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A BIBLIOMETRIC ANALYSIS OF RESEARCH ON FIBER REINFORCED GEOPOLYMER COMPOSITES

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To investigate and analyze the vast scientific data from the field of geopolymers, bibliometric analysis with different software is the most precise and efficient technique. In this field, the network visualization of keywords and authors of published papers is of particular significance. Therefore, the aim of this study is to present the progress and research interest in geopolymers, especially those reinforced with different types of fibers. Accordingly, the bibliometric data were retrieved from the Web of Science database and analyzed using the VOSviewer software. The data were retrieved from the database considering two sets of keywords: one analysis was performed for the most general term that describes the geopolymers field, i.e., "geopolymer"; the second analysis was performed to achieve the main objective of the study, and the terms "geopolymer and fiber" were used in the search. According to the WoS database, at the interrogation moment, the search for the term "geopolymer" shows 10.810 results from all databases indexed in WOS, while the search for the term "geopolymer fiber" will result in 1503 results. By processing these results with the VOSviewer software, different groups of keywords were obtained and their relevance was filtered based on different criteria as presented in the description of each map. Based on the data presented in this study, future research directions were presented.

Keywords: fiber-reinforced composites; bibliometric analysis; geopolymer composite; geopolymer review

1. Introduction

Because of its green qualities and superior mechanical properties, geopolymer is a possible replacement for Ordinary Portland Cement (OPC) in the construction industry, which strongly needs environmentally and energy-efficient building materials [1]. When compared to OPC, geopolymer substitution could reduce the current carbon emissions associated with human activities by around 9% [2]. Currently, OPC production is considered the worst operating sector in terms of CO_2 emissions to the atmosphere. Additionally, the three-dimensional molecular network specific to the geopolymer offers improved acid resistance,

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high-temperature stability, and early strength development [3]. Therefore, these materials are suitable for future architectural applications due to their superior performances and green futures.

Around the world, population expansion, urbanization, and widespread raw material usage are contributing to a wide range of environmental, social, and economic issues [4]. There are numerous other challenges connected to waste management, contamination, and land usage that is intimately connected to the effects of humanity's expansion into the natural world, while climate change is likely the most prominent of these issues to be found in scientific and political discourse. The global community defined the objective of sustainable development in an effort to lessen these adverse effects. In order to ensure that future generations may also satisfy their requirements, sustainable development fundamentally means making sure that we can meet the needs of the present without endangering the ecology. OPC is the second-most popular substance after water [5]. OPC is frequently used in the construction sector, and its use has a significant negative environmental impact. In addition to using a lot of energy and virgin raw materials in the production of OPC, this process also produces a lot of greenhouse emissions. Around 1.5 tons of raw materials are required for the production of 1 ton of OPC, and 1 ton of CO_2 is released into the atmosphere [6, 7]. Another disadvantage of OPC is that it might not offer the qualities needed for particular applications, such as quick mechanical strength development and great resistance to chemical attack.

As the best OPC substitute for sustainable development, geopolymers have recently attracted a lot of research attention. Geopolymers are inorganic materials based on silicon and aluminum oxides, chemically balanced by phosphorus or different chemical elements of the alkali group [8]. By designation, the prefix "geo" designates synthetic materials with a structure resembling that of natural rocks, while the term "polymer" designates these materials' chemical structure as being comparable to that of organic polymers [1]. Both room temperature and high temperatures can be used for the geopolymerization procedure that creates them [9]. In many applications, geopolymer not only performs similarly to OPC, but it also has a number of other benefits, such as rapid curing, high acid resistance, excellent adhesion to aggregates, immobilization of toxic and hazardous materials, and significantly lower energy consumption and greenhouse gas emissions [10]. Geopolymer has brittle behavior, has poor tensile strength, and is susceptible to breaking [11]. Additionally, their industrial development and application have been substantially curtailed due to the high price of sodium silicate [12]. These flaws influence the long-term endurance of structures as well as place restrictions on the structural design. The use of carbon fibers or steel to strengthen geopolymer has been studied [13]. Although these fibers can significantly improve the tensile strength, ductility, and toughness of geopolymer, they are all created using high energy-consuming processes, raising questions about what will happen to them once their useful lives are through. The search for alternative fibers has been prompted by rising environmental consciousness and the need to guarantee the sustainability of construction materials.

Even so, the majority of the geopolymers being created and researched at the moment are made from natural basic materials (kaolin). Since it is easier to manage the Si/Al ratio, has a high rate of dissolution in the reactant solution, and is white, metakaolin is favored. Geopolymer composites cannot, however, employ it in large quantities due to its expensive cost. Numerous studies [14,15] have shown that using secondary source materials to create geopolymers with good performance is also possible (industrial wastes such as fly ash or slag). Basically, any substance that is amorphous and has significant amounts of silicon and aluminum can serve as a source of geopolymers. This explains why countries with rapidly industrializing economies have such a keen interest in this technology. In addition, to address the waste issue, the use of waste in geopolymer synthesis could result in a decrease in the consumption of raw materials.

Currently, both the characteristics and the final properties of geopolymers are directly dependent on the used raw materials (aluminosilicate source and activator). At the base of these dependencies is the structure formed as a result of the geopolymerization chemical reaction, which occurs after mixing the solid component with the liquid one. According to previous studies [15-17], until now geopolymers with characteristics comparable to those of Portland Cement-based materials have been obtained using the following aluminosilicate sources: metakaolin, coal ash, slag, mine tailings, and other types of mineral waste. Therefore, in order to establish the future directions for this scientific field, a bibliometric analysis should be conducted to comprehensively report the current trends and to identify the geopolymers' research hotspots. This study aims to evaluate the previously published literature, indexed in the Web of Science database in order to provide a brief report on the progress of the most influencing authors, keywords, and articles in the geopolymers field.

2. Methods

The present study approaches the analysis of literature in the field of geopolymers using the bibliometric evaluation technique that provides the opportunity to create visual presentations by quantitatively analyzing the published literature. This technique provides the opportunity to highlight the clear relationships between the keywords specific to each field of study and to confirm the trend in each field of research. The analysis was performed on studies indexed in the Web of Science (WoS) database since it is the most selective one in terms of publisher ranking and indexing.

The data exported from the WoS databases on November 20, 2022, were processed using the VOSviewer software (version 1.6.18) developed at Leiden University (Netherlands) by Nees Jan VanEck and Ludo Waltman.

The data were retrieved from the databases in a tab-delimited format (TAB), considering two sets of data: one analysis was performed for the most general term that describe the geopolymers field, i.e., "geopolymer"; the second analysis was performed to achieve the main objective of the study, and the terms "geopolymer and fiber" were used in the search. According to the WoS database, at the interrogation moment, the search for the term “geopolymer” shows 10,810 results from all databases indexed in WOS, while the search for the term “geopolymer fiber” will result in 1503 results. By processing these results with the VOSviewer software, different groups of keywords were obtained and their relevance was filtered based on different criteria as presented in the description of each map.

3. Results and Discussion

3.1. Geopolymers development

The visualization of keywords co-occurrence of the search "geopolymer" is presented in Fig. 1. By choosing the fractional counting method, a number of 7570 keywords are identified. Once the results are filtered considering a minimum number of 150 occurrences of a keyword, only 28 meet the threshold. Surprisingly the keyword with the highest score was fly-ash, not geopolymer. The list of identified terms in descending order considering the occurrence is the following: fly-ash, geopolymer, compressive strength, strength, mechanical properties, microstructure, concrete, fly ash, cement, metakaolin, performance, behavior, durability, geopolymer concrete, slag, temperature, blast-furnace slag, mechanical properties, geopolymers, workability, Portland-cement, resistance, waste, rice husk ash, ash-based geopolymer, mortar, hydration, alkali activation. Also, the size of each point from the network visualization depends on the occurrence of that keyword in the processed data.

The visualization of co-authorship analysis, choosing the fractional counting method is presented in Fig. 2. The software identifies 13469 authors, out of which 29 meet the criteria of a minimum number of documents of 25. Moreover, it seems that the map shows 14 clusters that are related to the international distribution of the authors and the fact that these groups of researchers don’t have publications together. The largest cluster that meets the criteria includes 4 authors, while 3 of them consist of only one author.

The analysis of the geographical distribution of authors (Fig. 3) with publications in this field identifies 101 different countries, while 51 of them have at least 10 publications. The country with the highest number of citations (31599 citations for 490 documents) is Australia, followed by the People of Republic of China (17924 citations for 736 documents). The third position is occupied by Malaysia with 7584 citations for 273 documents, while Romania ranked 27.

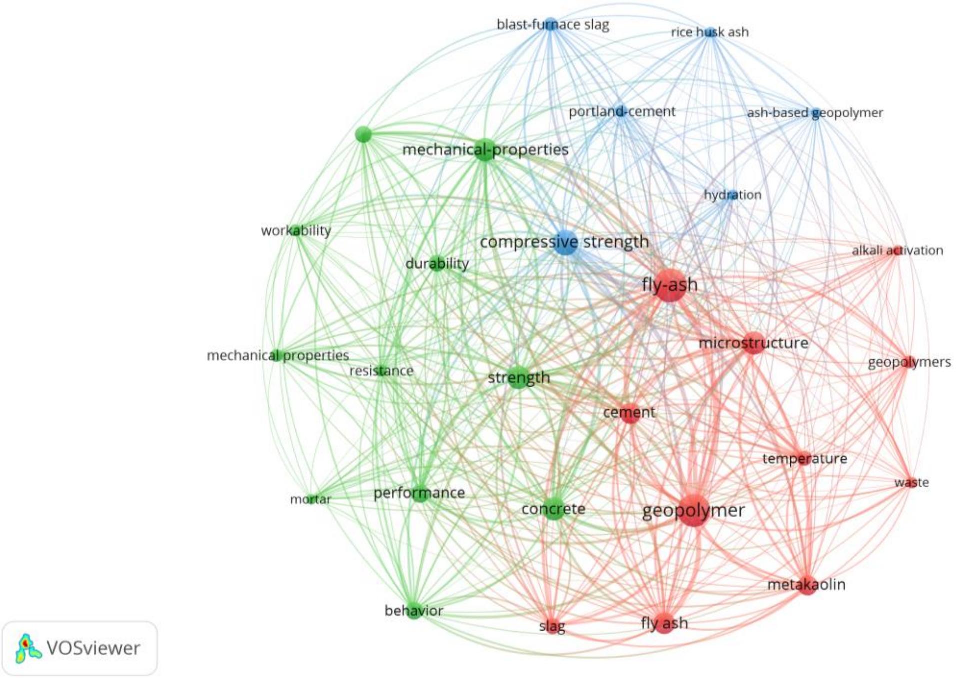

Fig. 1. Visualization of keywords co-occurrence for the term “geopolymer” in WoS database

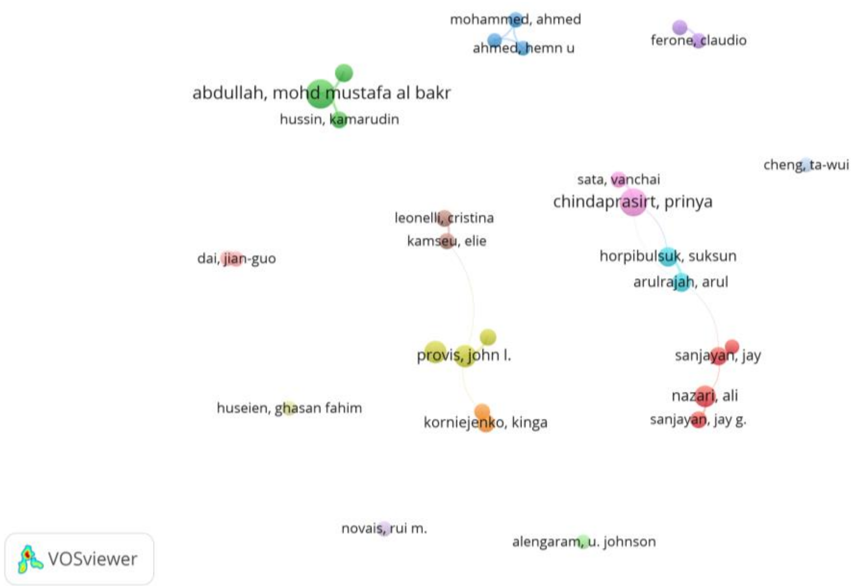

Fig. 2. Visualization of authors with a minimum of 25 publications in the geopolymer field

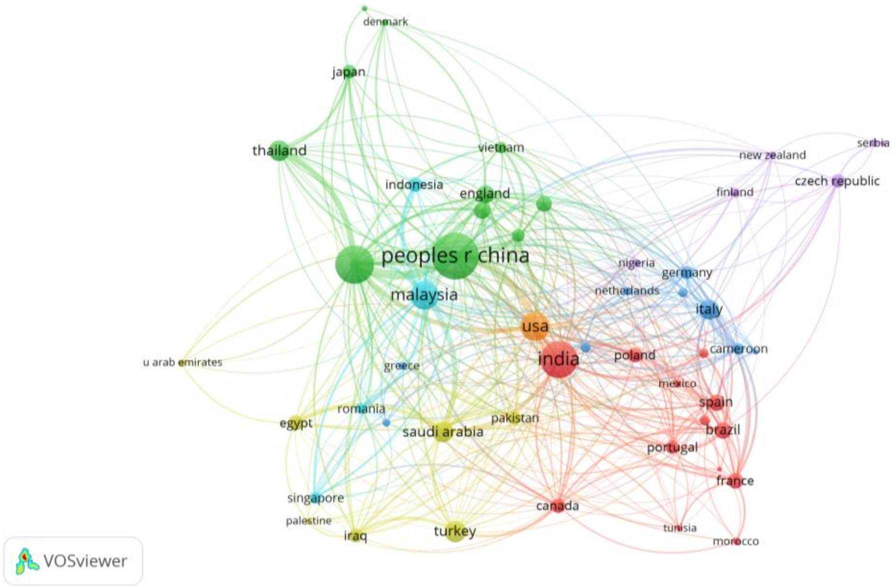

Fig. 3. Visualization of countries affiliated with a minimum of 10 publications

3.2. Fiber-reinforced geopolymers

The visualization of keyword occurrence of the search "geopolymer fiber" is presented in Fig. 4. As can be seen the most highlighted terms are "fiber", "effect", "composite", "type" and "advantage", which are correlated with both the interest of researchers from this field and the effect produced by the fiber addition on the geopolymers characteristics. Therefore, it can be stated that the fiber addition in the geopolymers matrix will increase the flexural strength of these composites by reinforcing their structure. Moreover, the publications on this topic seem to have a high level of novelty and most of the research was conducted on metakaolin-based geopolymers activated with alkaline solutions, especially sodium hydroxide. Also, the effect produced by the addition of different types of fibers was mostly evaluated by microstructural (scanning electron microscopy) and mechanical (compressive or flexural strength) tests. The microstructure analysis is mostly performed to evaluate the fiber distribution into the matrix of the geopolymer composites and to study the interface between the fibers and the matrix. The properties of the geopolymers composites are strongly dependent on the adhesion of the matrix to the surface of the fibers. A good adhesion will result in a composite with better mechanical properties, especially higher flexural strength. Moreover, the scanning electron microscopy (SEM) analysis may confirm the behavior of the fibers in the activator solution, since the concentration of the activator may affect the quality of the fibers. An alkaline solution of high concentration (high sodium hydroxide molarity) may also result in the dissolution of the reinforcements which will decrease the flexural strength of the fibers but may increase the properties of the geopolymer composite by creating a stronger interface. Therefore, the microstructure analysis is essential for understanding the durability and performance of each mixture. The mechanical properties were evaluated in most of the studies since the values are required to identify the application for when the developed composites are suitable.

The size of the circles from the keyword occurrence visualization depicts the frequency of these terms in the title or the abstract of the evaluated studies. The map was created based on text data using the binary counting method (the presence or the absence of the terms is considered, not the occurrence of the term in the same document). The software identified 24097 terms, while only 34 of them meet the occurrence limit of 150. Based on the relevance score of each term, the most relevant 23 terms (terms such as mpa, specimen, paper etc. were manually unselected) were used to create the network. Also, the software grouped the extracted data into three clusters. The first cluster (the red links) includes 11 items, namely addition, application, compressive strength, effect, geopolymer concrete, increase, influence, performance, strength, study, and type. The second cluster (the green links) includes 7 items, namely advantage, fiber, fly ash, geopolymer, metakaolin, novelty and water. The third cluster (the blue links) includes 5 items, namely composite, flexural strength, geopolymer composite, mechanical property and microstructure. One of the clusters is related to the effect produced by fiber addition, the second includes terms specific to the raw materials used for this type of geopolymers and the third one is mostly related to the properties/characteristics studied by the researchers.

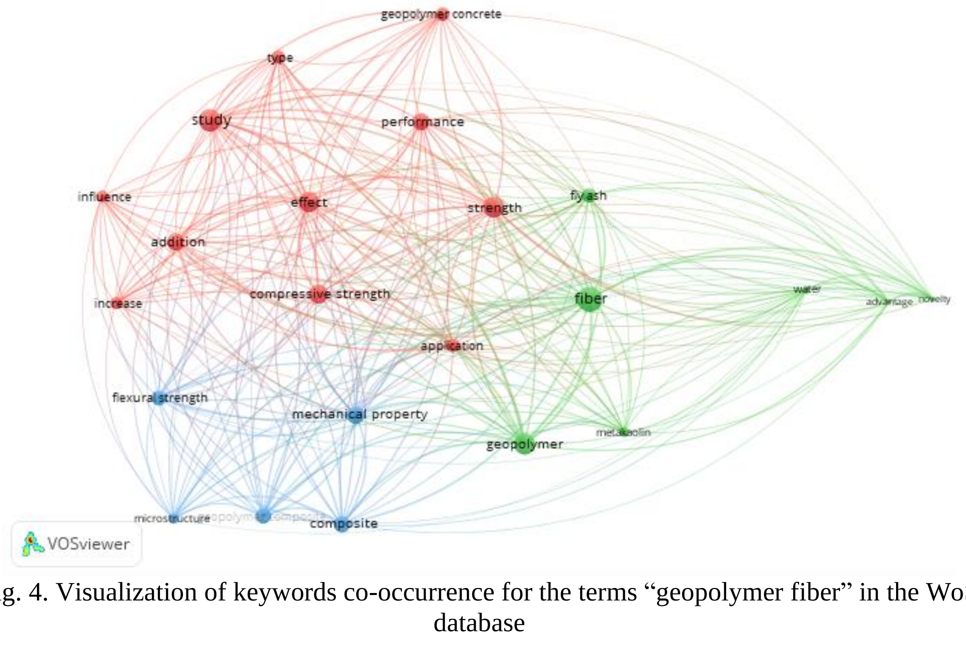

Fig. 4. Visualization of keywords co-occurrence for the terms “geopolymer fiber” in the WoS database

A map based on the retrieved bibliographic data that shows the authors with publications in the field of fiber-reinforced geopolymers is presented in Fig. 5. The network was created using co-authorship as the type of analysis, and fractional counting as the counting method. The software identified 4006 authors, but only 41 of them had associated a minimum of 10 publications.

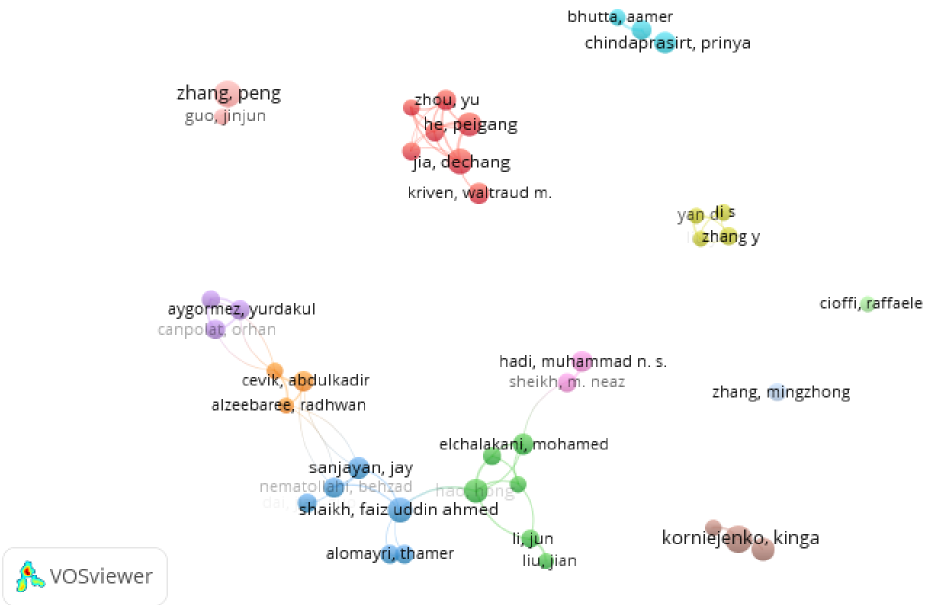

Fig. 5. Visualization of authors with a minimum of 10 publications in fiber-reinforced geopolymer field

The top 5 researchers in the field of fiber-reinforced geopolymers, in ascending order, are the following: Jia Dechang with 22 publications and 640 citations, He Peigang with 20 publications and 640 citations, Hao Hong with 20 publications and 331 citations, Nematollahi Behzad with 15 publications and 841 citations, and Sanjayan Jay with 17 publications and 993 citations. Also, it can be observed that some of the items from the created network are not connected to each other, with the largest set of connected items consisting of 20 items. The items were grouped into 12 clusters, the larger cluster includes 7 items, while two of them have only one item in the composition.

4. Limitations

Although this study contributes to the literature by highlighting the trends in the geopolymers field, especially in the case of fiber-reinforced geopolymers, the bibliometric analysis has some limitations. These limitations are related to the WoS indexing and inhomogeneity in describing the geopolymers by the authors. The limitations associated with the database are related to the difference between the publication date and the indexing date of the published literature. Also, there are a lot of journals that aren't indexed in the WoS database. The limitations associated with literature inhomogeneity are related to the different terms used by the researchers to substitute the term geopolymer, such as "green cement", "geocement", eco-cement" etc. Considering these restrictions, the study may not describe very accurately the current state of literature in the field of geopolymers. However, its relevance is given by the significant number of analyzed literature and the quality of the database.

5. Conclusions

The present study conducts a bibliometric analysis in the field of geopolymers using VOSviewer software that provides the opportunity to quantitatively analyze the published literature. This technique was used to evaluate the studies indexed in the Web of Science database to highlight the current trends in this field and the researchers that significantly contribute to the development of geopolymers.

The bibliometric analysis was performed on two sets of data, namely “geopolymer” and “geopolymer fiber”. The evaluation for the term geopolymer was conducted on a number of 7570 keywords and 13469 co-authors associated with the existing literature. Also, these co-authors are affiliated with institutions from 101 different countries. In the case of geopolymer fiber search, the software identified 24097 items, while the number of authors with publications in this field was 4006.

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