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Performance of Hybrid Fiber Reinforced Geopolymer Composites: Scientometric and Conventional Review

Maryam Firas Al-Baldawi[1], Farah Nora Aznieta Abdul Aziz[1]*, Al Ghazali Noor Abbas[1], Noor Azline Mohd Nasir[1] and Norsuzailina Mohamed Sutan[2]

[1]*Housing Research Centre (HRC), Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[2]*Department of Civil Engineering, Faculty of Engineering, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia*

ABSTRACT

Hybrid fibers are an interesting addition to reinforce geopolymer-based composites due to their advantages over single-fiber reinforcement. The performance of hybrid fibers is dependent on the fibers' composition, type, properties, length, and volume fraction. Therefore, this review discusses the state-of-the-art hybrid fiber-reinforced geopolymer composites (HFRGC) through two approaches: scientometric analysis and conventional review of HFRGC based on data extracted from Scopus from 2013 until 2023. The scientometric analysis was carried out by adopting VOS Viewer software and focuses on the annual publication of documents, top publication sources, co-occurrence keywords, researchers, top-cited papers, and countries. In contrast, the desk study refers to experimental data on the fresh properties and compressive, tensile, and flexural properties of HFRGC. This review output aids researchers in networking, promoting cooperative research, exchanging ideas, and creating joint ventures among researchers of HFRGC worldwide. The performance of HFRGC obtained from the desk study showed the potential of HFRGC as an option for a greener composite that will benefit the construction industry.

Keywords: Fresh properties, geopolymer concrete, hybrid fiber, mechanical properties, Scientometric analysis

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E-mail addresses:
mariamfiras436@gmail.com (Maryam Firas Al-Baldawi)
farah@upm.edu.my (Farah Nora Aznieta Abdul Aziz)
na706050@gmail.com (Al-Ghazali Noor Abbas)
nazline@upm.edu.my (Noor Azline Mohd Nasir)
msnorsuzailina@unimas.my (Norsuzailina Mohamed Sutan)
*Corresponding author

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INTRODUCTION

Geopolymer is a type of inorganic substance that forms a polymeric structure made of by-product materials or waste materials like fly ash and slag that consist of aluminum (Al) and silicon (Si) as binders when reacting with an alkaline activator (Yang et al., 2022b, 2022a). Geopolymer composites (GPC) exhibit high mechanical strength and durability (Amran et al., 2021). These significant features include low porosity, high early strength (Lan et al., 2022), high performance in sulfate and acid environments (Zhao et al., 2021), high-temperature resistance, low energy utilization, and the release of less pollution during manufacture (Valente et al., 2021), making these composites a viable candidate for a variety of industrial applications. However, these composites are brittle materials with poor tensile strength. Incorporating fibers into geopolymers can enhance their durability by augmenting the toughness of the composites (Li et al., 2022).

Short and randomly dispersed fibers impact the cracking behavior, regulate the brittle fracture process, and enhance the toughness post-cracking (Abbas et al., 2022). A variety of fiber types, including synthetic and natural fibers, are widely used in geopolymer technology (Kozub et al., 2021; Silva et al., 2020). Each type of these fibers is divided into different categories, as illustrated in Figure 1. Synthetic fiber has distinguished properties such as excellent tensile strength, an extraordinary strength-to-weight ratio, electrical conductivity, and fatigue stability (Farooq et al., 2019).

Natural fibers are easily accessible, and renewable resources are widely available in several places. They possess the advantages of being biodegradable and low-cost. Many attempts have been made to increase the toughness and ductility of GPC by using different kinds of short filaments (Firas et al., 2024; Ramamoorthy et al., 2015).

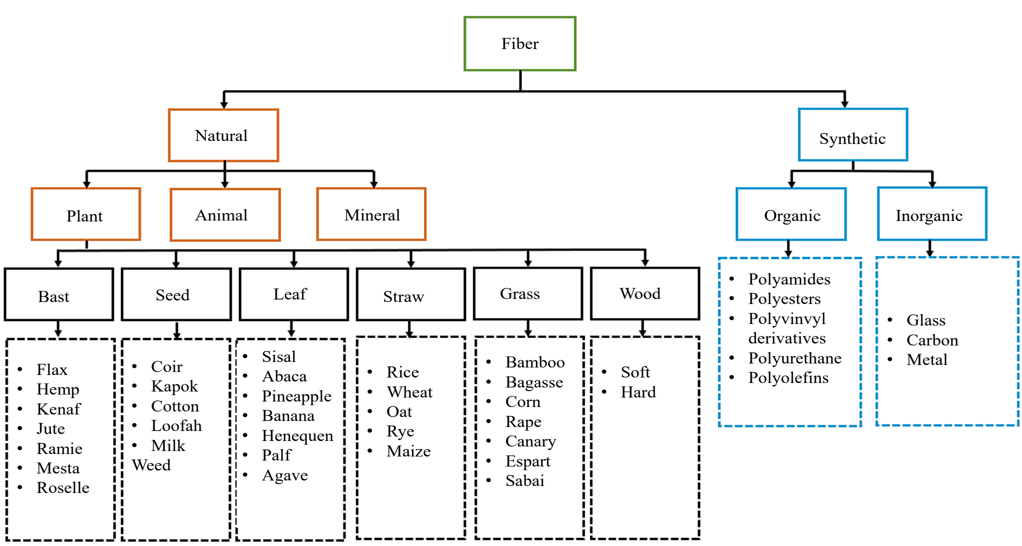


Figure 1. Classification of fibers according to their sources

Conventional fiber-reinforced concrete components only utilize a single kind of fiber. A single fiber possesses utility only within a restricted spectrum of strain and propagation of cracks. Consequently, a specific variety of fiber can enhance the strength or ductility of concrete composites. Steel, glass, polyvinyl alcohol, carbon, and asbestos fibers are examples of high-modulus and high-strength fibers that can efficiently increase the strength of geopolymer (Soe et al., 2013). Nevertheless, their inherent brittleness prevents significant enhancement in ductility. Low-strength fibers, such as polypropylene, nylon, and acrylic fibers, have greater efficacy in enhancing ductility and mitigating cracking (Pakravan et al., 2017).

As a result, mixing fibers with different chemical and mechanical properties is necessary for producing GPC with higher strength and ductility. Utilizing an appropriate combination of two or more fiber types can enhance the overall properties of concrete and synergistic performance (Feng et al., 2021). The combination of fibers is often known as hybridization (Geboes et al., 2022).

Therefore, lately, the majority of studies have been focused on utilizing different kinds of fiber in a geopolymer matrix to create hybrid composites, where the superior engineering properties of one fiber support the defects in the other type of fiber in the composite (Taghipoor & Sadeghian, 2022). Hybridization improves the mechanical characteristics of concrete to prevent cracks more effectively than single fiber-reinforced concrete. Incorporating two distinguished fibers leads to materials with distinctive properties (Alwesabi et al., 2022; Kan et al., 2020).

Bakthavatchalam and Rajendran (2021) stated that incorporating hybrid fiber steel and basalt fibers in a geopolymer matrix with the appropriate percentage could enhance the compressive, tensile, and flexural strength characteristics. Hybrid fibers improve the mechanical properties of the material by bridging cracks and distributing stress more uniformly, thereby inhibiting the propagation of cracks. Moreover, chopped basalt fiber has a great strength capability with concrete. Various hybridization systems depend on variations in several factors, like the fibers' diameter, length, and tensile strength. For instance, short fiber can prevent diffusion of the microcracks and then improve the strength of concrete, while long fiber can be effective in large-size cracks, hence improving the whole fiber's role in the concrete matrix (Chen et al., 2021a). Hence, in the hybrid composite, when one type of fiber fails, the load will transfer to another, making the composites depend on each other (Sapiai et al., 2020).

Traditional literature reviews are inadequate and subjected to prejudice in establishing an integrated and systematic correlation among multiple domains of investigation. The bibliometric analysis technique displays the current level of advancement of knowledge in different fields of science, providing data on the most active researchers and countries and providing an understanding of prior periods and future forecasts of research fields globally (Zakka et al., 2021). Numerous scientists have done bibliometric evaluations of geopolymers across various academic disciplines. As an illustration, Matsimbe et al. (2023) conducted a bibliographic analysis of geopolymer research in the Sub-Saharan Africa region, utilizing Vos viewer software. The study results indicated that the phrases with the greatest frequency of appearances were geopolymers, inorganic polymers, and compressive strength. Moreover, the Construction and Building Materials magazine was generally recognized as a major academic publication, publishing 41 articles and boasting a substantial citation record of approximately 1488. Cameroon, Nigeria, and South Africa were the states that demonstrated the highest volume of documents.

Gu et al. (2022) carried out a scientometric analysis and research mapping to investigate the current understanding of the application of coconut fibers in concrete. The findings revealed that the leading journal is "Construction and Building Materials," with 21 articles, while India, Malaysia, and New Zealand have made contributions of 41, 28, and 20 articles. Another study was conducted by Amin et al. (2022) on an analysis of scientific publications and knowledge visualization on the topic of steel fiber-reinforced concrete. The analysis revealed that 17 sources, including journals and conferences, have published a minimum of 100 articles on SFRC until June 2022. Alkadhim et al. (2022) conducted a research investigation on a scientometric review to analyze the knowledge mapping of the published research about fiber-reinforced geopolymers. The scientometric study revealed the commonly utilized keywords in FRGC (Fiber Reinforced Geopolymer Composites) research, which include inorganic polymers, geopolymers, reinforcement, geopolymer, and compression strength. Besides, it is worth noting that 27 authors have contributed to the body of literature on FRGC by publishing more than ten papers. Moreover, as of June 2022, a noteworthy 29 articles have garnered over 100 citations, indicating their significant impact within the field.

Despite existing reviews and bibliometric analyses, there is a noticeable absence of bibliometric studies about hybrid fiber-reinforced geopolymer composites. The lack of data relates to keyword searches that are not expansive enough to produce a comprehensive dataset. Therefore, there is a demand for an unbiased and more objective visual representation of the patterns and developments in this particular domain. The current study employed two approaches: a scientometric analysis of the bibliometric data and a normal review of the HFRGC. This research summarizes the studies carried out over the last decade using maps for bibliometric data to assess research development over the last ten years. The conventional review consists of the fresh and mechanical properties of HFRGC. On the other hand, a scientometric analysis sequence for bibliometric data is used in this study to present contemporary and elaborated analysis for previous studies in the area of hybrid fiber-reinforced geopolymer composites. A scientometric analysis is developed to analyze the yearly distribution and growth tendency and number of documents based on countries, keywords, sources, and citations of the HFRGC field, carried out using VOS viewer. The methodology of this review is addressed in Figure 2.

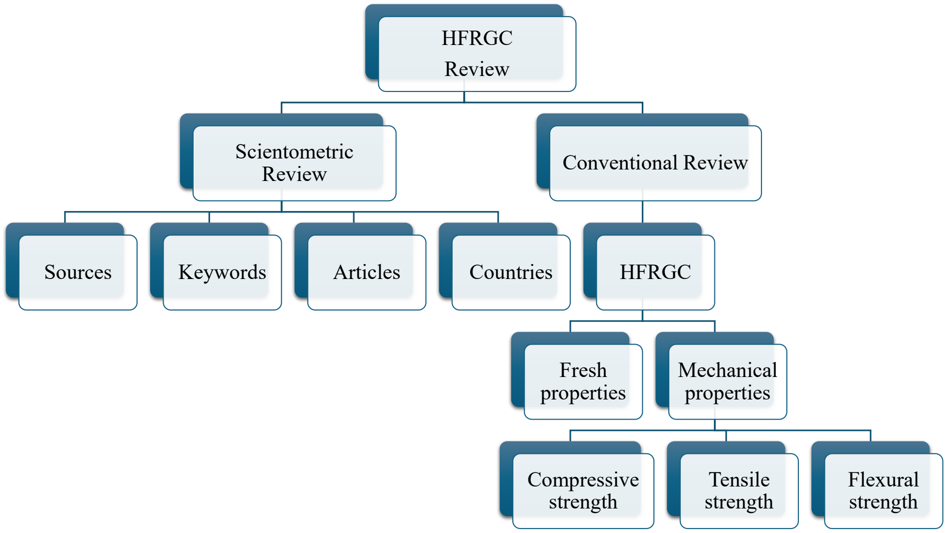


Figure 2. A schematic depicting the scientometric and conventional approaches will be covered in this review

RESEARCH STRATEGY AND DATA SOURCES OF HFRGC

The present study utilized a scientometric strategy-based review of HFRGC to evaluate scientific results and produce bibliometric geographical maps. The chosen methodology is suitable for this review since it methodically examines and evaluates the study's progress over a particular timeframe, utilizing a thorough collection of bibliographic data. (Hosseini et al., 2018). Numerous academic papers were published regarding the subject area, so selecting a dependable search tool is imperative. Scopus and WOS are renowned search platforms for their high accuracy, making them appropriate for this particular objective (Chadegani et al., 2013).

The bibliographical data related to the study on HFRGC was obtained using Scopus, a highly recommended academic resource (Meho, 2019). Nees Jan VanEck and Ludo Waltman developed VOS Viewer, a commonly employed program for data visualization. The system can build visual representations of researchers, journals, papers, and keywords by utilizing citation and co-occurrence data (van Eck & Waltman, 2021). Table 1 presents the criteria for obtaining data from Scopus between 2013 and October 2023.

The analysis focuses on the yearly publication of papers, Science visualization of top publication sources, science visualization of co-occurrence keywords, researchers, top-cited papers, and participating countries. The searched phrases in the Scopus library of "geopolymer" and "hybrid fiber" or "hybrid fiber" had successfully generated 90 from 98 articles as of October 2023 after using filtration by eliminating unnecessary documents. The limitation of the language was stated as the English language. The research focused on engineering and material science to facilitate a more comprehensive study. The information acquired via the Scopus collection has been saved in the Comma Separated Values (CSV) form to simplify evaluation by employing a suitable computer program. The scientific map and visualization software employed in this work was VOSviewer (version 1.6.17). Figure 3 depicts a schematic diagram that represents the scientometric approach.

Table 1
A filter is used to obtain data from the Scopus database web page

Option	Filter used
Publication date	2013–2023
Language	English
Subject area	Material Science Engineering

SCIENTOMETRIC ANALYSIS RESULTS AND DISCUSSIONS

Subject Area and Annual Publication of Documents

The evaluation was conducted utilizing the Scopus database to determine the relevant research areas. Figure 4 illustrates that "Engineering" and "Materials Science"

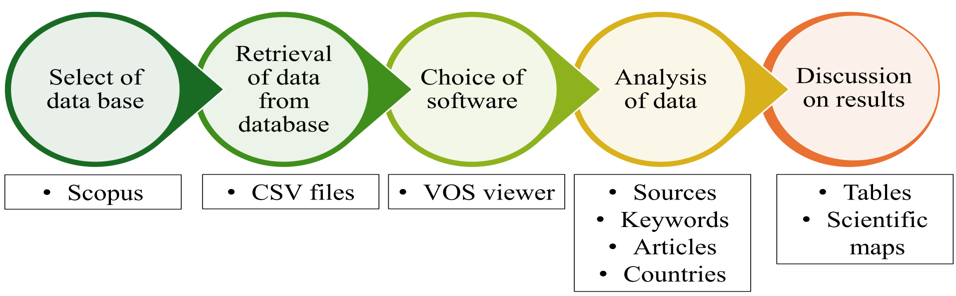


Figure 3. The sequential process of scientometric analysis employed in the present study

were the two subject areas that produced the most documents, with 42.08% and 34.97% of publications, respectively, resulting in a total of 77.05% of paperwork. Moreover, the Scopus search engine was used to search for the sources that included the paperwork in related areas of study (Figure 5). According to this analysis, articles, conference reviews, conference papers, book chapters, and reviews comprised around 58.16%, 18.37%, 15.31%, 4.08%, and 4.08% of the entire information, respectively. Figure 6 illustrates the yearly growth of the documents published in the present field of research between 2003 and October 2023, as the fresh document related to this research area was found in 2003. Based on the research done by Chen et al. (2022), the yearly number of papers can measure the trajectory of advancement within an area of interest. The data demonstrates a fluctuating pattern of studies conducted on HFRGC based on the Scopus document database between 2003 and 2023. There was a significant increase to 17 documents in 2018 from 7 in 2017. However, this trend was interrupted by a decline to 9 documents in

2019, indicating a temporary reduction. Following that, there was a slight increase to 10 documents in 2020. The year 2021 defined a notable upswing, reaching 17 documents, demonstrating a significant increase in academic output. However, this upward trajectory was not sustained, as evidenced by a reduction to 14 documents in 2022, indicating a slight downturn. Nevertheless, academic productivity rebounded in 2023, with a significant rise to 20 documents, representing a peak in research output for the analyzed period. The academic community has demonstrated a notable emphasis on the utilization of HFRGC in construction materials.

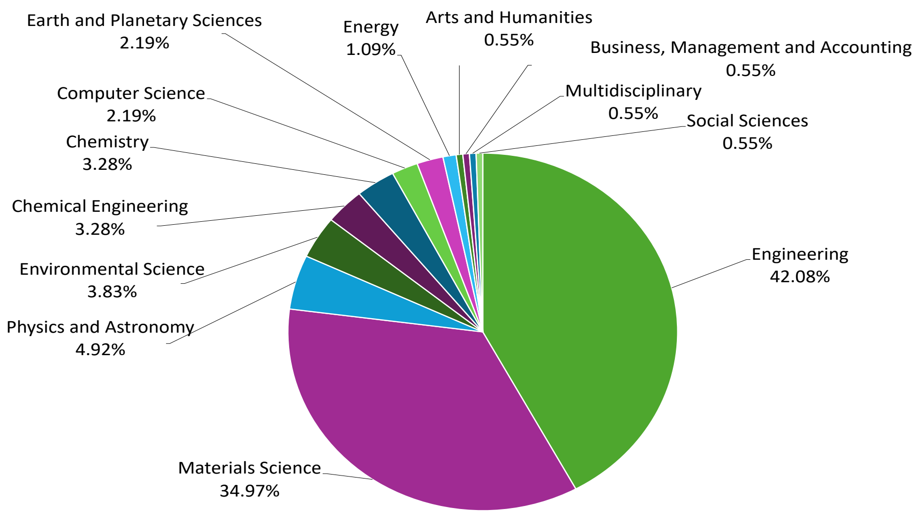


Figure 4. Subject area of documents published on HFRGC (Scopus database)

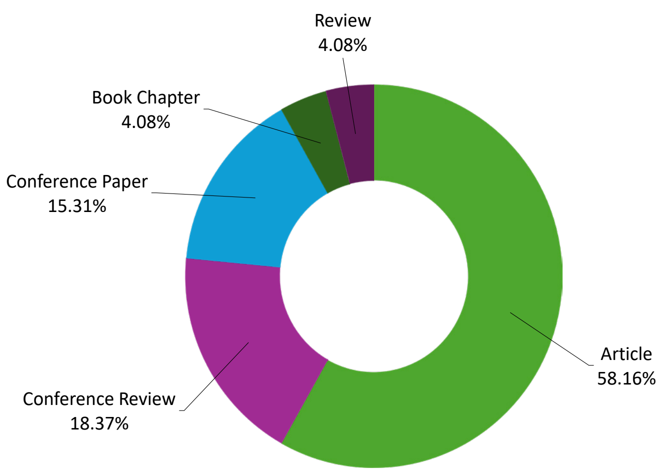


Figure 5. Types of documents released on HFRGC (Scopus database)

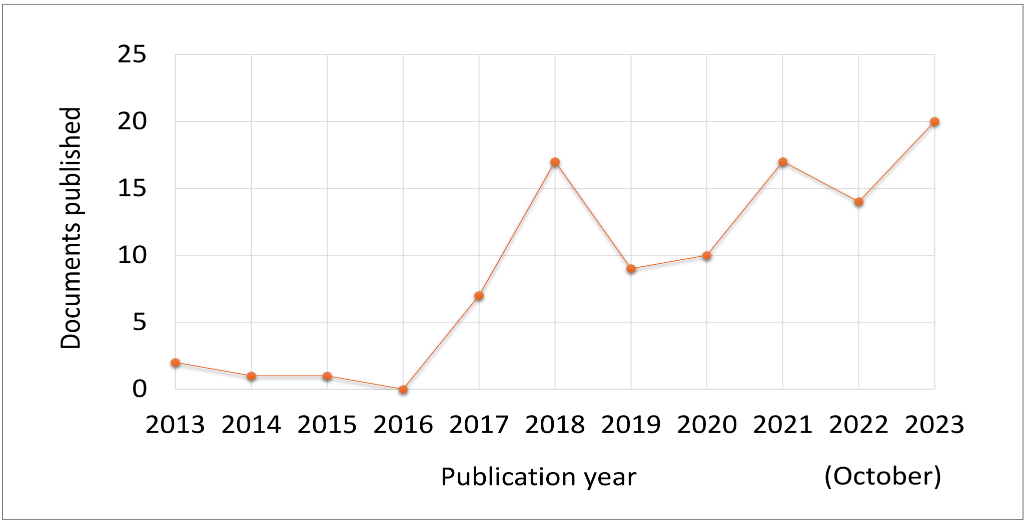


Figure 6. Annual publication of hybrid fiber reinforced geopolymer composites documents (Scopus database)

Top Publication Sources

The application of source mapping techniques promotes the analysis of growth and innovation. These sources provide the ability to access data that has some specified limitations. The research was conducted via the VOSviewer program, which employed bibliometric data from Scopus. The chosen analytical approach for this study was bibliographic coupling, whereas the selected type of analysis was sources. The minimal number of documents necessary from a source has been established to be 1, and all 42 publications fulfilled this requirement. A journal's impact can be evaluated by analyzing its overall link strength, the number of documents it has released, and its citation count, as shown in Table 2. The scientific journals "Construction and Building Materials," "Lecture Notes in Civil Engineering," and "Materials" are the most prolific three publication sources, with 15, 10, and 5 articles, respectively. The academic journals listed, specifically "Construction and Building Materials," "Lecture Notes in Civil Engineering," and "Materials," have been cited 441, 4, and 34, respectively. Furthermore, this investigation would establish a framework for future scientometric questions in HFRGC research. Moreover, prior conventional assessments could not generate visual representations of scientific maps.

The network representation in Figure 7(A) depicts the recently published journals. The journal's influence on the number of documents within the current research area is expressed by the node's dimensions; a larger node signifies a more significant impact. A noteworthy observation is that the category labeled "Construction and Building Materials" exhibited a bigger node size compared to the other categories, revealing its heightened significance as a source within the field of research. The artwork comprised six interconnected clusters, each represented by a separate color palette: red, green, dark blue, light blue, yellow, and purple. Groups are established according to the scope of study sources or the frequency with which each source is referenced in related academic papers (Wuni et al., 2020).

The degree of connection between the research sources indicates the volume of documents within the current study domain that exhibit co-citations. Moreover, quantifying connection strength offers valuable insights into the frequency with which two academic journals are cited in the same scientific publication. As an illustration, the construction and building materials field exhibited a higher number of citations than other study areas, with a link strength of 23. The relationships among the nodes in a cluster situated close together are more powerful compared to those that are farther distant. For instance, "Construction and Building Materials" is directly linked to the "Journal of Materials in Civil Engineering" rather than "Case Studies in Construction Materials."

The colors in Figure 7(b) corresponded to the densities observed in a scholarly publication. The primary color is red, with yellow, green, and blue denoting the decreasing concentration. The bright red color of "Construction and Building Materials" represented the more significant importance of the current research.

Table 2
Top sources based on the number of documents

No.	Source	Documents	Citations	Total link strength
1	Construction and building materials	15	441	23
2	Lecture Notes in Civil Engineering	10	4	2
3	Materials	5	34	42
4	Journal of Composites Science	3	31	48
5	Polymers	3	14	37
6	Materials Today: Proceedings	3	27	4
7	Cement and Concrete Composites	2	64	20
8	Buildings	2	21	7
9	Ceramics International	2	37	5
10	Composite Structures	2	49	2

Source: Table generated by VOS viewer according to Scopus database

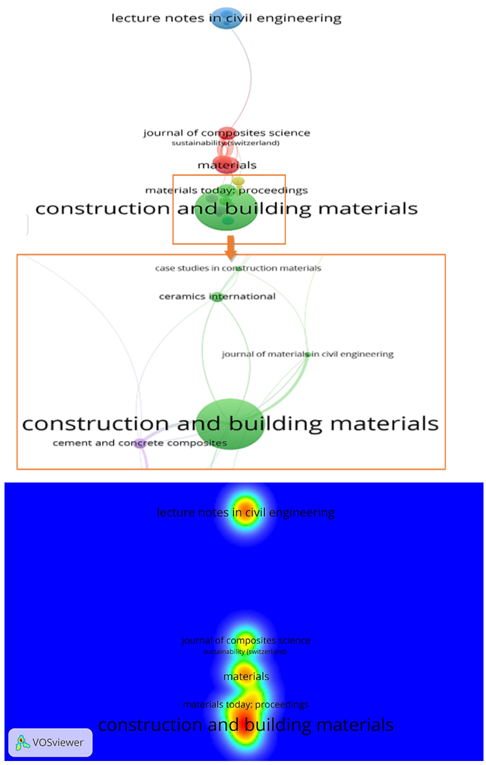


Figure 7. Science mapping of publication sources: (a) Network visualization; (b) Density visualization (Figure generated by VOS viewer according to Scopus database as a result of analysis)

Frequently Used Keywords

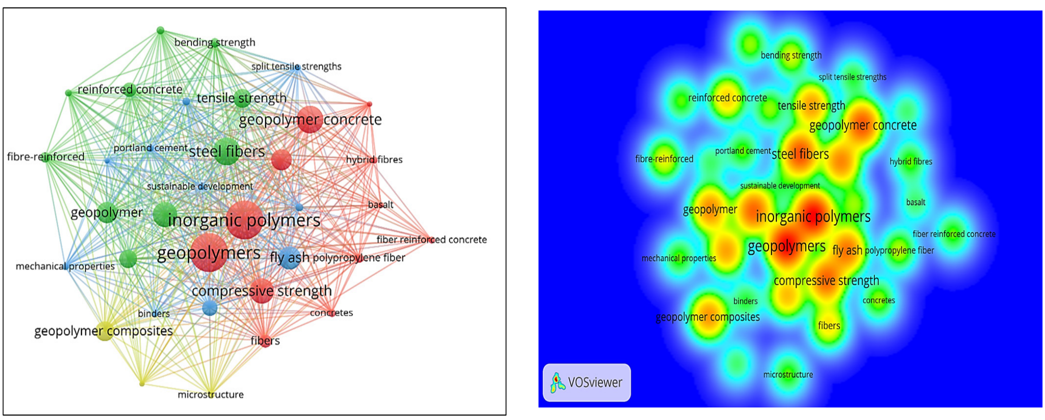
Keywords are essential elements of scholarly materials as they serve to recognize and represent the basic topic of the investigation. (Su & Lee, 2010). For evaluation, the method of analysis is "co-occurrence," with the unit of analysis defined as "all keywords." The minimal frequency of a keyword's occurrence was specified as 5, and only 48 of the 638 keywords met the condition. Table 3 shows the top 10 most frequently used keywords in this area. The top five most repeated in the related documents were inorganic polymers, geopolymers, steel fibers, geopolymer concrete, and hybrid fiber, with 51, 51, 35, 34, and 31 occurrences, respectively. The visual depiction of the primary keywords within the research topics is presented in Figure 8(a). The network visualization revealed the presence of four distinct groups: red, green, blue, and yellow. The larger node referred to the most important keywords and repeated more than other node sizes in the related publication documents. The various colors in Figure 8(b) represent the dense concentration of keywords. The colors red, yellow, green, and blue were arranged in increasing order based on their respective densities, with red having the highest density and blue having the lowest density. For instance, density visualization indicates that inorganic polymers and geopolymers had a higher density. This discovery will assist aspiring authors in choosing keywords that may improve access to previously published work in a specific subject area.

Table 3
Top 10 common keywords in publication articles

No.	Keyword	Occurrences	Total link strength
1	Inorganic polymers	51	537
2	Geopolymers	51	530
3	Steel fibers	35	357

Table 3 *(Continue)*

No.	Keyword	Occurrences	Total link strength
4	Geopolymer concrete	34	331
5	Hybrid fiber	31	322
6	Compressive strength	31	322
7	Fly ash	28	294
8	Polypropylenes	25	285
9	Geopolymer	25	237
10	Geopolymer composites	23	216



(a) (b)

Figure 8. Science mapping of mostly used keywords: (a) Network visualization; (b) Density visualization (Figure generated by VOSviewer according to Scopus database as a result of analysis)

Science Mapping of Published Articles

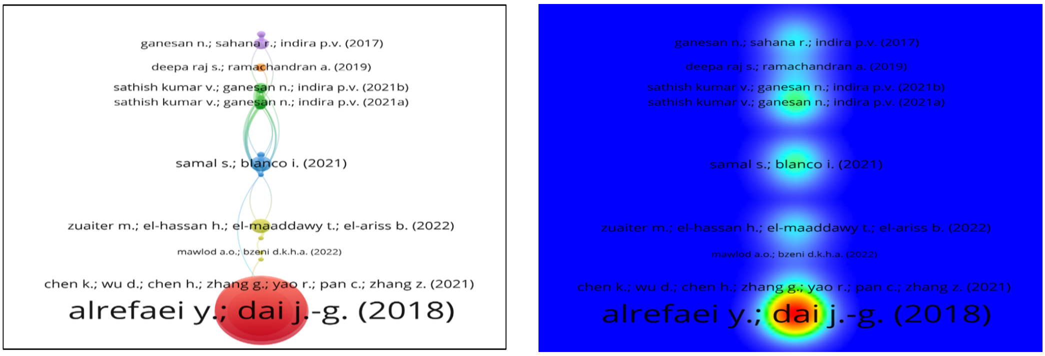
The total number of citations garnered by a scholarly text provides an indicator of its importance within the field of academic investigation. In this analysis in the VOS viewer, bibliographic coupling was set as the type of analysis, and documents were set as the unit of analysis. Table 4 displays a comprehensive collection of the top 10 papers with the highest citations in the hybrid fiber-reinforced geopolymer composites domain.

Table 4 includes pertinent information, such as the authors' names and essential citation details. The article titled "Tensile behavior and microstructure of hybrid fiber ambient-cured one-part engineered geopolymer composites" by Alrefaei and Dai (2018) received 114 citations, the most cited works in the field. Sukontasukkul et al. (2018) and Guo et al. (2020) have garnered significant attention, with 111 and 92 citations among the top three most cited works. Figure 9(a) illustrates the citation-based map of relevant publications, highlighting the clustering of these works within the scope of the current research topic. The findings of the inquiry revealed that a collective sum of 41 papers were interlinked via citations. In addition, Figure 9(b) illustrates the density mapping, highlighting the concentration of publications with greater citations in red for Alrefaei and Dai (2018).

Table 4
Higher cited documents of hybrid fiber geopolymer composites

No.	Document	Title	citations	Links
1	Alrefaei and Dai (2018)	Tensile behavior and microstructure of hybrid fiber ambient cured one-part engineered geopolymer composites	114	10
2	Sukontasukkul et al. (2018)	Flexural performance and toughness of hybrid steel and polypropylene fiber-reinforced geopolymer	111	1
3	Guo et al. (2020)	Sulfate resistance of hybrid fiber-reinforced metakaolin geopolymer composites	92	0
4	Asrani et al. (2019)	A feasibility of enhancing the impact resistance of hybrid fibrous geopolymer composites: Experiments and modeling	76	4
5	Khan et al. (2019)	Mechanical properties and behavior of high-strength plain and hybrid-fiber reinforced geopolymer composites under dynamic splitting tension	63	12
6	Gao et al. (2017)	Evaluation of hybrid steel fiber reinforcement in high-performance geopolymer composites	54	0
7	Tran et al. (2020)	Effect of hybrid fibers on shear behavior of geopolymer concrete beams reinforced by basalt fiber reinforced polymer (BFRP) bars without stirrups	48	4
8	Khan et al. (2018)	Mechanical properties of ambient cured high-strength plain and hybrid fiber reinforced geopolymer composites from triaxial compressive tests	48	0
9	Su et al. (2019)	Influence of different fibers on properties of thermal insulation composites based on geopolymer blended with glazed hollow bead	43	8
10	Chithambar Ganesh and Muthukannan (2019)	Experimental Study on the Behavior of Hybrid Fiber Reinforced Geopolymer Concrete under Ambient Curing Condition	40	1

Source: Table generated by VOSviewer according to Scopus database as a result of analysis



(a) (b)

Figure 9. Science mapping for higher citation documents: (a) Network visualization; (b) Density visualization (Figure generated by VOSviewer according to Scopus database as a result of analysis)

Science Mapping of Contributing Countries

Some countries have exhibited greater participation and continued achievements in HFRGC than others. The development of the network visualization was designed to offer readers a graphical depiction of the distinct areas focused on the study domain. The analysis method employed in this study was bibliographic coupling, with the unit of analysis representing countries. The minimal threshold for the number of documents restricted to a certain country was established at 1, and 27 donations met this criterion. The nations listed in Table 5 have produced at least ten publications in the specified topic of study. The countries that contributed the greatest number of papers were India, China, and Australia, with 35, 15, and 12 documents, respectively. Furthermore, it is noteworthy that the three nations that garnered the greatest number of citations were India, China, and Australia, with citation counts of 333, 378, and 266, respectively. The quantification of publications, citations, and total link strength served as an indicator of the extent to which every country has exerted an impact on the development of the subject field.

In Figure 10(a), the visualization presented illustrates the interconnectedness of nations through the medium of citations in the field of science. The size of a node is indicative of a nation's level of contribution to the field of research. The visualization network revealed the presence of four distinct groups of countries, each distinguished by its unique color. According to the data presented in Figure 10(b), countries exhibiting greater involvement were found to have a higher population density. Employing visuals and extensive data records pertaining to all participating nations will considerably facilitate young researchers in cultivating scientific relationships, initiating joint activities, and exchanging novel methodologies and ideas. Scientists from different nations who have an appetite for improving the study of HFRGC have the chance to collaborate with established experts in this field. Through these collaborations, researchers can gain important insights and benefit from these experts' deep understanding and expertise.

Table 5
Top 10 countries active in the related area

No.	Country	Documents	Citations	Total link strength
1	India	35	333	1118
2	China	15	378	501
3	Australia	12	266	885
4	Croatia	5	52	571
5	Pakistan	3	117	537
6	Iraq	3	20	89
7	United Arab Emirates	3	31	20
8	Saudi Arabia	2	12	619
9	Russian Federation	2	15	341
10	Poland	2	17	330

Source: Table generated by VOSviewer according to Scopus database as a result of analysis

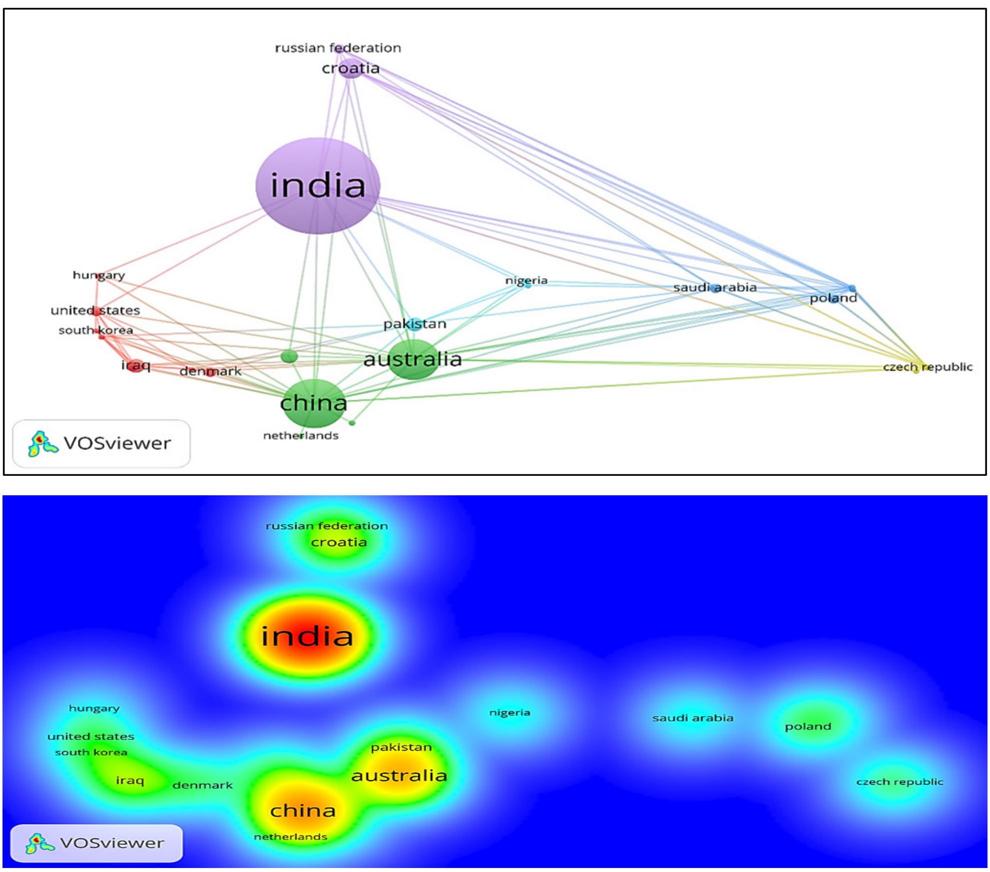


Figure 10. Science mapping of most active countries in documents and citation of related area documents: (a) Network visualization; (b) Density visualization (Figure generated by VOSviewer according to Scopus database as a result of analysis)

HYBRID FIBER REINFORCED GEOPOLYMER COMPOSITES (HFRGC)

The hybrid fiber technique involves mixing two or more sorts of fiber in a fiber-reinforced concrete mix to improve the characteristics of the concrete mix, reduce cracks, and enhance the performance of the concrete due to the superior properties of one type of fiber supporting the obstacles of the other kind (Vairagade & Dhale, 2023).

Figure 11 illustrates the function of short and long fibers in the hybridization system. Hybridization techniques rely on the length of the fiber; a short fiber can control micro-cracks at the fresh stages of loading and prevent their propagation, while another type is longer to offer a cross-macro crack bridging procedure. The hybridization technique depends on the interaction of the fiber elements, where one fiber is stronger than the other, which is more flexible. In addition, the behavior of fibers provides a vital role, where one type of fiber provides strength in the concrete while another type provides new mixing properties.

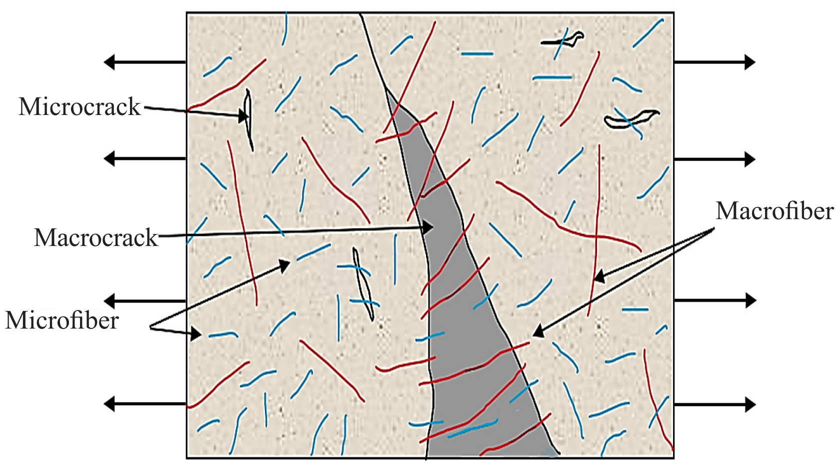


Figure 11. The distribution of short and long fibers across cracks in concrete

Fresh Properties of HFRGC

Chithambar Ganesh and Muthukannan (2019) reported that the inclusion of hybrid fiber, glass fiber (GF), and polypropene fibers (PPF) in the GPC mixture dropped the workability of the mixture, and the fiber's type and volume fraction are factors that affect workability properties. The results showed that the mixtures prepared with a higher amount of GF had a higher compaction factor. This effect was due to the overall quantity of GF material, which was less in volume than PPF for the chosen fiber weight. Hence, the mixtures prepared with GF contain a higher amount of fiber than other mixtures. Similarly, Guler and Akbulut (2022) observed that geopolymer mixture prepared with hybrid fiber (glass and basalt fibers) showed 32% lower workability than the control GPC mixture owing to the hydrophilic nature of basalt fiber (BF) and GF, which tend to absorb water mix causes a reduction in fluidity (Preda et al., 2021). Besides, the mixtures with a higher percentage of BF showed lower workability than other hybrid mixes because BF has a rougher and more filamentous surface GF.

Humur and Çevik (2022) also found that the workability of HFRGC with hybrid fibers polyvinyl alcohol (PVA) and polypropylene (PPF) was affected by the fiber type, and mixing with higher PVA content showed a lower relative slump because PVA fibers exhibited a greater capacity for water absorption compared to PPF fibers, causing higher water absorption in the mixture and reducing the flowability. Cheng et al. (2022) also indicated that the flowability of HFRGC with hooked-end steel fiber and PVA decreased by 29.4% with an increase in the content of hybrid fiber. Alrefaei and Dai (2018) investigated the impact of varying proportions of hybrid fiber on geopolymer composite, including steel fiber (SF) and polyethylene fiber (PE) as hybrid composites. The mix with 1.5% SF–0.5% PE showed better workability than other hybrid fiber geopolymer composite percentages. This trend can be ascribed to the augmented volume concentration of SF. The higher content of PE in the matrix increased the air trapped and then adversely impacted workability.

Zhang et al. (2021) indicated that integrating hybrid fiber with GPC had no impact on the slump of fresh concrete compared to a single fiber. In addition, steel fiber was more effective in workability than polyvinyl alcohol (PVA), polypropylene fiber (PPF), and recycled polypropylene fiber (RPF). However, the other fiber types in the mix had longer fibers than steel fiber. It is attributed to the varying density and length of fibers that substantially influence the slump test.

Another study was conducted by Gao et al. (2017) on the impact of two distinct lengths of SF of 13 mm (long fiber) and 6 mm (short fiber) in HFRGC with different percentages with a total fiber volume of 1% on the workability of HFRGC. The findings indicated that long SF influenced workability properties more than short ones, with a reduction from 259 mm to 206 mm and 231 mm for long and short steel fiber, respectively. This effect can occur due to the internal cohesive force of the mixture playing an important role in its workability properties.

Therefore, the previous study above showed that HFRGC showed a reduction in workability properties compared with the plan geopolymer mix. This reduction is affected by different factors like fiber type, length, content, and volume fraction of fiber (Table 6). Figure 12 summarizes the optimum hybrid workability percentage reduction vs. fiber volume fraction. It can be inferred that increasing the proportion of hybrid fibers leads to a greater decrease in workability.

Table 6
Summary of the workability findings of the HFRGC with the optimum mixes

Reference	Binder	Optimum hybrid fibers	Optimum total content (Vol.%)	Workability test	Control mix (mm)	Findings
Chithambar Ganesh and Muthukannan (2019)	GGBS	0.75GF-0.25PPF	1%	Compaction factor test	-	Higher by 5.3% compared to PPF and lower by 1.23% compared to GF
Guler and Akbulut (2022)	FA	24 mm GF-12mm GF	0.5%	Flowability	170	Lower by13.3% compared to the control mix
(Humur and Çevik (2022)	FA GGBS	PPF-PVA	2%	Relative Slump	2.75	Lower by 81% compared to control
Zhang et al. (2021)	FA GGBS	SF-PVA SF-PPF SF-RPP	1%	Slump	275	lower by 37.5% compared to control
Cheng et al. (2022)	FA GGBS	0.5%SF-2%PVA	2.5%	Flowability	280	Higher performance than other percentages and lower by 24.4% compared with the control sample
Alrefaei and Dai (2018)	FA GGBS	1.5%SF-0.5%PE	2%	Slump	-	Showed better performance than other hybrid fiber percentages.
Gao et al. (2017); Yu et al. (2014)	FA GGBS	13mm SF -6mm SF 0.5%SF-1.5%SF	2%	Flowability	-	It has a better effect than other hybrid percentages and is higher by 4.2% compared with 2% long steel fiber.
Heweidak et al. (2022)	FA GGBS	12mm BF-30mm BF 0.25BF-0.65BF	1%	Flowability	750	Lower by 5.6% compared to control

*FA: Fly ash, GGBS: Ground granulated blast furnace slag, GF: Glass fiber, PPF: polypropene fibers, PVA: polyvinyl alcohol,
SF: Steel fiber, RPP: Recycled polypropylene fiber, PE: Polyethylene fiber, BF: Basalt fiber

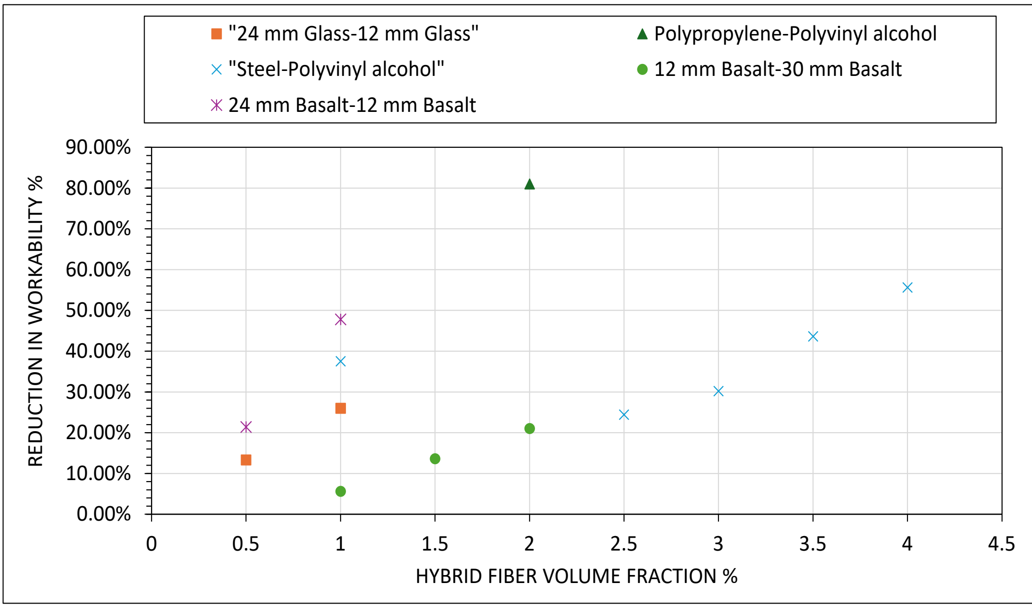


Figure 12. Summary of the reduction in workability versus. hybrid fiber volume fraction (Alrefaei & Dai, 2018; Cheng et al., 2022; Gao et al., 2017; Guler & Akbulut, 2022; Heweidak et al., 2022; Humur & Çevik, 2022; Zhang et al., 2021)

Mechanical Properties of HFRGC

Compressive Strength of HFRGC

The combination of different types of fibers in the GPC matrix has a significant impact on compressive strength. The impact of this phenomenon differs based on several criteria, such as the kind, composition, volume percentage, and length of the fiber (Sathish Kumar et al., 2021) evaluated the positive effects of HFRGC prepared with SF and PPF with different percentages. The findings indicated that the composite prepared with 1% SF–1% PPF provided a compressive strength of around 66.93 MPa, which is higher than other hybrid mix percentages and higher than the control sample by 17%. This effect may be ascribed to the hybrid fibers' capability to support each other and effectively absorb and transmit the loads from the matrix to the fiber.

Bakthavatchalam and Rajendran (2021) also found that HFRGC with 1.5% SF–0.5% BF showed a compressive strength of 62.4% higher than the strength of the control. Gao et al. (2017) researched the influence of single and hybrid long and short steel fibers (SF) in geopolymer composite on compressive strength. The SF had 6 and 13-mm lengths and were used in varying percentages ranging from 0.25 to 1% for single short and long steel fibers. A total volume of 1% was used for the hybrid fiber composite. The outcomes showed that HFRGC, with a 60/40 long/short SF ratio, attained the greatest compressive strength at around 98 MPa. The control mix had a compressive strength of 81 MPa, whereas the composites that included single fibers were around 86–90 MPa and 90–97 MPa for short and long fibers, respectively.

Similarly, Zhang et al. (2021) noticed that the inclusion of single PVA, PPF, and recycled PPF in GPC with a total volume of 1% showed a reduction in compressive strength around 4.3%, 18.8%, and 7.1%, respectively, except SF showed improvement around 4% compared with plain geopolymer. However, the incorporation of hybrid fiber in the mixture demonstrated better compressive strength than single fiber. This effect was attributed to the better adhesion of hybrid fiber than single fiber in a geopolymer mix, and the load will transfer from one type of fiber to the other type, resulting in a matrix with higher compressive strength. Guler and Akbulut (2022) also observed that HFRGC demonstrated superior compressive strength compared to a single fiber after exposure to elevated temperatures (500–800°C).

Sukontasukkul et al. (2018) examined the effect of single and hybrid SF and PPF in geopolymer composite with different percentages of 0.5% and 1% for every single fiber and 0.8 PPF–0.2 SF, 0.6 PPF–0.4 SF, 0.4 PPF–0.6 SF, and 0.2 PPF–0.8 SF for hybridization percentages. The findings indicated that the strength of HFRGC was higher than that of the control geopolymer and the composites with a single fiber. Besides, the compressive strength of HFRGC increased with the increasing replacement percentages of SF, and the composites of 0.2 PPF–0.8 SF had the highest strength of around 56.8 MPa. This effect proved that SF prevented cracks and produced bonding forces better than PPF in the hybridization system.

Mousavinejad and Sammak (2021) made similar observations, and the authors attributed this to the tensile strength of PPF (400 MPa), which was lower than the tensile strength of SF (2000 MPa). Baziak et al. (2021) also found that augmenting the proportion of SF to carbon fiber (CF) in the HFRGC enhanced compressive strength. The authors ascribed this phenomenon to the elevated modulus elasticity of SF to CF, which provided better internal bonding in the matrix.

Bakthavatchalam and Rajendran (2021) investigated the impact of varying SF and BF concentrations mixed with geopolymer concrete in different percentages with a total volume fraction of 2%. The findings indicated that HFRGC of 1.5% SF–0.5% BF showed a compressive strength of around 49.2 MPa, 62.4% higher than the plain sample.

In another study, Chithambar Ganesh and Muthukannan (2019) examined the effect of hybrid fiber, GF, and PPF in geopolymer composite with different percentages on the compressive strength of the matrix. The outcomes unveiled that HFRGC prepared with higher percentages of GF showed higher compressive strength compared to PPF, and HFRGC prepared with 0.75% GF–0.25% PPF achieved a strength of 58.2 MPa. This effect was due to insufficient cohesive strength between the PPF and the geopolymer mixture. Zuaiter et al. (2022) analyzed the effect of the fiber's length on the compressive strength of HFRGC by using GF of 24 mm (short fiber) and 43 mm (long fiber) with a total volume content of 1%. The findings indicated that the combination of 0.75% long glass fibers and 0.25% short glass fibers in the HFRGC resulted in the maximum compressive strength compared to other ratios, reaching a value of 42 MPa. The result can be ascribed to the elevated proportion of long glass fiber showing better control to macrocracks than short fiber by forming bridges that cause better bonding strength in the matrix. Similarly, findings published by Heweidak et al. (2022) showed that the authors used different lengths of BF to prepare HFRGC.

In short, HFRGC exhibited compressive strength that was 19% to nearly 41% higher than the control specimen. Besides that, according to the previous studies above, the optimum hybrid percentages of reinforced geopolymer composite depend on fiber type, volume, and length. All the studies above showed that incorporating hybrid fiber in the geopolymer matrix could provide better results than using single fiber alone because loads can transfer from one type to another. Each fiber type can support the other, increasing the internal bonding strength and leading to superior properties of the geopolymer composite (Figure 13).

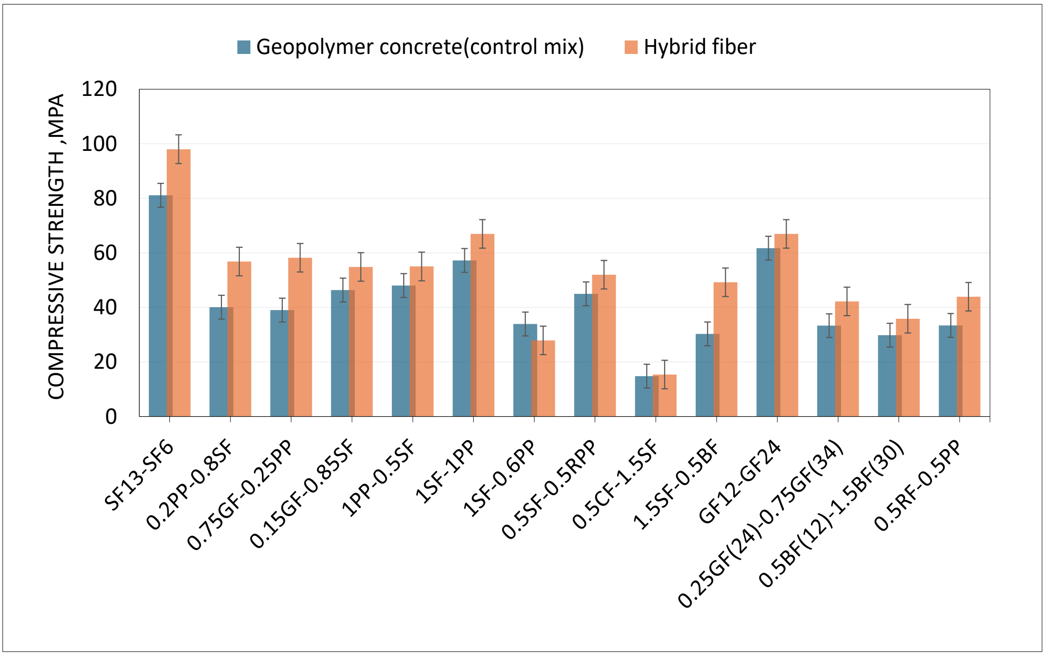


Figure 13. Compressive strength for the control and optimum mix of hybrid fiber (Aisheh et al., 2022; Arunkumar et al., 2022; Bakthavatchalam & Rajendran, 2021; Baziak et al., 2021; Chen et al., 2021b; Chithambar Ganesh & Muthukannan, 2019; Gao et al., 2017; Guler & Akbulut, 2022; Heweidak et al., 2022; Junior et al., 2021; Mousavinejad & Sammak, 2021; Sathish Kumar et al., 2021; Sukontasukkul et al., 2018; Zhang et al., 2021; Zuaiter et al., 2022)

Splitting Tensile Strength of HFRGC

Daniel et al. (2017) examined the tensile strength of HFRGC prepared with SF and GF with a total fiber content of 1%. Different percentages of SF and GF were used (90% SF–10% GF, 80% SF–20% GF, 70% SF–30% GF and 60% SF–40% GF). The results showed that HFRGC prepared with 90% SF–10% GF attained the maximum tensile strength of around 8.9 MPa, surpassing other mixtures by 12.5–29.8%. It proves that the higher content of SF in the HFRGC provided better results owing to the higher tensile strength of SF (1100 MPa) compared to GF (600 MPa).

Chithambar Ganesh and Muthukannan (2019) analyzed the efficacy of both single and hybrid fiber geopolymers, incorporating GF and PPF, by altering the fiber percentages at a volume fraction of 1%. The findings demonstrated that the geopolymer's tensile strength was 57.1% greater when reinforced with GF compared to when reinforced with PPF. Meanwhile, the tensile strength of optimum percentages of hybrid fiber (0.75% GF–0.25% PPF) was around 5.16 MPa. This influence was due to the high modulus elasticity of GF compared to PPF, which led to a higher amount of GF being incorporated in the hybrid composite, providing better results than other mixes. Hence, hybrid fiber achieved efficiency better than using single fiber due to the single fiber's tendency to reduce the composite stiffness and integrity, leading to the earlier reaching of the ultimate stress. Sathish Kumar et al. (2021) also examined the tensile strength performance of geopolymer composites reinforced with single SF or PPF and HFRGC containing both SF and PPF with different ratios. The findings indicated that the tensile strength of the composites prepared using single fibers was 28% greater than that of the plain geopolymer. Conversely, the HFRGC, with a 1% SF and 0.25% PPF composition, exhibited a tensile strength of 39% more than the plain geopolymer.

Similarly, Zhang et al. (2021) noted that the HFRGC exhibited a significant enhancement of approximately 48.9% in its tensile strength in comparison to the control sample. Similarly, Aisheh et al. (2022) revealed that the mixes with 1% SF–0.25% PPF, 1.5% SF–0.25% PPF, and 2% SF–0.25% PPF achieved tensile strengths of about 7.4 MPa, 7.3 MPa, and 8.4 MPa, respectively. This phenomenon can be ascribed to the impact of bridging on fractures. Kumar et al. (2019) also stated that the tensile strength of HFRGC prepared with SF and GF increased with increasing the amount of the SF, and the mix of 85% SF–15% GF showed the highest strength (4.52 MPa), which was 53% higher than plain geopolymer due to the SF's higher tensile strength than GF (2670 MPa).

Bakthavatchalam and Rajendran (2021) worked on the performance of HFRGC by including SF and BF with different percentages and a total volume fraction of 2%. The findings showed that the 25% SF–75% BF tensile strength was around 6.92 MPa, which was higher than the control (4.12 MPa) by 67.96%. In another study, Heweidak et al. (2022) analyzed the impact of the fiber percentage on the tensile strength of HFRGC by adding BF with two different lengths (30 and 12 mm) and different ratios of 1% to 2%. The findings indicated that HFRGC showed 61.96% higher tensile strength than the control, and the tensile strength of HFRGC increased with increasing fiber content. In addition, the HFRGC manufactured using a hybrid length of BF exhibited superior performance in terms of indirect tensile strength in comparison to the single-length BF with the same content.

Tensile strength increased with increasing strength, modulus of elasticity, and fiber stiffness in the geopolymer matrix. It resulted in higher interfacial bonding due to the bridge formation through which stresses were transferred from one type of fiber to another. Hence, the compound performed better than the plain sample and single fiber against the applied loads. Based on previous investigations, the tensile strength of hybrid fiber-reinforced geopolymer composite increased from 39% to almost 68% compared to plain geopolymer. Hence, hybrid fiber effectively converted geopolymer from brittle nature to ductile. Figure 14 illustrates the summary of the tensile strength of the HFRGC as compared to single fibers. “Single Fiber 1” and “Single Fiber 2” denote the different types of single fiber.

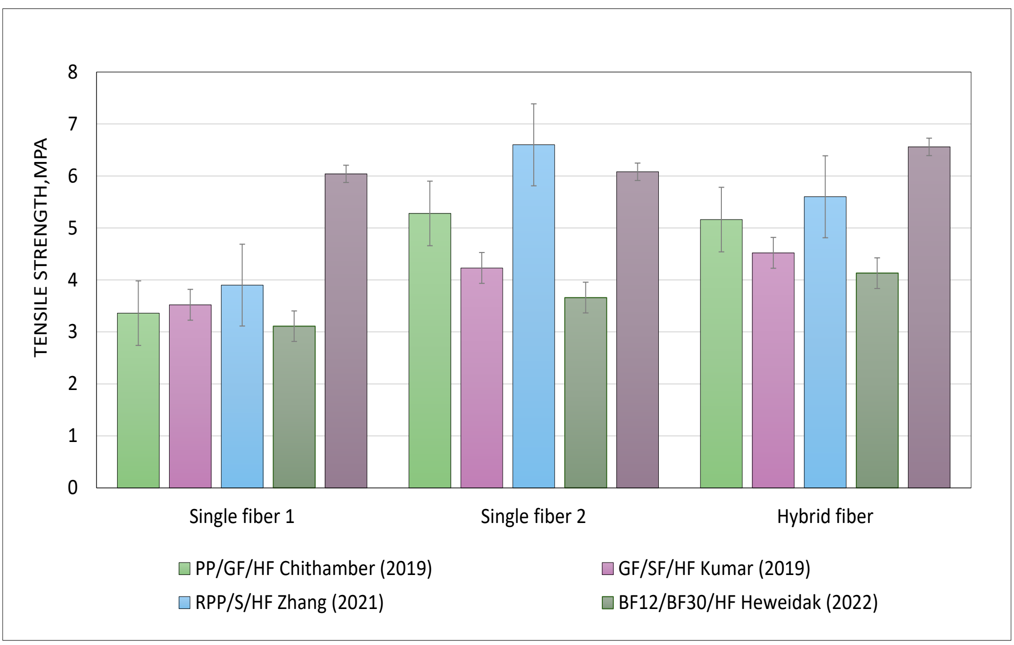


Figure 14. Summary of tensile strength of HFRGC (Bakthavatchalam & Rajendran, 2021; Chithambar Ganesh & Muthukannan, 2019; Daniel et al., 2017; Heweidak et al., 2022; Kumar et al., 2019; Sathish Kumar et al., 2021a; Zhang et al., 2021)

Flexural Strength and Toughness Index

Chithambar Ganesh and Muthukannan (2019) studied the flexural strength performance of single and HFRGC prepared with GF and PPF. The results showed that HFRGC of

0.75% GF–0.25% PPF achieved 56.7% higher flexural strength than composites prepared with single fibers. Similarly, Kumar et al. (2019) reported that HFRGC prepared with SF and GF achieved 53% higher flexural strength than the plain geopolymer. The observed result can be ascribed to the efficacy of fibers in creating bridges within the geopolymer composite, enhancing the composite's characteristics. Similar results were noted for the flexural strength, according to Zhang et al. (2021), where HFRGC showed 60% higher flexural strength compared with the control sample. Bakthavatchalam and Rajendran (2021) also observed that the flexural strength of HFRGC prepared with SF and BF of 25% SF–75% achieved 68% higher flexural strength than the control mix. This improvement was attributed to the combination of macro fiber (SF) and microfiber (BF). These hybrid fibers successfully increased flexural strength by preventing the transmission of micro and macro-cracks at various stages of loading.

Asrani et al. (2019) studied the flexural strength of two different composites of HFRGC, the first one prepared with the combination of two fibers with a total volume fraction of 1.6% (1.3% SF–0.3% GF), (1.3% SF–0.3% PF), and (0.3% PF–0.3% GF), and the second one was composed of a mix of three fibers, with a fiber content of 1.6% (1.0% SF–0.3% PF–0.3% GF). The findings indicated that the utmost increase in flexural strength was about 242.2% in HFRGC, which contained 1.3% SF–0.3% GF, compared to the control. This effect is due to the efficiency of the control cracks in the cracking area because of the presence of SF and GF, which control micro-cracking and macro-cracks in the composite. Chen et al. (2021a) discovered that the inclusion of nanoparticles has no impact on the flexural strength of a material, but it does affect its compressive performance. However, when nanomaterials are mixed with hybrid fibers, the mechanical strengths of the material can be significantly improved. The HFRGC prepared with hybrid fiber and nano-silica achieved a 200% higher flexural toughness than plain geopolymer. It could be attributed to the higher strength of steel fiber (1650 MPa) than polypropylene fiber (900 MPa), which led to better performance against cracks in the geopolymer composite, and the presence of nano-silica, which enhanced the pore enlargement due to its gel.

Junior et al. (2021a) analyzed the efficacy of the incorporation of single and hybrid fibers within geopolymer composite with different hybrid types (SF, PVA, alkali resistance glass (ARG), and PPF) and percentages. The results demonstrated that the flexural strength exhibited a notable enhancement upon the integration of hybrid fiber into the geopolymer matrix. By merging 0.5 SF with 1 PPF, the flexural strength increased by around 37.8% compared to the control sample, and toughness increased as well. Moreover, the hybridization with SF enhanced the residual strength factors for PVA and ARG single fiber by 78% and 82%, respectively. This effect was due to SF's higher modulus of elasticity than PPF, which effectively prevented macrocracking diffusion by providing better crack control and bonding strength in the composite (Figure 15).

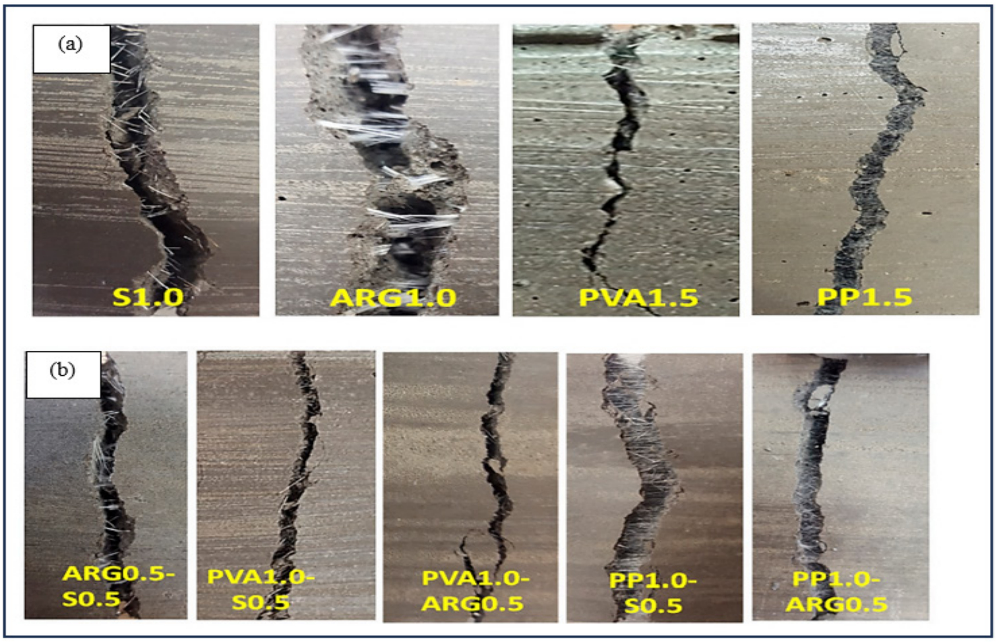


Figure 15. Failure patterns in flexural strength for (a) single fiber and (b) hybrid fiber (Junior et al., 2021a)

Sathish Kumar et al. (2021) examined single and hybrid fibers in different percentages of SF and PPF within a geopolymer composite. The flexural strength of hybrid values for the optimum hybridization percentages of 1% SF–0.25% PPF recorded a flexural strength of 40% higher than the control sample. This effect is attributed to the effectiveness of PPF in the early stages of controlling microcracks, and with increasing the load, SF acted to arrest the expansion of macrocracks, thus improving the bending strength. Similar observations were made by Mousavinejad and Sammak (2021) and Aisheh et al. (2022) when the authors used HFRGC with SF and PPF. The presence of fiber was responsible for this impact in different lengths and percentages, providing better bonding force in micro and macro cracks, which positively impacted flexural strength.

In short, the inclusion of both single and hybrid fibers had an important influence on the flexural strength of the geopolymer compound. Flexural strength was increased using the optimum hybridization value among fibers and the properties of incorporated values like modulus of elasticity, length, and volume. According to the single and HFRGC, the flexural strength increased from 20% to almost 68% compared to plain geopolymer without fiber. Hybrid fiber effectively acted as a crack arrester. Figure 16 illustrates a summary of the flexural strength of the HFRGC as compared to single fibers. “Single Fiber 1” and “Single Fiber 2” denote the different types of single fiber. Different HFRGC study summaries are listed in Table 7.

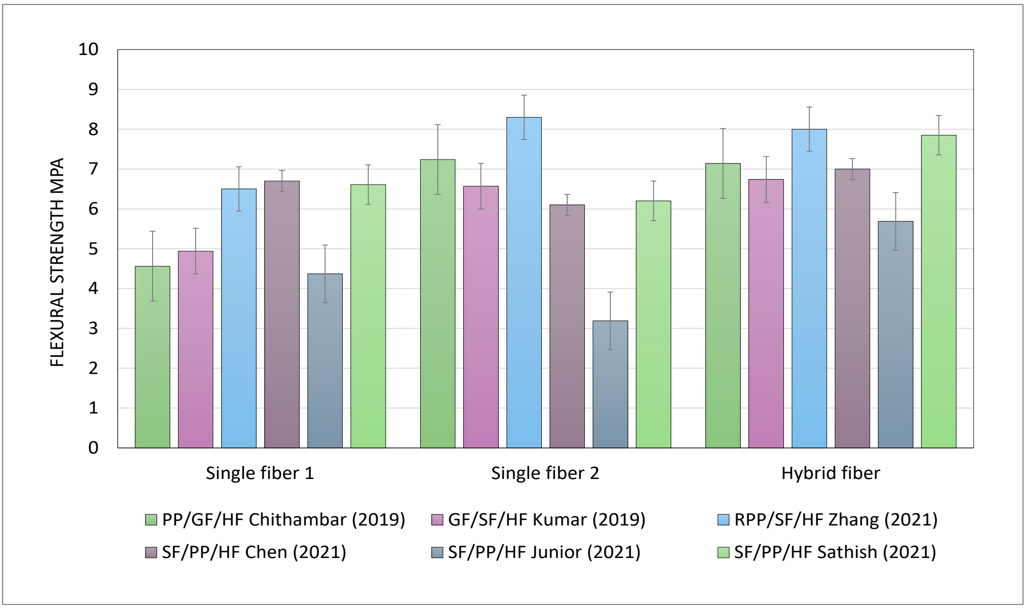


Figure 16. Summary of flexural strength of HFRGC (Chithambar Ganesh & Muthukannan, 2019; Junior et al., 2021a; Chen et al., 2021a; Kumar et al., 2019; Sathish Kumar et al., 2021; Zhang et al., 2021)

Table 7
Summary of different hybrid fibers findings of the HFRGC with the optimum mixes

Author	Source material*	Hybrid fiber % *	Optimum hybrid mix	Findings
Daniel et al. (2017)	GGBS	90 SF-10 GF 80 SF-20 GF 70 SF-30 GF 60 SF-40 GF	90 SF-10 GF	Significant enhancements were observed in FS, such as stiffness degradation, cumulative energy dissipation capacity, ductility, and ultimate load.
Sukontasukkul et al. (2018)	FA Silica fume	0.8 PP-0.2 SF 0.6 PP-0.4 SF 0.4 PP-0.6 SF 0.2 PP-0.8 SF	0.2 PP -0.8 SF	The incorporation of hybrid fibers has demonstrated favorable impacts on the characteristics of PFRG.
Alrefaei and Dai (2018)	FA GGBS	1.5 SF-0.5 PE 1 SF-1 PE 0.5 SF-1.5 PE	0.5 SF-1.5 PE	Better T.S compared to the control mix

Table 7 *(Continue)*

Author	Source material*	Hybrid fiber % *	Optimum hybrid mix	Findings
Chithambar Ganesh and Muthukannan (2019)	GGBS	0 GF-1 PP 0.25 GF-0.75 PP 0.5 GF-0.5 PP 0.75 GF-0.25 PP 1 GF-0 PP	0.75 GF-0.25 PP	The optimum hybrid fiber percentages increase ductility compared with other mixes.
Kumar et al. (2019)	FA	0.15 GF-0.85 SF 0.3 GF-0.7 SF 0.5 GF-0.5 SF	0.15 GF-0.85 SF	Enhancement in the attained C.S, T.S and F.S in comparison to control
Guo et al. (2020)	MK	(1-3) PP-1PVA (1-3) PP-2PVA (1-3) PVA-5WS (1-3) PVA-10WS (1-3) PVA-15WS	1 PP-1 PVA 2 PVA+15 WS	The optimum mixture exhibited superior C.S and F.S when compared to the control mixture.
Chen et al. (2021a)	FA NS	1 SF-0 PP 0 SF-6 PP 1 SF-6 PP	1 SF-6 PP	Hybrid fibers resulted in composites with superior internal properties and strong fiber/matrix interfacial bonds. FS increased significantly compared to the control mix.
Zhang et al. (2021)	FA GGBS	0.5 SF-0.5 PVA 0.5 SF-0.5 PP 0.5 SF-0.5 RPP	0.5 SF-0.5 RPP	Hybrid fibers effectively improve C.S, T.S and F.S. Enhanced the resilience of GPC and transformed the mode of failure from brittle to ductile.
Baziak et al. (2021)	FA slag	1.5 CF-0.5 SF 1 CF-1 SF 0.5 CF-1.5 SF	1.5 wt. CF-0.5 wt. SFs	The addition of fiber increased C.S and F.S.
Zhong and Zhang (2022)	FA GGBS	1.75 PVA-0.25 RTP 1.5 PVA-0.5 RTP 1.25 PVA -0.75 RTP 1 PVA-1 RTP	1.75 PVA-0.25 RTP	Hybrid fibers improved dynamic C.S and T.S properties while maintaining acceptable quasi-static mechanical characteristics.

Table 7 *(Continue)*

Author	Source materials*	Hybrid fiber %*	Optimum hybrid mix	Findings
Cheng et al. (2022)	FA GGBS Metakaolin Silica Fume	2 PVA-0.5 SF 2 PVA-1 SF 2 PVA-1.5 SF 2.5 PVA-0.5 SF 2.5 PVA-1 SF 2.5 PVA-1.5 SF	2.5 PVA-1 SF	Improvement of TS, ductility, and ability to control cracks.
Guler and Akbulut (2022)	FA	GL24GL12-0.5 GL24GL12-1 BA24BA12-0.5 BA24BA12-1	GL24GL12-1	Hybrid fibers enhanced the workability of GPC and exhibited superior residual CS and FS characteristics in comparison to single fibers.
Lin et al. (2023)	FA GGBS	0 PE-1 PP 0.25 PE-0.75 PP 0.5 PE-0.5 PP 0.75 PE-0.25 PP 1 PE-0 PP	0.5 PE-0.5 PP	The hybrid blend provides superior TS as well as great overall economic performance.

* FA: Fly ash, GGBS: Ground granulated blast furnace slag, NS: Nano silica, SF: Steel fiber, GF: Glass fiber, PP: Polypropylene fiber, PE: Polyethylene fiber, RPP: recycled polypropylene, CF: carbon fiber, PVA: polyvinyl alcohol, RTP: recycled tire polymer, WS: wollastonite fiber, MK: Metakaolin. CS: Compressive strength, TS: Tensile strength, FS: Flexural strength

CONCLUSION

This review summarizes previous studies using scientometric analysis and normal review analysis of the available literature on HFRGC to evaluate several metrics. A systematic search was performed in the Scopus database, yielding a total of 90 publications from 2013 to 2023 that were deemed relevant to the research topic. The data obtained from the search was subsequently evaluated using the VOSviewer program. According to the results, several conclusions can be derived:

- Scientometric analysis of data extracted from Scopus data by using a VOS viewer was performed. The top documents, keywords, citations, and countries were mentioned. Bibliometric analysis using scientific mapping provided a better view in detail of the researcher's search data in the same area related to hybrid fiber-reinforced geopolymer composite. Most of the citations were for "construction and building materials," with around 15 documents and 441 citations in the related field. Inorganic polymers, geopolymers, steel fibers, geopolymer concrete, and hybrid fiber were the most frequent keywords, with 51, 51, 35, 34, and 31 occurrences, respectively. Moreover, the article titled "Tensile behavior and microstructure of hybrid fiber ambient-cured one-part engineered geopolymer composites" by Alrefaei and Dai (2018) received 114 citations. In addition, India was the most active country in the related area, with 35 documents. The utilization of scientometric analysis will assist researchers from different countries in fostering collaborative research, sharing ideas and knowledge, and establishing collaborative enterprises to augment their research efforts.

- The integration of hybrid fiber in the geopolymer matrix decreased the composite's workability properties. This reduction increased with the fiber's volume fraction due to its hydrophilic nature, which tends to absorb water and reduce workability. The reduction ranged from 20% to 50% compared with the control sample.
- In most studies, HFRGC showed higher compressive strength than single fibers, strongly affected by fiber types, volume, content, and length. Besides, HFRGC showed 19% to almost 41% higher strength than the control sample. This outcome was a result of the capability of hybrid fiber to control cracking better than single fiber because each fiber type supported the other type; hence, the loads transferred from one type to another, and this mechanical is responsible for increasing the interfacial bonding in the matrix and strengthening the overall hybrid composite.
- HFRGC showed better performance of tensile and flexural strengths than the control sample and single fiber in the geopolymer matrix. Tensile strength increased from 39% to almost 68% compared to the plain. In addition, the tensile and flexural strengths exhibited a positive correlation with an increase in the tensile strength and modulus of elasticity of the fiber used, which proved efficiency in the formation of bridges to control micro and macro-cracks and prevent diffusion with the applied loads.
- Further research could focus on investigating the durability and environmental impact of hybrid fiber-reinforced composites. Exploring advanced manufacturing methods and optimizing fiber compositions may lead to stronger and lighter materials. Additionally, exploring potential applications in sectors like aerospace, automotive, and construction holds promise for addressing engineering challenges. Hybrid fiber composites offer exciting opportunities to advance material science and engineering technologies by addressing these areas.

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