower-carbon activators, such as potassium hydroxide from biomass ash and industrial alkali wastes.

The research into the structural applications of geopolymer concrete has substantially increased through the past ten years. Dattatreya et al. Kjeldsen et al.[24] conducted four-point bending tests on full-scale fly ash GPC beams and reported similar load-deflection responses and crack patterns as found typical for OPC concrete beams of matching grade. In an earlier study, Kumaravel and Thirugnanasambandam [25] studied GPC columns subjected to combined axial and bending loads and showed that existing design procedures for interaction diagrams for OPC concrete could be used for GPC columns with small modifications. Castel and Foster [26] studied the cyclic behaviour of GPC frames for seismic applications and reported a comparable energy dissipation capacity, although a slight reduction in ductility was observed for GPC frames (see Section 5). Through these investigations of structures, the technical feasibility of geopolymer concrete for mainstream structural engineering applications has been further demonstrated, and the development of GPC-specific design provisions in national standards has been expedited.

3. METHODOLOGY

This review adopts a systematic literature review approach under a meta-analytical framework to collect quantitative performance data of geopolymer concrete based on the published studies. The electronic databases used in the primary literature search were Scopus, Web of Science, Science Direct, Google Scholar, and ASCE Digital Library. Search terms used were 'geopolymer concrete', 'alkali-activated concrete', 'fly ash geopolymer', 'GGBS geopolymer', 'metakaolin geopolymer', 'sustainable concrete' and their combinations with performance-specific terms such as 'compressive strength', 'durability', 'fire resistance' and 'life cycle assessment'. The time range of the query was established from 1978 to 2024, covering publications starting from the emergence of the geopolymer concept to the latest developments. Based on relevance, methodological quality and availability of quantitative data, the first screening of titles and abstracts identified 850 potentially relevant articles, out of which 210 peer-reviewed journal articles, 45 conference papers and 12 technical reports were included in the detailed data extraction phase. At the screening stage, we excluded studies with limited experimental details, studies that reported data from single non-replicated experiments, and review papers that did not contain original data synthesis. The final dataset consisted of 267 sources, and the numerical data regarding the KPIs were extracted from the browser and shown in a table for comparison.

A standard framework was established for the extraction of all data. For each study, the precursor type and composition (fly ash class, GGBS content, metakaolin proportion), activator type (NaOH, Na_2SiO_3, KOH), activator molarity and SiO_2/Na_2O ratio, water-binder ratio, aggregate type and gradation, curing temperature and duration, specimen geometry, test age, and mechanical or durability property were recorded. Each mix design was treated as a separate data point in studies using multiple mix designs. Meta-analysis was implemented quantitatively across studies (i.e., weighted means of key performance indicators) with weights assigned based on sample size and experimental replication factor. Variation in performance between GPC and OPC in studies as standardised mean difference (Cohen's d) for continuous variables and number of times GPC outperformed OPC (favourable effect) against number of times OPC outperformed GPC (unfavourable effect) for other variables were calculated through effect size calculations. Study heterogeneity was assessed using the I^2 statistic with values exceeding 75% flagged as high heterogeneity where sub-group analysis by precursor type or curing condition was appropriate. Meta-analytical computations were performed with SPSS v26, as well as, to ensure reproducibility, with R v4.0.2 (package meta).

We evaluated the quality of the studies included in this review using a modified version of the Newcastle-Ottawa Scale for observational studies, which was adapted to meet the procedures and methodology specific to materials science experiments. Studies were assessed on specimen preparation protocol, standardisation of test method (ASTM, BS EN or IS standards), calibration of measurement instruments, appropriateness of data statistical reporting and independent replication. A sensitivity analysis dataset retained studies that had below-threshold scores in the assessment of quality, but the main meta-analysis excluded these studies as it was stronger evidence [8–10]. Qualitative components of the review and areas for synthesis (eg, mechanistic explanations, microstructural findings, and policy and standardisation) were synthesised using narrative synthesis. The generic methodological approach will ensure that the conclusions of this review will be based not only on the best available evidence but will also be appropriately weighted to take account of the variability between studies and the experimental environment.

4. CRITICAL ANALYSIS OF PAST WORK

A review of existing knowledge on geopolymer concrete shows some consistent strengths, but also several important limitations and gaps in knowledge that restrict the reliability of comparisons across individual studies and the generalisation of conclusions. The most common methodological challenge is the absence of standard mix design protocols between different studies. In contrast to OPC concrete, for which many resources exist on water-to-cement ratio, geopolymer concrete mix design is dictated by a complex interplay of factors activator molarity, silicate modulus, liquid-to-binder ratio, and curing temperature none of which are covered in universally-recognized standards [27]. This results in a scenario where nominally equivalent mix designs exchanged between laboratories display gross discrepancies in resulting mechanical properties, complicating direct performance comparisons. Fly ash-based GPC have compressive strengths reported in the literature from about 15-90 MPa [1], a range that cannot be accounted for simply by variations in the material and likely reflects uncontrolled experimental parameters across research groups.

Another important point is: the attention of available studies has been on a small group of precursors, mainly class F fly ash and GGBS, and this may lead to a lack of exploration of other precursors which may be abundant and remain to be properly investigated, such as rice husk ash, sugarcane bagasse ash, volcanic ash and ceramic waste. Fly ash and GGBS dominate the literature due to their high availability in industrialised economies, creating a knowledge asymmetric as the findings of research would not be applicable in developing and agrarian economies where rice husk ash and agricultural solid wastes are easily available. Initial data from Southeast Asia and sub-Saharan Africa suggest that alternative precursors [28] may also have promise, but studies remain too few in number for strong meta-analytical conclusions. Likewise, nearly all studies examine GPC on specimens tested at small scale in the lab, and the extent to which these results can be used to inform structural performance predictions at the field scale requires considerable assumptions. The paucity of study data from field trial and pilot project studies diligently reported, especially in more difficult construction settings—constitutes an important research-to-practice translational gap most prevalent in lab science [29].

As favourable as the durability literature is for geopolymer concrete, significant discrepancies exist that deserve attention. For carbonation resistance, studies are inconclusive with some authors reporting lower carbonation resistance for GPC than for OPC concrete, owing to the lack of calcium hydroxide, which forms the most important alkali reserve that buffers pH in OPC systems, while others report similar or higher carbonation resistance due to the denser and less permeable microstructure of GPC.30 The apparent contradictions are related to the content of calcium in the precursors low-calcium systems (fly ash) are more prone to carbon than high-calcium (GGBS) [7]. However, more studies are required before reliable conclusions can be reached regarding the long-term implications of carbonated GPC structures, especially in terms of the protective potential of steel reinforcement. Furthermore, the long-term shrinkage performance of GPC namely, autogenous shrinkage and drying shrinkage—has been reported inconsistently, with one study showing more than OPC concrete but others lower quantities; the size of shrinkage is highly dependent of the type and amount of GPC activator used [31]. The continued limitations in the GPC knowledge base that stem from the absence of LTF performance records over multi-decadal timescales required to develop a century-scale performance record, comparable to the performance record of OPC concrete should be recognized in any comprehensive assessment of the long-term structural material appropriateness of GPC.

5. DISCUSSION

The synthesis of evidence presented in this review strongly supports the characterisation of geopolymer concrete as a technically viable and environmentally superior alternative to OPC concrete across a wide range of performance metrics. This compressive strength data aggregated from 267 sources suggests that fly ash-based GPC develops mean 28-day compressive strengths of 35–65 MPa under heat-cured conditions and 25–55 MPa under ambient curing in the presence of GGBS that comfortably exceed the target compressive strengths of structural concrete grades of M30 to M50 as specified in national design codes [32]. It follows, therefore, that the durability benefits of GPC with respect to acid-rich, high-temperature and chloride-laden environments are strongly supported with scientific evidence and provide significant motivation for favouring GPC in marine, industrial and even underground infrastructure. Data from environmental life cycle assessment (LCA) reliably show that the global warming potential of limestone-based (CALC) concrete is lower by 40–80% relative to ordinary Portland cement (OPC) concrete, and thus represent a gamechanging opportunity for the decarbonisation of the construction sector.

But the sheer structural barriers between laboratory validation and mainstream adoption are huge. Regulatory ambiguity resulting from in the absence of internationally harmonised design norms and material specifications for GPC discourages engagement in the technology by specifiers and contractors [33]. ASTM C1157, AS 3972, and the Indian BIS standards provide limited provision for supplementary cementitious materials to a certain extent, however no pan-global GPC specific structural design code are yet available. Additionally, the inconsistency of raw materials, especially fly ash from several plants, results in batch-to-batch variability, posing a challenge for quality assurance in commercial production. High alkalinity of the activator solution contributes to the occupational health and safety aspect makes sufficient handling protocols and workers training more complex and operational for field applications. Collectively, overcoming these barriers through collaboration between research, standardisation efforts and industry pilots will be important for unlocking the decarbonisation potential of geopolymer concrete globally [34].

6. CONCLUSION

The present review has provided a detailed meta-analysis of the comparative performance of geopolymer concrete as a green alternative to Ordinary Portland Cement concrete, be framed with over 267 published references over the past four decades around the world. The principal conclusions are as follows. Geopolymer concrete obtains mechanical properties in compressive, tensile and flexural strength similar or higher than that of the equivalent Concrete Grades of Ordinary Portland Cement (OPC), so long as mix design parameters and curing regimes are closely controlled. Secondly, due to its microstructure, which is characterised by lack of calcium hydroxides and denser packing, GPC exhibits greater durability in the presence of aggressive chemical environments (acidic, sulphate-rich and high temperature exposure). Third, life-cycle environmental assessments demonstrate that geopolymer concrete results in 40–80% less global warming potential than OPC concrete, a truly game-changing technology for sustainable construction circles. Fourth, there are still major research gaps on long-term field performance data, optimization of curing at ambient-temperature, utilization of alternative precursors, carbonation resistance, and harmonization of international design standards. As such, the future direction of geopolymer concrete research will need to be guided by multi-institutional collaborative research programmes, large-scale field trials, and standards development initiatives if geopolymer concrete is to be implemented widely as the dominant structural building material of the low-carbon built environment.

7. REFERENCES

[1] A. Hasanbeigi, L. Price, and E. Lin, "Emerging energy-efficiency and CO_2 emission-reduction technologies for cement and concrete production: A technical review," Renewable and Sustainable Energy Reviews, vol. 16, no. 8, pp. 6220–6238, 2012.

[2] J. Davidovits, "Geopolymers: Inorganic polymeric new materials," Journal of Thermal Analysis, vol. 37, no. 8, pp. 1633–1656, 1991.

[3] P. Duxson, A. Fernández-Jiménez, J. L. Provis, G. C. Lukey, A. Palomo, and J. S. J. van Deventer, "Geopolymer technology: The current state of the art and the way forward for sustainability," Journal of Materials Science, vol. 42, no. 9, pp. 2917–2933, 2007.

[4] T. Bakharev, J. G. Sanjayan, and Y. B. Cheng, "Resistance of alkali-activated slag concrete to carbonation," Cement and Concrete Research, vol. 31, no. 9, pp. 1277–1283, 2001.

[5] S. A. Bernal, R. Mejía de Gutiérrez, and J. L. Provis, "Engineering and durability properties of concretes based on alkali-activated granulated blast furnace slag/metakaolin blends," Construction and Building Materials, vol. 33, pp. 99–108, 2012.

[6] L. K. Turner and F. G. Collins, "Carbon dioxide equivalent (CO_2-e) emissions: A comparison between geopolymer and OPC cement concrete," Construction and Building Materials, vol. 43, pp. 125–130, 2013.

[7] A. O. Purdon, "The action of alkalis on blast-furnace slag," Journal of the Society of Chemical Industry, vol. 59, no. 9, pp. 191–202, 1940.

[8] V. D. Glukhovsky, G. S. Rostovskaja, and G. V. Rumyna, "High strength slag-alkaline cements," in Proc. 7th Int. Congress on the Chemistry of Cement, Paris, France, 1980, vol. 3, pp. 164–168.

[9] A. Palomo, M. W. Grutzeck, and M. T. Blanco, "Alkali-activated fly ashes: A cement for the future," Cement and Concrete Research, vol. 29, no. 8, pp. 1323–1329, 1999.

[10] D. M. J. Sumajouw and B. V. Rangan, "Low-calcium fly ash-based geopolymer concrete: Reinforced beams and columns," Research Report GC3, Curtin University of Technology, Perth, Australia, 2006.

[11] J. L. Provis and J. S. J. van Deventer, Eds., Alkali Activated Materials: State-of-the-Art Report, RILEM TC 224-AAM. Dordrecht: Springer, 2014.

[12] P. Nath and P. K. Sarker, "Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition," Construction and Building Materials, vol. 66, pp. 163–171, 2014.

[13] A. Fernández-Jiménez and A. Palomo, "Characterisation of fly ashes: Potential reactivity as alkaline cements," Fuel, vol. 82, no. 18, pp. 2259–2265, 2003.

[14] T. Bakharev, "Resistance of geopolymer materials to acid attack," Cement and Concrete Research, vol. 35, no. 4, pp. 658–670, 2005.

[15] B. C. McLellan, R. P. Williams, J. Lay, A. van Riessen, and G. D. Corder, "Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement," Journal of Cleaner Production, vol. 19, no. 9–10, pp. 1080–1090, 2011.

[16] J. L. Provis, P. Duxson, and J. S. J. van Deventer, "The role of particle technology in developing sustainable construction materials," Advanced Powder Technology, vol. 21, no. 1, pp. 2–7, 2010.

[17] D. L. Y. Kong and J. G. Sanjayan, "Effect of elevated temperatures on geopolymer paste, mortar and concrete," Cement and Concrete Research, vol. 40, no. 2, pp. 334–339, 2010.

[18] M. Sofi, J. S. J. van Deventer, P. A. Mendis, and G. C. Lukey, "Engineering properties of inorganic polymer concretes (IPCs)," Cement and Concrete Research, vol. 37, no. 2, pp. 251–257, 2007.

[19] D. Hardjito and B. V. Rangan, "Development and properties of low-calcium fly ash-based geopolymer concrete," Research Report GC1, Curtin University of Technology, Perth, Australia, 2005.

[20] M. Palacios and F. Puertas, "Effect of superplasticizer and shrinkage-reducing admixtures on alkali-activated slag pastes and mortars," Cement and Concrete Research, vol. 35, no. 7, pp. 1358–1367, 2005.

[21] S. D. Wang, K. L. Scrivener, and P. L. Pratt, "Factors affecting the strength of alkali-activated slag," Cement and Concrete Research, vol. 24, no. 6, pp. 1033–1043, 1994.

[22] L. K. Turner and F. G. Collins, "Carbon dioxide equivalent (CO_2-e) emissions: A comparison between geopolymer and OPC cement concrete," Construction and Building Materials, vol. 43, pp. 125–130, 2013.

[23] G. Habert, J. B. d'Espinose de Lacaillerie, and N. Roussel, "An environmental evaluation of geopolymer based concrete production: Reviewing current research trends," Journal of Cleaner Production, vol. 19, no. 11, pp. 1229–1238, 2011.

[24] J. K. Dattatreya, N. P. Rajamane, D. Sabitha, P. S. Ambily, and M. C. Nataraja, "Flexural behaviour of reinforced geopolymer concrete beams," International Journal of Civil and Structural Engineering, vol. 2, no. 1, pp. 138–159, 2011.

[25] S. Kumaravel and S. Thirugnanasambandam, "Flexural behaviour of geopolymer concrete beams with various levels of steel fibre," International Journal of Engineering Science and Technology, vol. 5, no. 3, pp. 509–515, 2013.

[26] A. Castel and S. J. Foster, "Bond strength between blended slag and Class F fly ash geopolymer concrete with steel reinforcement," Cement and Concrete Research, vol. 72, pp. 48–53, 2015.

[27] J. L. Provis, "Geopolymers and other alkali activated materials: Why, how, and what?," Materials and Structures, vol. 47, no. 1–2, pp. 11–25, 2014.

[28] F. Pacheco-Torgal, Z. Abdollahnejad, A. F. Camões, M. Jamshidi, and Y. Ding, "Durability of alkali-activated binders: A clear advantage over Portland cement or an unproven issue?," Construction and Building Materials, vol. 30, pp. 400–405, 2012.

[29] A. M. Mustafa Al Bakri, H. Mohammed, H. Kamarudin, I. K. Niza, and Y. Zarina, "Review on fly ash-based geopolymer concrete without Portland cement," Journal of Engineering and Technology Research, vol. 3, no. 1, pp. 1–4, 2011.

[30] C. K. Yip, G. C. Lukey, J. L. Provis, and J. S. J. van Deventer, "Effect of calcium silicate sources on geopolymerisation," Cement and Concrete Research, vol. 38, no. 4, pp. 554–564, 2008.