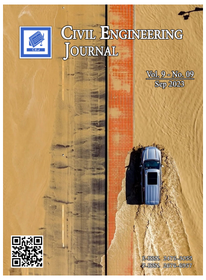
Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 9, No. 09, September, 2023



Review Article

Influential and Intellectual Structure of Geopolymer Concrete: A Bibliometric Review

Salam Al-Kasassbeh [1*], Jafar Al-Thawabteh [2], Eslam Al-Kharabsheh [1], Amani Al-Tamseh [1]

[1] *Civil Engineering Department, Faculty of Engineering Technology Al-Balqa Applied University, 11134 Amman, Jordan.*

[2] *Civil Engineering Department, Faculty of Engineering, Al-Balqa Applied University, Al-Salt, Jordan.*

Received 08 June 2023; Revised 06 August 2023; Accepted 11 August 2023; Published 01 September 2023

Abstract

The objective of this bibliometric review is to deliver an in-depth examination of the dynamic field of geopolymer concrete, revealing its evolution, current trends, and possible future trajectories. The method involves a rigorous bibliometric analysis of research output since the field's inception in 2003, underlining key milestones and mapping research patterns. Findings show a consistent surge in geopolymer concrete research, exemplified by over 1360 annual publications, with notable contributions predominantly from Australia and India. The paper also uncovers the increasing practical applications of geopolymer concrete, especially in construction processes, underpinned by a wealth of research on fly ash, a crucial manufacturing component. Additionally, prevalent research themes include compressive strength, fly ash, and geopolymer itself. The review's novelty lies in its comprehensive overview of geopolymer concrete research, elucidating past and present trends and identifying potential future research areas. It thereby serves as a firm foundation for further studies, fostering continued growth in this promising field.

Keywords: Geopolymer Concrete; Building Materials; Alternative Materials; Bibliometric Review.

1. Introduction

The global construction industry stands as one of the most significant contributors to greenhouse gas emissions, primarily due to the wide-ranging use of cement. Traditional concrete structures—comprising the backbone of our built environment—exert a substantial environmental toll, giving rise to a compelling need for more sustainable alternatives [1]. The ubiquity of Ordinary Portland Cement (OPC) in both conventional and non-conventional concrete typifies this problem [2]. This pervasive material, an indispensable element in extensive water infrastructure projects, comprises gypsum, calcareous, and several other constituents. Although OPC has proven durability, even in freezing temperatures as low as -40ºC, its production incurs a heavy environmental cost [3]. The production of OPC involves a high-energy, resource-intensive process, resulting in significant carbon dioxide (CO_2) emissions [4].

Roughly one ton of CO_2 is produced for every ton of OPC, making cement production a leading source of anthropogenic CO_2 emissions. This industry alone accounts for between 5% and 7% of all CO_2 emissions, with CO_2 being responsible for about 65% of the warming experienced on Earth over the past 150 years [5]. The inescapable conclusion is that cement plays a leading role in global warming [6]. These findings in the literature point towards a glaring gap—the need for viable, sustainable alternatives to OPC in the construction industry. To address this gap, researchers and engineers worldwide have recently turned their attention toward alternative materials and techniques

* Corresponding author: salamkasassbeh@bau.edu.jo

http://dx.doi.org/10.28991/CEJ-2023-09-09-017

that could maintain or even enhance the performance of concrete while drastically reducing its environmental footprint [7]. For instance, the incorporation of by-products such as fly ash and granulated blast furnace slag into concrete mixtures has gained traction. Furthermore, the growing trend of utilizing recycled aggregates, including post-consumer glass, discarded tires, plastics, paper, and other industrial wastes, is providing a promising approach to green construction [1]. These methods are not only environmentally advantageous but also economically beneficial, considering the escalating prices of fine aggregates globally [8].

In the quest for long-lasting, low-energy, and eco-friendly building materials, academics and industry professionals have converged on a promising solution: geopolymers. As opposed to the high-temperature calcination process required to create OPC from calcium carbonate, geopolymers are synthesized from aluminosilicate-rich minerals and industrial waste ($CaCO_3$). As an emerging material, geopolymers offer potential advantages in sustainability over traditional Portland cement. The widespread application of materials like fly ash (FA) and ground-granulated blast furnace slag (GGBFS) in geopolymer concrete (GPC) production is attributed to their affordability and availability [4]. Geopolymers are rapidly gaining recognition as a viable substitute for Portland cement.

The introduction of geopolymers into the construction process could lead to a 73% reduction in greenhouse gas emissions and a 43% decrease in energy consumption [1, 9]. This alternative, deemed a green building material, circumvents the need for cement [10], and GPC possesses the potential to supersede conventional concrete due to its lower CO_2 emissions. GPC relies on fly ash and/or ground-granulated blast furnace slag for geopolymerization, as opposed to OPC [11]. As such, GPC emerges as a sustainable and environmentally friendly alternative to traditional concrete [8]. This paper primarily seeks to distill the existing knowledge within the realm of geopolymer concrete, thus laying the groundwork for future innovation. More specifically, this research performs a comprehensive bibliometric analysis, spotlighting the historic progression and contemporary status of research related to this topic. The focus herein lies not only on recognizing established directions but also on emphasizing identifiable gaps within the field that need to be addressed, ultimately suggesting potential future research topics for further exploration. The primary aim of this study is to engage in a critical review of the current literature, identify research gaps, and propose novel strategies to unravel potential advancements. Within this context, we seek to address three fundamental research questions:

- What formative factors within the GPC field have contributed most significantly to its current state?
- How does existing literature on GPC enhance our understanding of the field?
- To broaden our comprehension of GPC, what unanswered questions remain the most crucial, and what potential research avenues should be pursued?

To answer these questions, the study commences with an overview of the history of geopolymer concrete, underlining some of the most significant works, influential journals, countries, and institutions in the field. Further, it scrutinizes the intellectual quality of existing literature and categorizes the current resources. Notably, this study pinpoints what is missing from current research and suggests directions for future research crucial for the evolution of geopolymer concrete. However, the merit of this study is not solely in providing an extensive review. It makes a significant contribution by conducting a comprehensive gap analysis in the field of GPC. This includes examining all facets of the problem, addressing assumptions, limitations, and constraints, along with the pros and cons, and comparing the relative merits of this research to other publicly available studies and proposals. By doing so, the study not only justifies its necessity but also underlines its significance to the reader. This rigorous investigation into the field of GPC is of high importance to practitioners, researchers, and those invested in the field, as it offers a guidepost for research directions while encapsulating key findings from the literature. In doing so, it signifies the criticality of understanding and addressing the gaps in our knowledge to foster the progression of geopolymer concrete technology. In general, this study finds its foundation in previous literature.

Important works like that of Yang et al. (2022) [12], who provided a comprehensive overview of geopolymer composites through a bibliometric analysis and literature review; Zakka et al. (2021) [13], who conducted a scientometric review of geopolymer concrete; and Matsimbe et al. (2022) [14], who executed a bibliometric analysis of research trends in geopolymer, all offer valuable insights that helped shape our research design. However, this study diverges from these previous efforts in its explicit aim to provide a comprehensive gap analysis in the field of GPC, examine all facets of the problem, address assumptions, limitations, and constraints, as well as the pros and cons, and compare the relative merits of this research to other publicly available studies and proposals. Unlike the aforementioned works, this study emphasizes not only recognizing established directions but also the identification of gaps within the field that need to be addressed, ultimately suggesting potential future research topics for further exploration.

2. Geopolymer

In the 1980s, Joseph Davidovits developed a geopolymerization process to make OPC stronger and more durable [15]. Geopolymer is a chemical that binds things together and is much better for the environment than any other construction material used now. Alumina-silicate can be made by mixing a source material with a solution of an alkali activator. There are many different raw materials on the alumina-silicate market, such as glass powder GP, fly ash FA, ground granulated blast slag, meta-kaolin, palm oil fuel ashes, red mud, silica fume, fuel ash, palm oil, pulverized fuel ash, rice husk ashes, etc. ([16, 17]). Silica acts as an organic polymer when the temperature is below 100ºC. "*Geopolymerization*", Figure 1, as a term, refers to the process by which alumina-silicate oxides react with alkali polysilicates to make polymeric Si-O-AI linkages (1991). Figure 2 shows how to differentiate between geopolymers that have been treated with acid and those that have been treated with alkaline. Alkaline-activated geopolymers have a lot in common with those made with acid. The terms sialate, silaxo, and silaxo di sil are given to sialates based on the specific composition of the aluminum silicate matrix from which they are made.

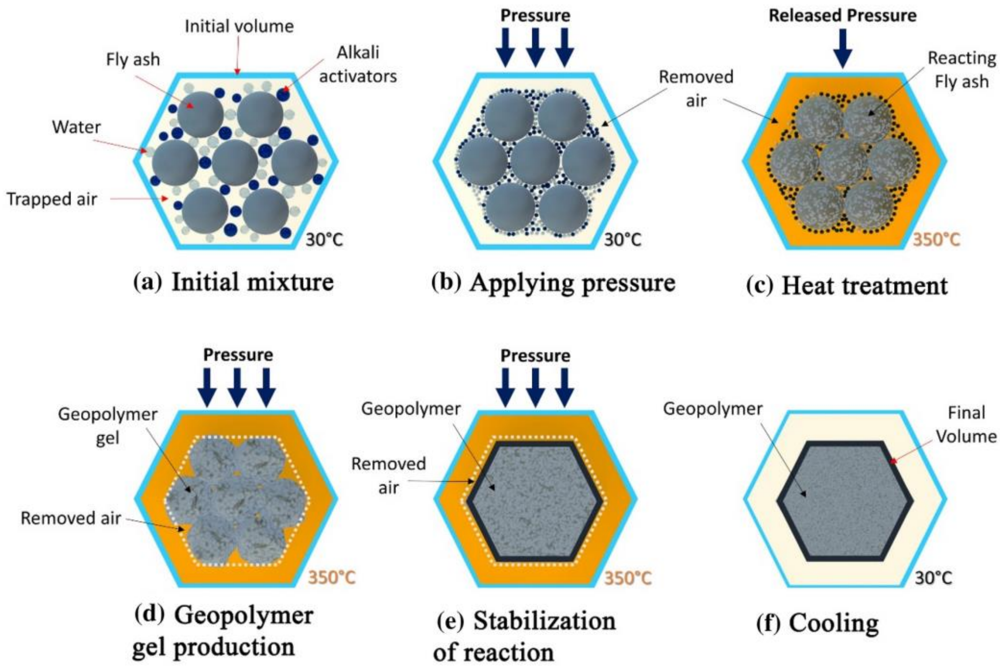


Figure 1. Illustration of the geopolymerisation method under hot pressing [18]

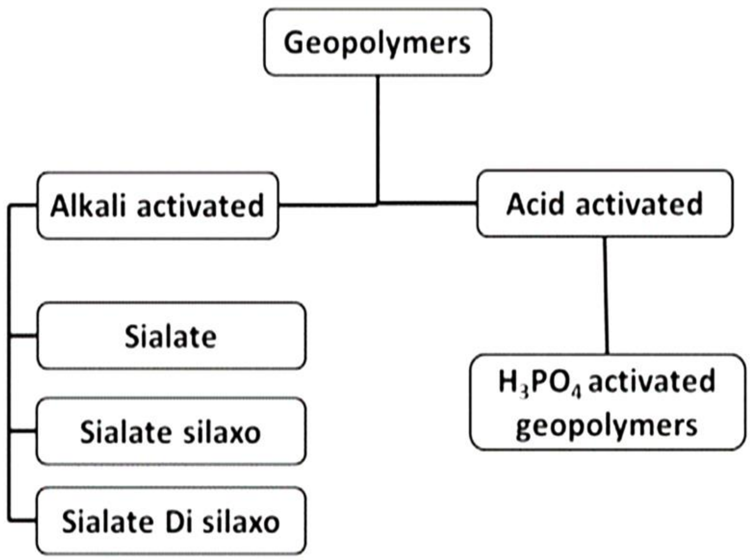


Figure 2. Classification of geopolymers by Khan et al. (2014) [19]

Even though fly ash is the most common raw material for producing geopolymer, other solid wastes such as slags, mining tailings, and metallurgical wastes have also been considered possible sources for making geopolymer [20]. Industrial wastes such as fly ash can be used in place of cement because of their pozzolanic activity.

2.1. Compressive Strength

Various factors influence the compressive strength of geopolymer concrete, such as particle size, wet-mixing time, curing time, and temperature [21], and the inclusion of additives, such as silica fume [18]. The increase in temperature up to 400 °C produced a constant decrease in the primal compressive strength of geopolymer concrete that contains fly ash, despite the coarse aggregate size and molarities [22, 23]. Furthermore, the increase in excessive water by 12% of the fly ash mass minimizes the geopolymer's concrete compressive strength [24]. Earlier studies suggested that incorporating wastepaper sludge ash during the 28-day period as a replacement for fly ash and slag increased the compressive strength of geopolymer concrete with recycled coarse aggregates by 10%. Additionally, geopolymer concrete showed a high molarity of sodium hydroxide, reflecting a larger compressive strength than traditional concrete [25–27]. The increase in slag content is accompanied by the reduction of a fresh concrete slump, which results from the concentration of the setting time with a larger slag volume in the mixture [28]. Another approach for increasing the compressive strength is the addition of FA as a replacement for 30% of GGBS, which indicated a 60% increase in the compressive strength of geopolymer concrete at 28 days and a 12% increase in compatibility during the fresh state [29]. In harsh environments, geopolymer concrete can be implemented in the production of ultra-high compressive strengths with a higher durability performance.

2.2. Splitting Tensile Strength

Concrete is a poor material in tension because of its brittle nature, which cannot bear a direct tensile load [30]. Typically, the splitting tensile strength of conventional concrete is 30% less than that of self-compacting concrete [31, 32]. The splitting tensile strength of geopolymer concrete can be enhanced through the partial replacement of fly ash by slag; the incorporation of 10% palm oil shell aggregate can lead to a reduction in the splitting tensile strength [33], and the implementation of 10% and 30% of recycled coarse aggregate decreased the splitting tensile strength [27]. Furthermore, geopolymer concrete splitting tensile strength can be decreased by silica fume ash concentrations of more than 10% [34]. According to research by Al-Majidi et al. (2017) [35], increasing ground-granulated blast-furnace slag can boost geopolymer concrete splitting tensile strength by 9 to 11%.

2.3. Modulus of Elasticity

The compressive strength of geopolymer concrete is substantially connected with its modulus of elasticity. As a result, a higher level of geopolymerization might produce a matrix made of geopolymers that is denser, which in turn has a higher modulus of elasticity [36]. On the other hand, geopolymerization is sometimes referred to as the production of polysialates, which are highly dependent on the mineralogical, chemical, and physical characteristics of raw materials, as well as the amount of activator and the curing circumstances [37]. The number of aggregates in geopolymer concrete mixes affects the modulus of elasticity property and the chemical activator dose [38]. A low modulus of elasticity can reduce the degree of fracture propagation caused by the corrosion of steel bars. A geopolymer concrete with an equal or greater modulus of elasticity can be created using a high aggregate-to-total aggregate ratio [39]. Numerous studies have shown that a higher silicate concentration will increase the elasticity modulus of geopolymer concrete while decreasing the elasticity modulus of OPC concrete [40]. For specimens with moduli of elasticity around 23.0 and 30.8 GPa, 10.7–18.4 GPa, and 30.3–34.5 GPa, modulus of elasticity values were found in many experiments using fly ash-based geopolymer concrete [41–43].

3. Research Methodology

Typically, bibliometrics and content analysis are used by many researchers when investigating a specific topic [44]. Within this context, meta-analyses and systematic, integrative, and descriptive reviews are used to classify past studies [45]. Generally, bibliometrics uses numbers to study libraries and the things they have in them [46]. On the other hand, quantitative methods are used to judge the quality of papers published in a journal [47]. Bibliometrics generally help researchers understand the past, make sense of the present, and look into the future [48].

In this study, the Scopus database was used to collect the information and data required for the analysis. This database was selected because it has been used extensively in similar research. Besides, it offers the following:

- A comprehensive database of scientific engineering literature, it is the largest of its kind.
- It is one of the best-accessible databases, including nearly all the best academic publications in its index.
- It facilitates bibliometric research by allowing for refined searches and a simple means of cleaning and exporting relevant data.

The analysis was done using Microsoft Excel, VOSviewer, and RStudio to help understand the study's hypotheses and findings. Generally, VOSviewer connects publications, researchers, institutions, countries, and ideas into networks. Some ways that nodes in these networks can be linked to each other are through co-occurrence, co-authorship, citation, bibliographic coupling, and co-citation. Indeed, this tool can be used to make bibliometric networks, also called maps, which are just groups of references [49]. Ultimately, Microsoft Excel was used to turn the gathered information into graphs and charts. RStudio is an integrated development environment (IDE) for the computer language R, which is used for statistical analysis and making graphs. The information required herein comes from analyses of citation data, the structure of social networks, and the results. The overall rating includes information about the field's most influential authors, countries, and organizations and a timeline of how the field has changed over time. Generally, using citation counts allows for finding out which authors, papers, and journals are most often referred to by other researchers. Lastly, methods like co-citation, bibliographical coupling, and co-occurrence analysis were used to look at the content and clustering of the network.

4. Results and Discussion

Here are the results for the three main groups developed in this study. This study starts by looking at the publishing landscape before putting in the data, then discusses the citation analysis, and ends with a look at the network analysis.

4.1. Publication Overview

Bibliometric analysis necessitates a thorough summary of primary and secondary sources. The data, as indicated in Table 1, comprises 1437 documents, including 932 articles and 400 conference papers produced by 309 distinct publishers. Interestingly, only 51 documents were penned by solitary authors; the remainder saw collaboration among multiple authors. This exhibits a trend towards scholarly collaboration in this research field. The Scopus database presents an interesting datum: the average citation per document in this field is 23.77. This number clearly implies substantial academic engagement in the area, with about 305 works published in 2021 and 233 in the preceding year, 2020. The increase in the number of works shows an escalating interest and demand for research in this field. Moreover, the documents, particularly those related to geopolymer concrete research, had an annual citation increase rate of 4.6. This demonstrates the influence and reach of the research conducted, as newer citations indicate that ongoing studies are continually referencing these foundational works. This prevalence of the subject, along with the steady augmentation of citations, signifies its importance in academic discourse and its potential for future research directions.

Table 1. Publication overview

Description	Results
Main Information About Data	
Timespan	2003:2021
Sources (Journals, Books, etc.)	309
Documents	1437
Average years from publication	4.18
Average citations per document	23.77
Average citations per year per document	4.61
References	41255

Throughout the span of this 18-year study (2003–2021), there has been a noteworthy escalation in the volume of scientific articles investigating the unique characteristics of geopolymer concrete. This research momentum is reflected in the quantifiable increase in the number of related papers indexed within the Scopus database. As illustrated in Figure 3, there were only three papers addressing the subject in 2003. This figure pales in comparison to the exponential growth observed, with the count reaching an impressive total of 305 papers by the year 2021. The significant surge suggests a growing scientific interest and acknowledgement of the potential of geopolymer concrete in various fields.

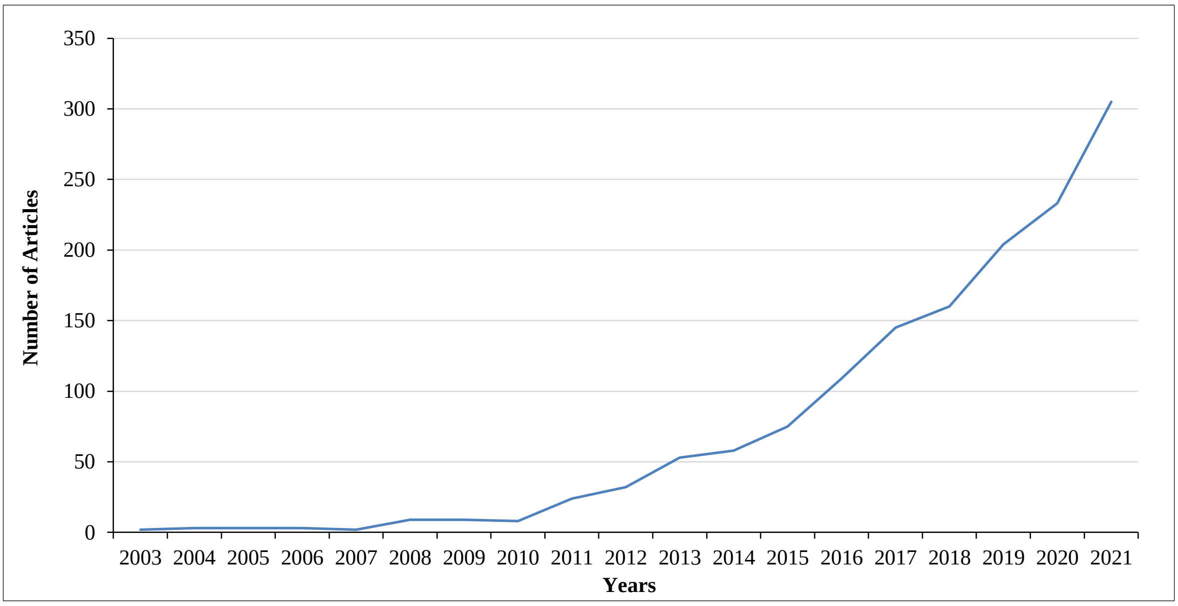


Figure 3. Growth in research about geopolymer concrete

Table 2 collates a comprehensive assembly of results from top-tier academic journals, forming a convenient resource for scholars intending to publish geopolymer concrete-related research. Esteemed scientific periodicals such as Nature and Science consistently rank highly due to their respective publishers, MDPI, Springer, and Elsevier, who are among the most successful in the academic publishing sphere. Another valuable platform is the IOP Conference Series: Materials Science and Engineering. With its 154 publications, it presents an extensive repertoire of research work in the discipline. Scopus, an established indexing platform since 1987, compiles scholarly articles spanning diverse fields such as civil and structural engineering, building and construction, as well as general material science. These areas are intrinsically connected to the construction and building materials industries, making Scopus an invaluable tool for researchers. The aforementioned resources amalgamate the very best in scientific literature, thereby propelling forward the understanding and development of geopolymer concrete and its subsequent applications in the construction industry.

Table 2. Most relevant journals

Sources	Articles	Publisher	SJR 2021
Construction and Building Materials	154	Elsevier	1.777
IOP Conference Series: Materials Science and Engineering	64	Institute of Physics Publishing	0.249
International Journal of Civil Engineering and Technology	55	IAEME Publication	Not index
Materials Today: Proceedings	49	Elsevier	0.355
Lecture notes in Civil Engineering	43	Springer Nature	0.133
Indian Concrete Journal	31	Scientific Publishers	0.219
Journal of Materials in Civil Engineering	28	ASCE	1.055
AIP Conference Proceedings	24	American Institute of Physics	0.189
Materials	24	MDPI	0.604
IOP Conference Series: Earth and Environmental Science	23	Institute of Physics Publishing	0.202
Journal of Building Engineering	23	Elsevier	1.164
Journal of Cleaner Production	23	Elsevier	1.921

India is the country that has made the most geopolymer concrete papers, with about 597, and Australia comes in second place with 264 publications. Nonetheless, most citations have been given to the research done in Australia, about 11040, followed by India with a total score of 8546 (Table 3).

Table 3. Most relevant countries

Country	Documents	Citations
India	597	8546
Australia	264	11040
Malaysia	117	3671
China	122	2753
Indonesia	66	735
United States	60	2135
Iraq	54	854
Saudi Arabia	39	1577
Thailand	32	1730
Turkey	30	1043

This study delves deep into the rich field of geopolymer concrete research, highlighting the most impactful articles that have been published in acclaimed academic journals. These articles serve as a gateway to the innovative developments and pioneering studies in the realm of geopolymer concrete. The study identifies the institutions that are making significant contributions to this field, not just by quantity, but also the quality and influence of their scholarly works. Table 4 delineates the top three institutions contributing based on publication numbers. The University Malaysia Perlis (UNIMAP) takes the lead with the most extensive academic collection and library in the world pertaining to geopolymer concrete. They have demonstrated exceptional dedication to advancing knowledge in this field. The second place belongs to the Swinburne University of Technology, which has contributed significantly with a total of 80 scholarly articles. The University of Technology Petronas (UTP), however, shines through as Malaysia's fourth most-cited university, showcasing their influential contributions with 68 citations. These citations signify that their research has played a pivotal role in shaping contemporary understanding of geopolymer concrete. By analyzing these results, academics, researchers, and industry practitioners can gain a clearer perspective on which areas of study are gaining traction and therefore, may be the most beneficial for their respective audiences. The study bridges the gap between academia and industry, offering insights that could drive informed decision-making and strategic planning in both sectors.

Table 4. Most relevant institutions

Affiliations	Articles
University Malaysia Perlis (UNIMAP)	82
Swinburne University of Technology	80
Curtin University	75
University Technology Petronas	68
Khon Kaen University	61
National Institute of Technology	58
University Technology Malaysia	49
Sichuan University	48
University Of Malaya	44
National Institute of Technology Calicut	39

As per Scopus citations, Table 5 clearly portrays the broad influence of these distinguished authors in the realm of geopolymer concrete. The leader of this prestigious group is Dr. Castel from the University of New South Wales, Sydney, Australia. Her groundbreaking work has paved the way for significant advancements in this field. With innovative research, she has effectively bridged the gap between traditional concrete practices and more sustainable solutions. Notably, her tireless commitment to geopolymer concrete research has had a resounding impact, extending well beyond the academic sphere and touching upon industry practices and policy formulation. Trailing closely behind is Dr. Chindaprasirt, a highly respected professor at Khon Kaen University in Thailand. His contribution to geopolymer concrete research has had a profound influence, particularly in Asia. Known for his meticulous approach, Dr. Chindaprasirt's work is marked by an unyielding pursuit for excellence and commitment to sustainable development. It's the collective impact of such scientists that has expanded our understanding of geopolymer concrete and its potential for reshaping construction practices worldwide. This table is a testament to the importance of rigorous, innovative research and the far-reaching implications it can have.

Table 5. Most cited documents

Authors	Articles	Articles Fractionalized
CASTEL A	28	9.50
CHINDAPRASIRT P	25	5.90
GANESAN N	23	7.58
SARKER PK	23	9.82
ELAVENIL S	22	9.83
ELCHALAKANI M	20	4.00
ABDULLAH MMAB	18	3.21
SANJAYAN J	18	4.88
SHAFIQ N	18	4.49
KARRECH A	17	3.54
NURUDDIN MF	17	4.54
RANGAN BV	17	9.25
EKAPUTRI JJ	16	5.46
SATA V	16	3.85
WANG Q	16	2.97
DONG M	15	3.04
HADI MNS	15	4.80

4.2. Citation Analysis

The implementation of citation analysis enables a systematic exploration of the patterns and frequency of citations within a specific body of work. This process involves identifying the links from one document to another, hence allowing us to understand how research ideas are disseminated, influenced, and interconnected. By employing such a bibliometric technique, we are able to delve deeper into the academic landscape, uncovering complex networks of knowledge that could have otherwise remained concealed. To elucidate further, imagine this method being applied to the niche field of geopolymer concrete. Here, the citation analysis serves as a robust tool to trace the lineage of research, illuminating the intricate relationships between different scholarly articles. By utilizing this approach, it becomes simpler to locate linkages between various works in the literature, promoting a more comprehensive understanding of the research ecosystem. Additionally, this can lead to the identification of core research papers or influential authors within the geopolymer concrete sphere, potentially assisting in spotting emerging trends and future research trajectories. Consequently, such a bibliometric method, when used in citation analysis, enhances our ability to connect the dots in the vast ocean of scientific literature.

4.2.1. Most Cited Documents

Figure 4 provides a detailed account of the 20 most-referenced articles pertaining to the subject matter from the years 2003 to 2021, based on data from the Scopus database. The list is ordered by the frequency of citation, with all the enlisted works being cited over 200 times. This analysis specifically probes whether references made to these Q1 articles in other Scopus publications have any significant impact on the journals' overall rankings. In this context, the top three papers were examined and their key findings are as follows:

i. "On the development of fly ash-based geopolymer concrete," an article authored by Hardjito et al. (2004) [50] in the Materials Journal, was cited 919 times. The central objective of this paper was to examine the process of combining a waste product rich in silicon and aluminum with a high-alkalinity substance to create a binding element that holds together fine and coarse aggregates in geopolymer concrete. Notably, this waste product could potentially be low-calcium fly ash (ASTM C 618 Class F).

ii. Singh et al.'s (2015) [51] paper titled "Geopolymer concrete: A review of some recent advances," published in Construction and Building Materials, was referenced 718 times. The paper aimed to scrutinize recent advancements in the development of geopolymers, created through the activation of aluminosilicates with alkali. It further discusses potential applications of these materials within the construction industry.

iii. The article "Effect of GGBFS on the setting, workability, and early strength properties of fly ash geopolymer concrete cured under ambient condition" penned by Nath & Sarker (2014) [52], was cited 692 times. This publication, found in Construction and Building Materials, sought to explore whether fly ash could be utilized in the production of materials that can endure high temperatures.

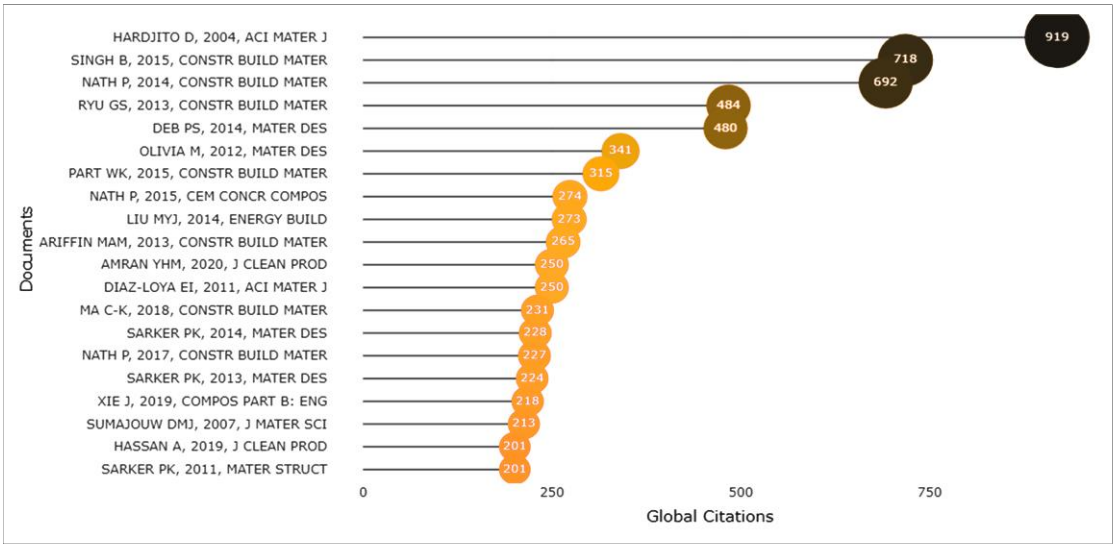


Figure 4. Most cited documents

In summary, these significant articles, based on their substantial citation frequency, have evidently played a key role in shaping the scholarly discourse in their respective areas of research.

4.2.2. Most Cited Countries

Figure 5 graphically presents a compilation of countries with the most prolific contributions to geopolymer concrete research from 2003 to 2021. Evidently, the author's academic associations and collaborations predominantly lie with these nations. Australia and India, renowned for their rigorous research pursuits, lead the list, reflecting their keen interest and dedication towards developing sustainable alternatives to traditional concrete (Table 6). What is striking, however, is the close competition posed by Malaysia and China. Both nations are rapidly rising in their research commitments to geopolymer concrete, indicating a strategic shift towards sustainable construction materials in their urban development policies. These countries have been successful in creating a robust research environment that fosters the exploration of novel materials like geopolymers. Interestingly, the pattern of book publication mirrors that of research paper citations, reinforcing the stature and influence of these countries in this specialized field. The countries that frequently publish books are also those that garner a high number of citations. This signifies their pivotal role in knowledge dissemination and the global impact of their research on geopolymer concrete. Hence, this diagram not only showcases the top contributors but also underlines the interconnectedness of global academic communities in advancing sustainable construction practices.

Table 6. Most cited countries

Country	Documents	Citations
Australia	264	11040
India	597	8546
Malaysia	117	3671
China	122	2753
United States	60	2135
Thailand	32	1730
Saudi Arabia	39	1577
Turkey	30	1043
South Korea	20	872
Iraq	54	854

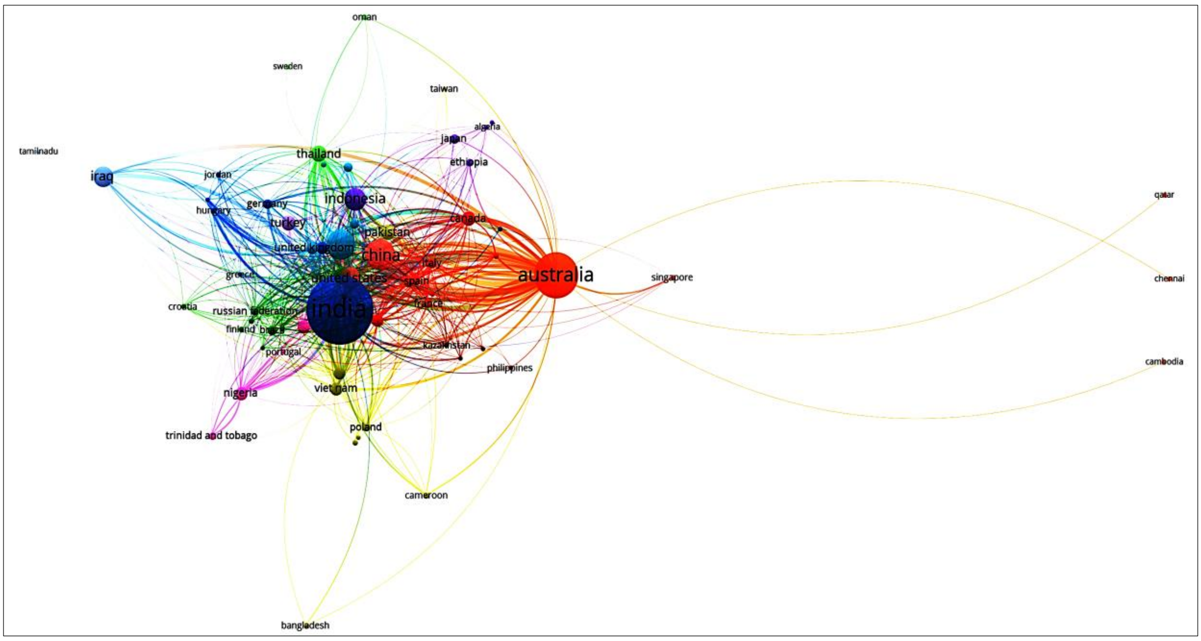


Figure 5. Most cited countries

4.2.3. Co-Citation Analysis

Co-citation analysis, as an automated technique, has a remarkable capability to collate large data sets and, importantly, distinguish when two articles share a common third source. This method is typically employed to gauge the proximity between two works in terms of similarity or thematic overlap [53]. Figure 6 encapsulates the results of the present analysis, offering a snapshot of the co-citation landscape within the selected corpus. Of note in the analysis are three prominent journals. First, the Journal of Cleaner Production, boasting 2247 citations, has proven to be a central hub of knowledge in this field, evidenced by its link strength of 401. This suggests a significant extent of shared sources with other works. Second, Materials and Design Journal, though less cited with 1342 citations, exhibits a substantial link strength of 332, indicating that it too shares many common sources with other publications. The third journal, Construction and Building Materials, offers a compelling case. With 1738 citations and a link strength of 332, it demonstrates a similar level of influence and intertextuality as the other two. This is a testament to the utility of co-citation analysis in providing a holistic view of the academic conversation surrounding a given topic, thereby enabling a better understanding of the interrelationships and intellectual structure of the field.

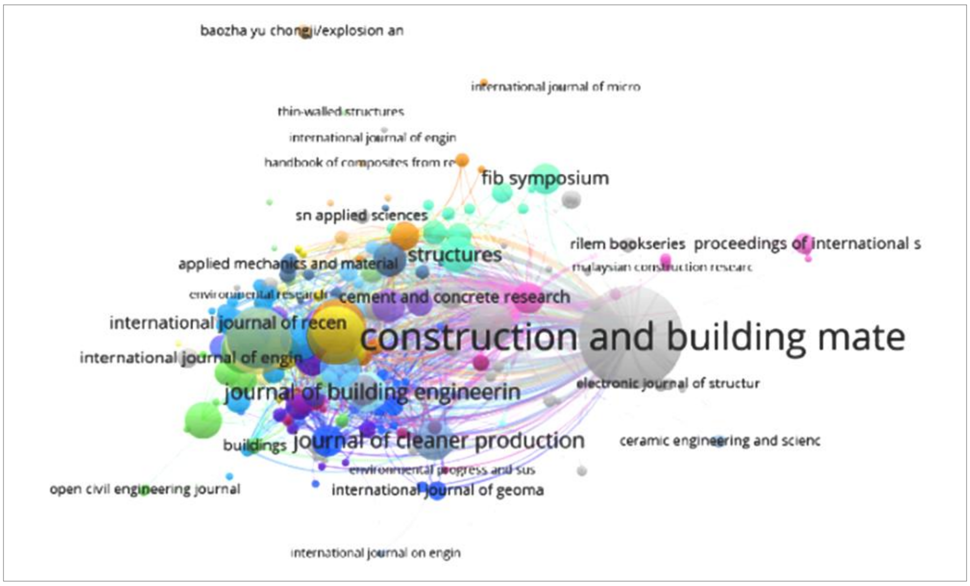


Figure 6. Co-citations of sources

4.3. Co-Authorship Analysis

Authorship analysis and network visualization are unique methods of harnessing citation data to draw connections between esteemed authors and their scientific impacts [54]. This approach enables us to understand the dynamics of academic influence and measure the prominence of key scholars in their respective fields. An application of this methodology led to the identification of 16 most-quoted papers in the area of geopolymer concrete research. Among these, the findings displayed in Figure 5 reveal that the paper penned by Rangan [55] commands the highest respect, being cited a whopping 1554 times. The scholar's contribution has shaped the understanding and development in this area substantially. Close on his heels is Davidovits [56], another recognized figure whose paper has been referenced 1253 times, showing the significant clout he holds in this scientific community. Moving to Figure 7, a network of co-authors is presented, making use of node and edge representations. The size and thickness of a node are proportional to the author's influence in the field, visually portraying the weight of their contributions. The bigger and thicker the node, the more impactful and respected the author is, leading to a deeper understanding of their standing in the field.

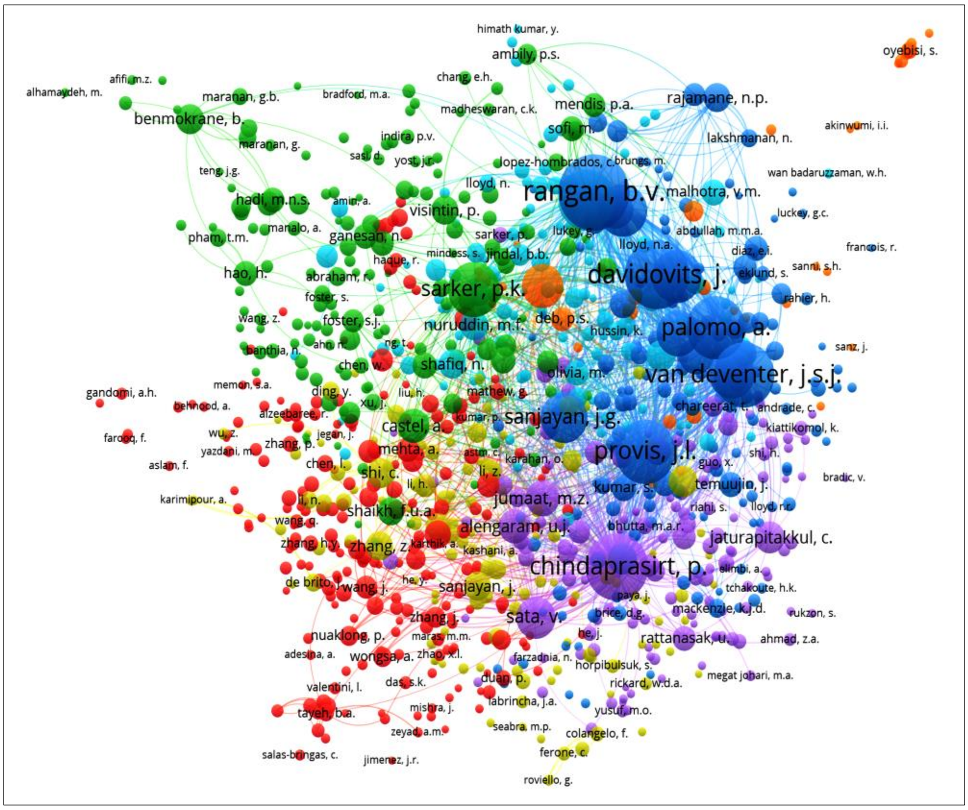


Figure 7. Co-citation of authors

4.4. Keyword Occurrence and Connectivity

The results of a keyword analysis done in VOSviewer are shown in Figure 8. Generally, the keyword analysis was used to make the clusters even more specific and give ideas for new ways to study. After geopolymer concrete, the following most popular areas of study are data analytics, inorganic polymers, geopolymers, and fly ash. These studies give a solid foundation for future research combined with the bibliographical coupling of finding the streams inside geopolymer concrete (Figure 9). In the literature, geopolymer concrete is first discussed in terms of its main properties.

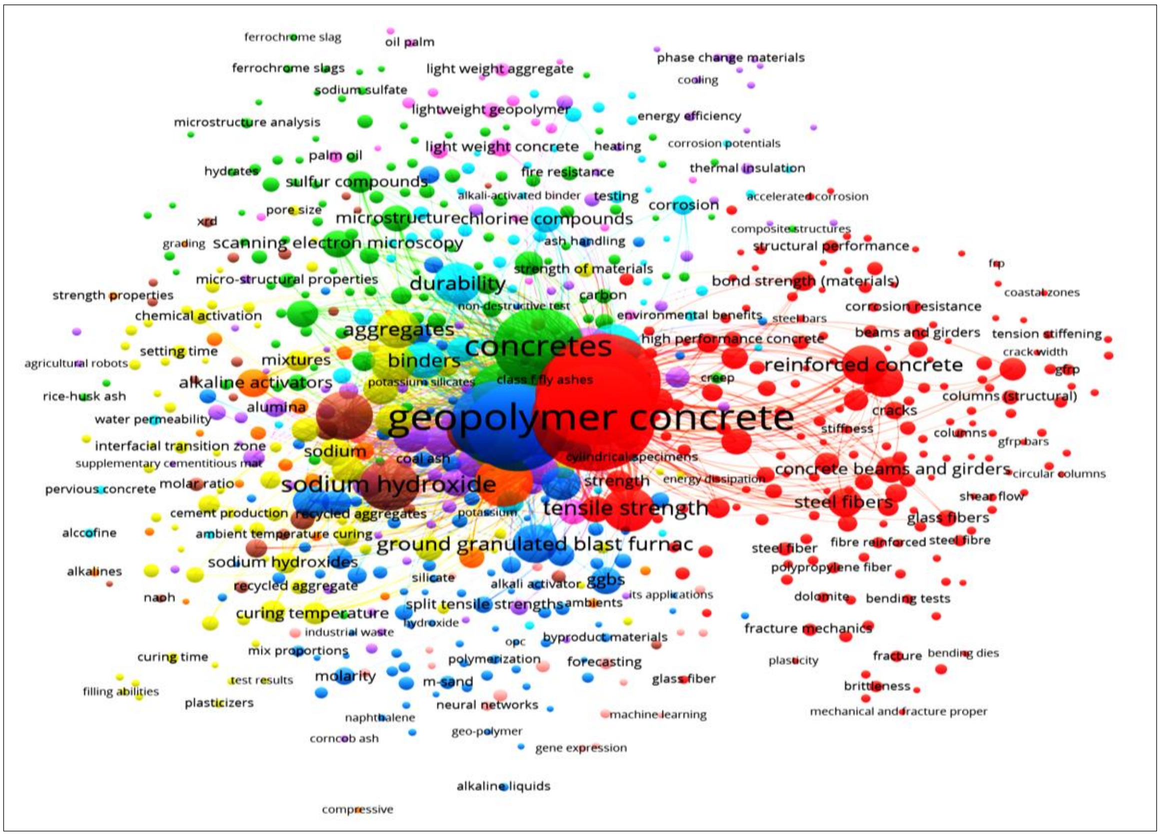


Figure 8. Keyword occurrence and connectivity

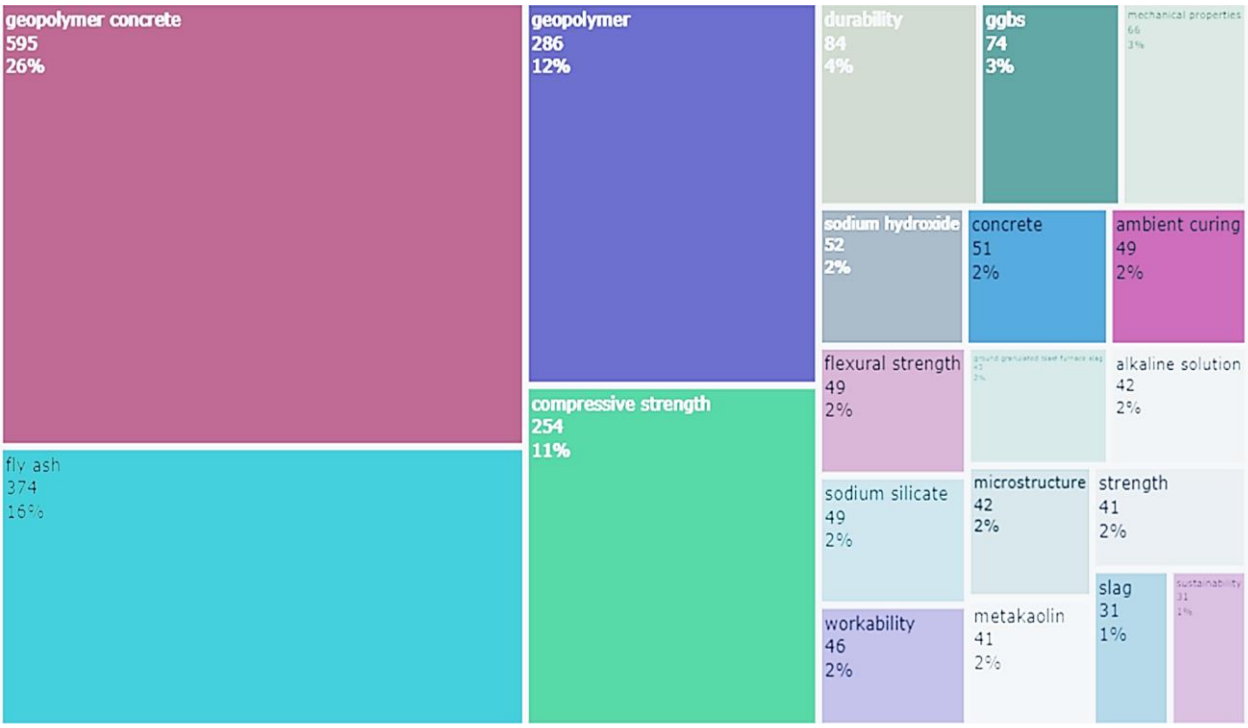


Figure 9. Treemap for the top 20 keywords used by the authors

5. Conclusion

This study embarked on a bibliometric review with the objective of delivering an in-depth examination of the dynamic and burgeoning field of geopolymer concrete. The aim was to unravel its evolution, current trends, and possible future trajectories, offering a comprehensive overview of the topic since its inception in 2003. Rigorous bibliometric analysis allowed for underlining key milestones, mapping research patterns, and highlighting the consistent growth in the field. This growth is exemplified by the surge in geopolymer concrete research, as evidenced by over 1360 annual publications. The geographical distribution of research revealed Australia and India as the primary contributors, marking these regions as crucial hubs of innovation in the geopolymer concrete domain.

The study also uncovered the increasing practical applications of geopolymer concrete, especially within construction processes. This trend is underpinned by extensive research focusing on fly ash, a key component in the manufacture of geopolymer concrete. Furthermore, prevailing research themes were identified, including compressive strength, fly ash, and geopolymer itself, shaping the discourse within the field. This bibliometric review contributes to the field in several ways. Firstly, by providing a comprehensive overview of the research landscape, it elucidates past and present trends in geopolymer concrete research. Secondly, it identifies potential future research areas, such as the exploration of various cement alternatives in combination. Thirdly, by highlighting the growing practical applications of geopolymer concrete, it opens new avenues for its increased use in construction processes. Hence, this review serves not just as a retrospective synthesis but also as a forward-looking guide, underlining potential research directions to foster continued growth in this promising field.

6. Declarations

6.1. Author Contributions

Conceptualization, S.A., J.A., and E.A.; Methodology, J.A. and A.A.; Formal analysis, S.A., J.A., and A.A.; Writing—original draft preparation, S.A. and E.A.; writing—review and editing, J.A. and A.A.; Visualization, S.A., J.A., E.A., and A.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Meyer, C. (2009). The greening of the concrete industry. Cement and Concrete Composites, 31(8), 601–605. doi:10.1016/j.cemconcomp.2008.12.010.

[2] Malhotra, V. M., & Mehta, P. K. (2002). High-performance, high-volume fly ash concrete: materials, mixture proportioning, properties, construction practice, and case histories. Supplementary Cementing Materials for Sustainable Development, Ottawa, Canada.

[3] Lämmlein, T. D., Messina, F., Wyrzykowski, M., Terrasi, G. P., & Lura, P. (2019). Low clinker high performance concretes and their potential in CFRP-prestressed structural elements. Cement and Concrete Composites, 100, 130–138. doi:10.1016/j.cemconcomp.2019.02.014.

[4] Zhang, P., Gao, Z., Wang, J., Guo, J., Hu, S., & Ling, Y. (2020). Properties of fresh and hardened fly ash/slag based geopolymer concrete: A review. Journal of Cleaner Production, 270, 122389. doi:10.1016/j.jclepro.2020.122389.

[5] Nguyen, K. T., Ahn, N., Le, T. A., & Lee, K. (2016). Theoretical and experimental study on mechanical properties and flexural strength of fly ash-geopolymer concrete. Construction and Building Materials, 106, 65–77. doi:10.1016/j.conbuildmat.2015.12.033.

[6] Teh, S. H., Wiedmann, T., Castel, A., & de Burgh, J. (2017). Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia. Journal of Cleaner Production, 152, 312–320. doi:10.1016/j.jclepro.2017.03.122.

[7] Ma, Q., Shi, Y., Xu, Z., Ma, D., & Huang, K. (2022). Research on a multivariate non-linear regression model of dynamic mechanical properties for the alkali-activated slag mortar with rubber tire crumb. Case Studies in Construction Materials, 17, 1371. doi:10.1016/j.cscm.2022.e01371.

[8] Rao, G. M., Kumar, K. S., Poloju, K. K., & Srinivasu, K. (2020). An Emphasis of Geopolymer Concrete with Single Activator and Conventional Concrete with Recycled Aggregate and Data Analyzing using Artificial Neural Network. IOP Conference Series: Materials Science and Engineering, 998(1), 12060. doi:10.1088/1757-899X/998/1/012060.

[9] Benalia, S., Zeghichi, L., & Benghazi, Z. (2022). A Comparative Study of Metakaolin/Slag-Based Geopolymer Mortars Incorporating Natural and Recycled Sands. Civil Engineering Journal, 8(8), 1622-1638. doi:10.28991/CEJ-2022-08-08-07.

[10] Rehman, F., Khokhar, S. A., & Khushnood, R. A. (2022). ANN based predictive mimicker for mechanical and rheological properties of eco-friendly geopolymer concrete. Case Studies in Construction Materials, 17. doi:10.1016/j.cscm.2022.e01536.

[11] Tran, T. T., Pham, T. M., & Hao, H. (2019). Experimental and analytical investigation on flexural behaviour of ambient cured geopolymer concrete beams reinforced with steel fibers. Engineering Structures, 200, 109707. doi:10.1016/j.engstruct.2019.109707.

[12] Yang, H., Liu, L., Yang, W., Liu, H., Ahmad, W., Ahmad, A., Aslam, F., & Joyklad, P. (2022). A comprehensive overview of geopolymer composites: A bibliometric analysis and literature review. Case Studies in Construction Materials, 16, 830. doi:10.1016/j.cscm.2021.e00830.

[13] Zakka, W. P., Abdul Shukor Lim, N. H., & Chau Khun, M. (2021). A scientometric review of geopolymer concrete. Journal of Cleaner Production, 280, 124353. doi:10.1016/j.jclepro.2020.124353.

[14] Matsimbe, J., Dinka, M., Olukanni, D., & Musonda, I. (2022). A Bibliometric Analysis of Research Trends in Geopolymer. Materials, 15(19), 6979. doi:10.3390/ma15196979.

[15] Davidovits, J. (1980). Polymere Mineral, French Patent Application´FR 79.22041 (FR 2,464,227), (1979), and FR 80.18970 (FR2, 489, 290), Mineral polymer, US Patent.

[16] Kashani, A., Ngo, T. D., Walkley, B., & Mendis, P. (2017). Thermal performance of calcium-rich alkali-activated materials: A microstructural and mechanical study. Construction and Building Materials, 153, 225–237. doi:10.1016/j.conbuildmat.2017.07.119.

[17] Sarker, P. K., Haque, R., & Ramgolam, K. V. (2013). Fracture behaviour of heat cured fly ash based geopolymer concrete. Materials & Design, 44, 580–586. doi:10.1016/j.matdes.2012.08.005.

[18] Nodehi, M., & Aguayo, F. (2021). Ultra high performance and high strength geopolymer concrete. Journal of Building Pathology and Rehabilitation, 6(1). doi:10.1007/s41024-021-00130-5.

[19] Irfan Khan, M., Azizli, K., Sufian, S., Khan, A. S., Ullah, H., & Man, Z. (2014). Geopolymers as a Sustainable Binder of 21st Century: A Review. Proceedings of the 4th World Sustainability Forum. doi:10.3390/wsf-4-d010.

[20] Zain, H., Abdullah, M. M. A. B., Hussin, K., Ariffin, N., & Bayuaji, R. (2017). Review on Various Types of Geopolymer Materials with the Environmental Impact Assessment. MATEC Web of Conferences, 97, 1021. doi:10.1051/matecconf/20179701021.

[21] Lakshmi, R., & Nagan, S. (2011). Utilization of waste e plastic particles in cementitious mixtures. Journal of Structural Engineering (Madras), 38(1), 26–35.

[22] Kong, D. L. Y., & Sanjayan, J. G. (2010). Effect of elevated temperatures on geopolymer paste, mortar and concrete. Cement and Concrete Research, 40(2), 334–339. doi:10.1016/j.cemconres.2009.10.017.

[23] Chu, H., Jiang, J., Sun, W., & Zhang, M. (2016). Mechanical and physicochemical properties of ferro-siliceous concrete subjected to elevated temperatures. Construction and Building Materials, 122, 743–752. doi:10.1016/j.conbuildmat.2016.06.104.

[24] Memon, F. A., Nuruddin, M. F., Demie, S., & Shafiq, N. (2012). Effect of superplasticizer and extra water on workability and compressive strength of self-compacting geopolymer concrete. Research Journal of Applied Sciences, Engineering and Technology, 4(5), 407–414.

[25] Shi, X. S., Wang, Q. Y., Zhao, X. L., & Collins, F. (2012). Discussion on Properties and Microstructure of Geopolymer Concrete Containing Fly Ash and Recycled Aggregate. Advanced Materials Research, 450–451, 1577–1583. doi:10.4028/www.scientific.net/amr.450-451.1577.

[26] Posi, P., Teerachanwit, C., Tanutong, C., Limkamoltip, S., Lertnimoolchai, S., Sata, V., & Chindaprasirt, P. (2013). Lightweight geopolymer concrete containing aggregate from recycle lightweight block. Materials & Design (1980-2015), 52, 580–586. doi:10.1016/j.matdes.2013.06.001.

[27] Nuaklong, P., Sata, V., & Chindaprasirt, P. (2016). Influence of recycled aggregate on fly ash geopolymer concrete properties. Journal of Cleaner Production, 112, 2300–2307. doi:10.1016/j.jclepro.2015.10.109.

[28] Deb, P. S., Sarker, P. K., & Barbhuiya, S. (2016). Sorptivity and acid resistance of ambient-cured geopolymer mortars containing nano-silica. Cement and Concrete Composites, 72, 235–245. doi:10.1016/j.cemconcomp.2016.06.017.

[29] Ganeshan, A., & Venkataraman, S. (2017). Self-Consolidating Geopolymer Concrete as an Aid to Green Technologies - Review on Present Status. Asian Journal of Research in Social Sciences and Humanities, 7(3), 510. doi:10.5958/2249-7315.2017.00187.3.

[30] Druta, C. (2003). Tensile strength and bonding characteristics of self-compacting concrete. Master Thesis, Louisiana State University and Agricultural & Mechanical College, Baton Rouge, United States.

[31] Kavitha, O. R., Shanthi, V. M., Arulraj, G. P., & Sivakumar, V. R. (2016). Microstructural studies on eco-friendly and durable Self-compacting concrete blended with metakaolin. Applied Clay Science, 124–125, 143–149. doi:10.1016/j.clay.2016.02.011.

[32] Reddy, C. J., & Elavenil, S. (2017). Geopolymer concrete with self-compacting: A review. International Journal of Civil Engineering and Technology, 8(2), 163–172.

[33] Liu, M. Y. J., Alengaram, U. J., Santhanam, M., Jumaat, M. Z., & Mo, K. H. (2016). Microstructural investigations of palm oil fuel ash and fly ash based binders in lightweight aggregate foamed geopolymer concrete. Construction and Building Materials, 120, 112–122. doi:10.1016/j.conbuildmat.2016.05.076.

[34] Memon, F. A., Nuruddin, M. F., & Shafiq, N. (2013). Effect of silica fume on the fresh and hardened properties of fly ash-based self-compacting geopolymer concrete. International Journal of Minerals, Metallurgy, and Materials, 20(2), 205–213. doi:10.1007/s12613-013-0714-7.

[35] Al-Majidi, M. H., Lampropoulos, A., & Cundy, A. B. (2017). Tensile properties of a novel fibre reinforced geopolymer composite with enhanced strain hardening characteristics. Composite Structures, 168, 402–427. doi:10.1016/j.compstruct.2017.01.085.

[36] Topark-Ngarm, P., Chindaprasirt, P., & Sata, V. (2015). Setting Time, Strength, and Bond of High-Calcium Fly Ash Geopolymer Concrete. Journal of Materials in Civil Engineering, 27(7), 4014198. doi:10.1061/(asce)mt.1943-5533.0001157.

[37] Ahmari, S., & Zhang, L. (2012). Production of eco-friendly bricks from copper mine tailings through geopolymerization. Construction and Building Materials, 29, 323–331. doi:10.1016/j.conbuildmat.2011.10.048.

[38] Khandelwal, M., Ranjith, P. G., Pan, Z., & Sanjayan, J. G. (2013). Effect of strain rate on strength properties of low-calcium fly-ash-based geopolymer mortar under dry condition. Arabian Journal of Geosciences, 6(7), 2383–2389. doi:10.1007/s12517-011-0507-0.

[39] Castel, A. (2017). Bond Between Steel Reinforcement and Geopolymer Concrete. Handbook of Low Carbon Concrete, 375–387, Butterworth-Heinemann, Oxford, United Kingdom. doi:10.1016/b978-0-12-804524-4.00014-2.

[40] Yusuf, M. O., Megat Johari, M. A., Ahmad, Z. A., & Maslehuddin, M. (2015). Impacts of silica modulus on the early strength of alkaline activated ground slag/ultrafine palm oil fuel ash based concrete. Materials and Structures/Materiaux et Constructions, 48(3), 733–741. doi:10.1617/s11527-014-0318-3.

[41] Sumajouw, D.M.J., Hardjito, D., Wallah, S.E., & Rangan, B. V., (2004). Geopolymer concrete for a sustainable future. Green Processes Conference. Fremantle, Australia.

[42] Hardjito, D., Wallah, S. E., Sumajouw, D. M. J., & Rangan, B. V. (2005). Introducing fly ash-based geopolymer concrete: manufacture and engineering properties. 30th conference on our world in concrete & structures, 23-24 August. 2005, Singapore.

[43] Hardjito, D., Cheak, C. C., & Lee Ing, C. H. (2008). Strength and Setting Times of Low Calcium Fly Ash-based Geopolymer Mortar. Modern Applied Science, 2(4), 3–11. doi:10.5539/mas.v2n4p3.

[44] Alrawashdeh, N., Alsmadi, A. A., & Al-Gasaymeh, A. (2022). FinTech: A Bibliometric Analysis for the Period of 2014-2021. Quality - Access to Success, 23(188), 176–188. doi:10.47750/QAS/23.188.24.

[45] Alshater, M. M., Atayah, O. F., & Khan, A. (2022). What do we know about business and economics research during COVID-19: a bibliometric review. Economic Research, 35(1), 1884–1912. doi:10.1080/1331677X.2021.1927786.

[46] Pritchard, A. (1969). Statistical Bibliography or Bibliometrics. Journal of Documentation, 25, 348.

[47] Hota, P. K., Subramanian, B., & Narayanamurthy, G. (2020). Mapping the Intellectual Structure of Social Entrepreneurship Research: A Citation/Co-citation Analysis. Journal of Business Ethics, 166(1), 89–114. doi:10.1007/s10551-019-04129-4.

[48] Lezama-Nicolás, R., Rodríguez-Salvador, M., Río-Belver, R., & Bildosola, I. (2018). A bibliometric method for assessing technological maturity: the case of additive manufacturing. Scientometrics, 117(3), 1425–1452. doi:10.1007/s11192-018-2941-1.

[49] van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics, 84(2), 523–538. doi:10.1007/s11192-009-0146-3.

[50] Hardjito, D., Wallah, S. E., Sumajouw, D. M. J., & Rangan, B. V. (2004). On the development of fly ash-based geopolymer concrete. ACI Materials Journal, 101(6), 467–472. doi:10.14359/13485.

[51] Singh, B., Ishwarya, G., Gupta, M., & Bhattacharyya, S. K. (2015). Geopolymer concrete: A review of some recent developments. Construction and Building Materials, 85, 78–90. doi:10.1016/j.conbuildmat.2015.03.036.

[52] Nath, P., & Sarker, P. K. (2014). Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. Construction and Building Materials, 66, 163–171. doi:10.1016/j.conbuildmat.2014.05.080.

[53] Small, H. (1999). Visualizing science by citation mapping. Journal of the American Society for Information Science, 50(9), 799–813. doi:10.1002/(SICI)1097-4571(1999)50:9<799::AID-ASI9>3.0.CO;2-G.

[54] Pattnaik, D., Hassan, M. K., Kumar, S., & Paul, J. (2020). Trade credit research before and after the global financial crisis of 2008 – A bibliometric overview. Research in International Business and Finance, 54, 101287. doi:10.1016/j.ribaf.2020.101287.

[55] Rangan, B. V. (2014). Geopolymer concrete for environmental protection. The Indian Concrete Journal, 88(4), 41-59.

[56] Davidovits, J. (1991). Geopolymers - Inorganic polymeric new materials. Journal of Thermal Analysis, 37(8), 1633–1656. doi:10.1007/BF01912193.