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Promoting use of waste materials for sustainable geopolymer concrete: a scientometric review

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Abstract. The building industry considerably contributes to the use of energy, depletion of resources and emission of carbon dioxide, all of which harm the environment. Currently, this industry is moving away from cement and natural materials in favour of substitute materials lowering environmental impacts and fostering sustainability. Fly ash, metakaolin, silica fume, slag, and rice husk ash are some of the wastes that are high in aluminosilicate contents and are examples of wastes produced by industries and agriculture that can be used to make geopolymer concrete, which is a substitute in Ordinary Portland cement concrete due to its exemplary strength, stabilization at elevated temperatures, denser microstructure, elevated bond strength and opposing chemical nature. This review investigates using various industrial wastes to be used as source materials in geopolymer concrete in the scientometric review using bibliometric from Scopus. Examination of the bibliometric data that is currently available and identifying relevant publication areas, year of publication, keywords, co-authorship, countries and papers with the most citations etc. have been used to assess the current state of the art.

Keywords: Scientometric review, Source materials, Geopolymer concrete, Bibliometric data, Scopus.

Classification numbers: 2.9.3, 3.3.2,3.3.3.

1. INTRODUCTION

According to the United Nations report on the "Future of the World", the world's population has seen an exponential rise in population and today it is around 8.1 billion people. A large population poses a great challenge in the achievement of sustainable development goalsparticularly in consumption of natural resources and greenhouse gas emissions [1]. The increase in population also puts pressure on existing infrastructure facilities, housing sector and industrial sectors which will also impact the environment to a large extent [2]. It is estimated that only 40 % of the total infrastructure required for an existing population is built and hence huge gap exists which needs to be filled up [3]. Also, in the modern era, the development of any nation is judged by the amount of energy consumed and the rate of development of infrastructure in the country [4]. It is also a well-known fact that in most infrastructure projects ordinary portland cement (OPC) is chiefly used as a binder material [5]. The rapid expansion of the construction industry has made cement the second most widely used construction material after water [6]. Production of cement requires a huge amount of energy and natural resources and also releases a huge amount of greenhouse gas into the environment. Approximately one ton of CO_2 is released into the environment during the manufacturing of one ton of cement [7]. Climate change brought on by greenhouse gas emissions is a serious ecological problem that the world is currently confronting. Cement production thus accounts for 5 - 7 % of greenhouse gas emissions [8]. More than 120 countries have pledged at the Copenhagen Summit to restrict the rise of temperatures above 2 °C. This maximum allowable temperature increase is based on advice from numerous scientific studies which warns that the increase in temperature above the given mark can result in various climatic activities which will affect water supply management, agricultural productivity, sea level etc. [9]. Not only release of huge greenhouse gases a huge issue, cement industry requires huge resources in the form of natural resources like limestone and also large energy for the calcination process [10]. There are many durability issues when OPC is used in concrete like sulphate attack, weak resistance to acid, and alkali-aggregate reaction which reduces the life span of the structure and imposes additional economic burden [11 - 14]. Besides, this rapid industrialization has led to a huge discharge of waste materials which are generally disposed of as landfills. These pollute land, water and air and hence effective utilization of these waste materials is a need of the day. Also, for the sustainable development and development of low-carbon or zero-carbon concrete, industrial wastes should be used to decrease the use of Portland cement and other natural resources, thereby reducing environmental pollution [15].

Various alternatives to Ordinary Portland cement concrete are researched and one of them is geopolymer concrete. Davidovits coined the word "geopolymer" in the late 1970s which refers to an aluminosilicate binder, which is a member of an amorphous alkali [16]. Numerous investigations have been done to create a novel and ecologically friendly building material known as geopolymer concrete or alkali-activated concrete to decrease and further eliminate greenhouse gas emissions. To improve the quality of concrete and decrease the consumption of natural resources, it is essential to replace cement with industrial waste by-product substances such as red mud, fly ash, rice husk ash (RHA), silica fume and ground granulated blast furnace slag (GGBFS), which are activated by a high alkaline solution [17]. The aluminosilicate source determines the origin of the materials used as the binder in geopolymer concrete. These aluminosilicate substances must be abundant in silica and alumina. The GGBFS, fly ash, silica fume, metakaolin, red mud are a few examples of by-products that can contain these aluminosilicate compounds [18 - 22]. Geopolymers provide a vital solution to the consumption and disposal of wastes from the mineral extraction and processing sectors [23]. The recycling of waste materials and energy consumption put geopolymer concrete in the spotlight [24]. The best use of industrial waste is to utilize it as a building material which promotes sustainable building techniques and offers a way to minimize the use of traditional OPC in the construction sector, hence minimizing the significant environmental impact [25]. Figure 1 shows the advantages of geopolymer concrete in different areas.

Different source materials widely used in geopolymer concrete are fly ash, bottom ash, GGBFS, metakaolin, red mud, RHA and silica fume [27 - 29]. As geopolymer concrete properties are mainly dependent on a combination of source material and alkaline activators it is of utmost importance that proper selection of both are done [29, 30]. Though there are many reviews done by researchers in the area of geopolymer concrete, however, a systematic review of source materials is required to have a large impact on developing products which will be real-life applications. To maximize the research outcomes, it is also necessary to develop linkages with institutions that have expertise in areas of geopolymer concrete and hence knowledge of these institutes is required. Hence scientometric review is carried out over here which will give a brief overview of authors, institutes and countries working in the area of geopolymer concrete.

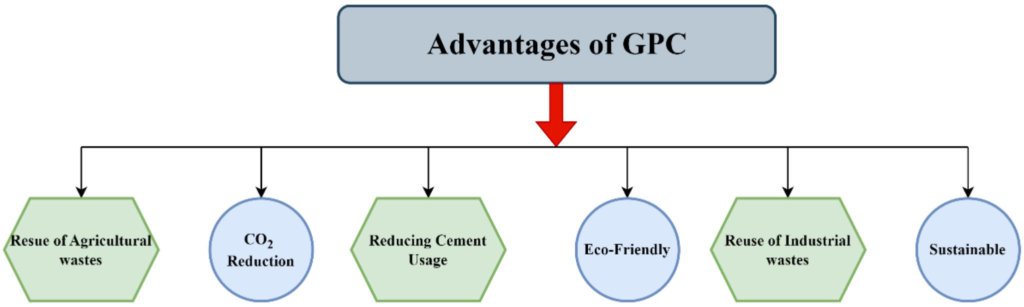

Figure 1. Image of advantages of geopolymer concrete.

Scientometric, also known as scientometric analysis includes a category of scientific mapping and is a useful method for gaining a thorough grasp of the ongoing research fields [31]. The goal of the present research work is to highlight the most significant publication source, most frequently used keywords, countries doing the research using various source materials and various institutions contributing to the research in the area of geopolymer concrete. This will help in the identification of the research gaps and further research required in this area. As a result of this research, researchers from various areas across the world may gain insight into further collaboration between research institutes, starting joint ventures, and exchanging groundbreaking ideas and technology [32].

2. METHODOLOGY

The main research methodology in this work is called "scientometric analysis" or "science mapping". This approach was chosen because it has a track record of successfully identifying systematic patterns in massive quantities of literature and bibliographic units [33 - 35]. In this study Scopus database was taken because it offers a wide range of coverage, a quicker indexing procedure and it includes current articles also. The keywords used to search the Scopus database included geopolymer concrete with fly ash, GGBFS, metakaolin, silica fume, RHA etc. To give a comprehensive database of results, the Scopus search algorithm takes up the pertinent phrases and related synonyms associated with the search query and keywords [32, 36]. Expert evaluation and research matrices have been used to gradually address fundamental scientific enquiry. Particularly important is the network visualization of bibliometric co-occurrence and co-citation [37].

2.1. Bibliometric analysis and data acquisition

The first stage of this study involved performing a bibliometric analysis to acquire the data needed for the scientometric analysis. Bibliometric analysis is a crucial component of the study evaluation approach employed by many researchers in the scientific field [31]. Because the scientific community posts a huge number of research articles, it becomes critical to know which database to rely on when looking for information. According to a study, the most thorough, efficient and objective databases for literature searches are Scopus and Web of Science, with Scopus having the database with the broadest coverage and the most current publications. The visibility and citation counts in these databases rank journals according to their importance, stature and influence [38]. One technique for undertaking bibliometric analysis that helps to illustrate the dynamic and structural element of scientific research is scientific mapping.

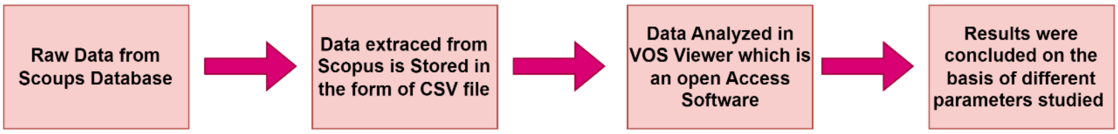

Figure 2. Process of scientometric review.

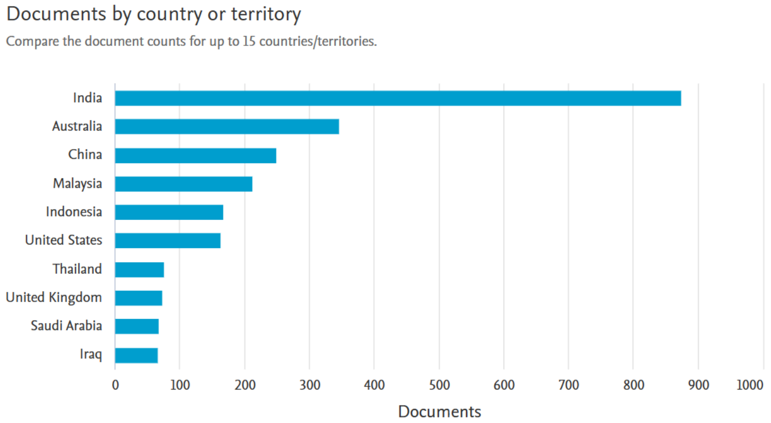

Figure 3. Image of documents by various authors using fly ash in geopolymer concrete (Scopus database).

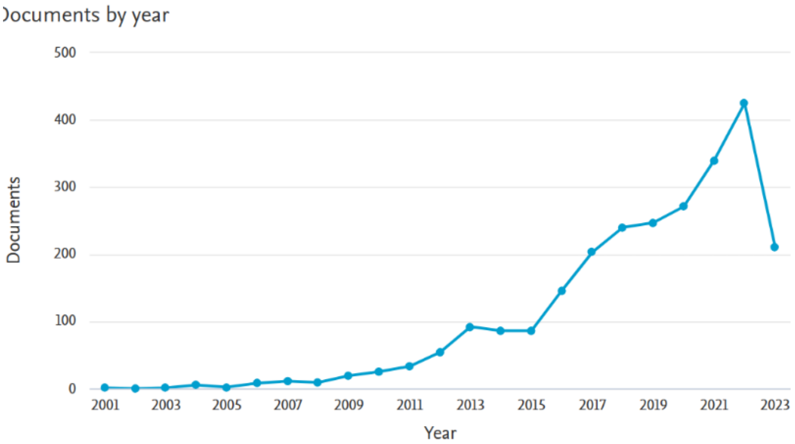

Figure 4. Image of annual publications of literature samples using fly ash in geopolymer concrete (Scopus database).

It offers a spatial representation of the relationship between different fields, publications, research groups, etc. There are many software programs accessible for science mapping [39]. VOSviewer [40] is a software that provides better visualization and graphical representation, than other scientific mapping tools, therefore, it was chosen for this investigation. Data was first imported from Scopus into VOSviewer, and then acquired data was utilized to create maps displaying objects like authors, journals, countries, keywords etc. from the database as shown in Figure 2.

The analysis of source material in geopolymer concrete was taken at different years for different materials. For fly ash, slag and silica fume the data acquisition was taken from 2001 to 2023, for metakaolin the set of material collected was from 2005 to 2023 and for RHA the record observed was from 2008 till present. The cluster of co-authors and co-occurrence of data with country, authors, organization and keywords was taken as a database and the analysis was done through scientific mapping including the network diagram, the overlapping diagram and the density diagram. Figure 3 represents the documents by authors of different countries who represented the work on geopolymer concrete with fly ash. Also, the literature sample collected per year for fly ash in geopolymer concrete is depicted in Figure 4. Both these images have been extracted with the help of Scopus analyzer.

2.2. Scientometric analysis

Since fly ash and GGBFS are two main industrial wastes widely used in geopolymer concrete, above 2,000 data samples were collected for the analysis of fly ash in geopolymer concrete and geopolymer mortar to explain changes in the mechanical and durability properties. Nearly 1,500 data samples were collected for geopolymer concrete with GGBFS, however, the data sample size of silica fume, RHA and metakaolin were below 500 which tends to show that fly ash and GGBFS have been widely used by researchers across the globe as major aluminosilicate material in geopolymer concrete production. Two fundamental scientometric analysis techniques were used in this study. These methods are co-author analysis and co-occurrence analysis. Co-author analysis consists of a network of authors, countries and organization lists whereas the co-occurrence analysis consists of a network for all types of keywords, the keywords given by authors and the indexed keywords. Figure 5 represents the visual aspects of the document type taken with the help of Scopus Analyzer. Journal publications and conference papers make up 64.5 % and 24.8 %, respectively. Conference reviews and book chapters were found to be around 3.7 % and 3.1%, respectively.

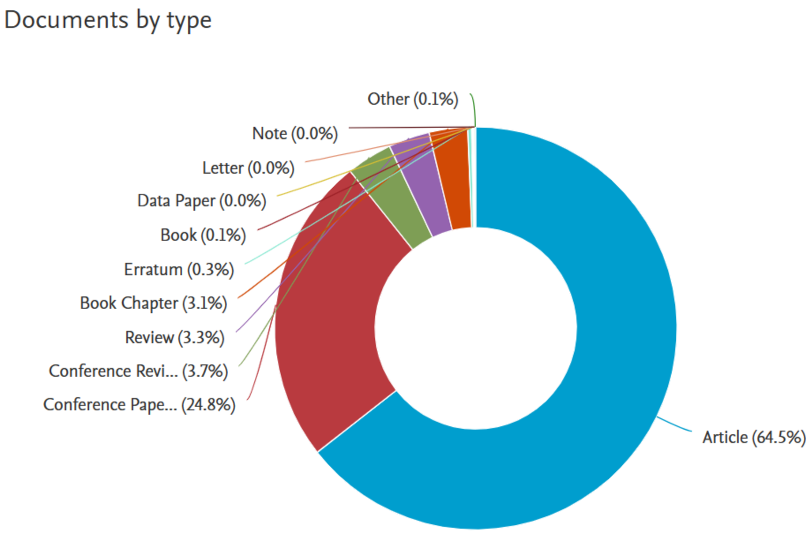

Figure 5. Image of type of document in geopolymer concrete using fly ash (Scopus database).

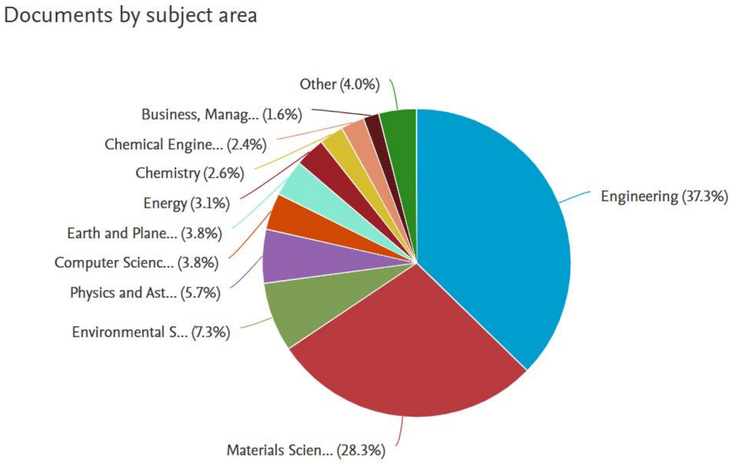

Figure 6. Image of subject areas where geopolymer concrete was prepared using fly ash (Scopus database).

Figure 6 represents the streams that took the research area based on subjective classification. It can be observed that Engineering and Material Science has published the majority of documents related to the incorporation of fly ash in geopolymer concrete. The total accountability of these subject areas nearly comprises 65.6 % of the whole document database. The least contribution is from the business and management section with a contribution of 1.6 % of the total literature taken with the help of the Scopus analyzer. Figure 7 represents the listed documents on the Scopus database using fly ash as a keyword in geopolymer concrete. Maximum articles were published in construction and building materials.

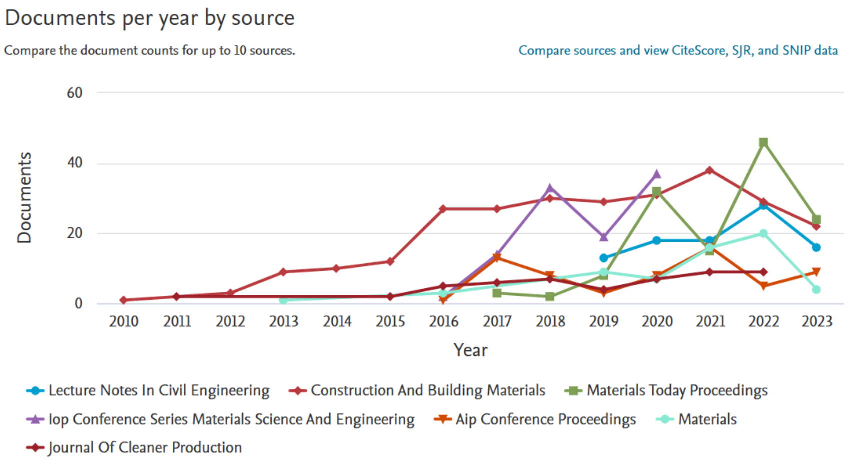

Figure 7. Image of various source publishing articles on fly ash in geopolymer concrete (Scopus database).

3. RESULTS AND DISCUSSION

Co-author and co-occurrence analysis was conducted to study the trends and patterns in geopolymer concrete with varied source materials.

3.1. Literature sample

The total literature sample shows the publication years spanning from the period of the first publication till date. The first publication of fly ash, silica fume and GGBFS commenced in the year 2001. The peaks for the use of fly ash were observed in the years between 2021 and 2023. The most productive years of research were between 2015 to 2021. The trends show that the researchers used fly ash as the primary source material in the geopolymer concrete production process. In the case of GGBFS, the peak was observed similarly to that of fly ash. However, the use of silica fume as a source material in geopolymer concrete was not extensively studied which can be attributed to the cost of raw silica fume available in the public domain. The study of metakaolin as a source material started from the year 2005 and the exemplary duration of the research was observed between 2017 and 2021.

The highest peak observed for the study on metakaolin as a source material was highest in the year 2021. However, the case with RHA was different as the first publication commenced in 2008, attained its high in 2021 and the most productive years were found between 2015 and 2021. Figure 8 depicts the literature sample of geopolymer concrete using RHA as a source material.

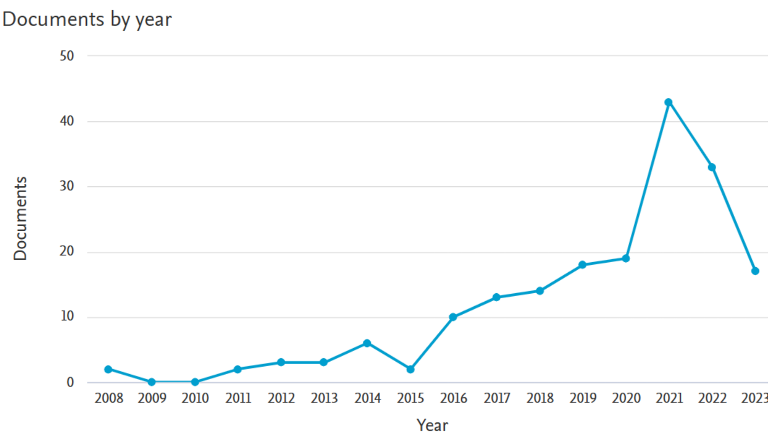

Figure 8. Image of literature sample as per year of publication on geopolymer concrete with RHA (Scopus database).

3.2. Research keywords

Keywords are the representation of words based on the core area of study signifying the research domain. Table 1 represents the keywords in most occurrences in the research articles used for the study of silica fume in geopolymer concrete. Silica fume, fly ash, geopolymer and compressive strengths were among the keywords that were occurring mostly with the link strength of 175, 149, 132 and 107; respectively. Similarly, the keywords selected by authors occurred mostly for fly ash and geopolymer concrete with link strengths of 1600 and 1119 in the fly ash geopolymer concrete database. The highest link strength was 377 and 268 in metakaolin-based geopolymer while that with RHA was 119 and 101. The keywords attained by authors in occurrence with slag as a source material and geopolymer concrete had the highest link strength of 971 and 943, respectively. The link strength above 15 was considered for selecting the keyword “silica fume in geopolymer concrete”. Figure 9 represents the network diagram of work done by different authors using “silica fume in geopolymer concrete” as a keyword.

Table 1. Keywords about authors with silica fume in geopolymer concrete

Keyword	Occurrences	Total link strength
Silica fume	70	175
Fly ash	58	149
Geopolymer	61	132
Compressive strength	52	107
Geopolymer concrete	64	104
Metakaolin	15	38
Slag	13	35
GGBFS	17	35
Durability	16	35
Concrete	12	29
Ground granulated blast furnace slag	12	27
Mechanical properties	15	25
Flexural strength	9	25
Sodium hydroxide	8	23
Ambient curing	8	22
Alkaline activator	7	18
Sodium silicate	7	18

Figure 9. Image of scientific mapping using network model for keywords by authors using silica fume with geopolymer concrete

3.3. Research institution

Table 2 represents the names of institutions working on silica fumes in geopolymer concrete whereas. Figure 10(a) represents the research institution with RHA in geopolymer concrete. On the other hand, Table 3 and Figure. 10(b) represent the name of the organization working with GGBFS in geopolymer concrete. These representations give an insight into different institutions working with different kinds of source materials around the world. The maximum citation with silica fume was 581 but none of the institutions had link strength hence, it was clear that a continuous need of collaborative research is required among institutions across the globe. On the other hand, Curtin University of Australia had the highest citation number of 1779 while the maximized link strength was found in the University of New South Wales, Sydney, Australia with a link strength value of 3 are working on GGBFS as a source material.

Table 2. Keywords about authors with silica fume in geopolymer concrete

Organization/Institution	Documents	Citations
University of South Carolina, Dept. of Civil and Environ. Engineering, Columbia, United States	6	581
Research and Technology Development Centre, Sharda University, Greater Noida, India	5	476
Department of Civil Engineering, University of Guilan, Rasht, Iran	4	43

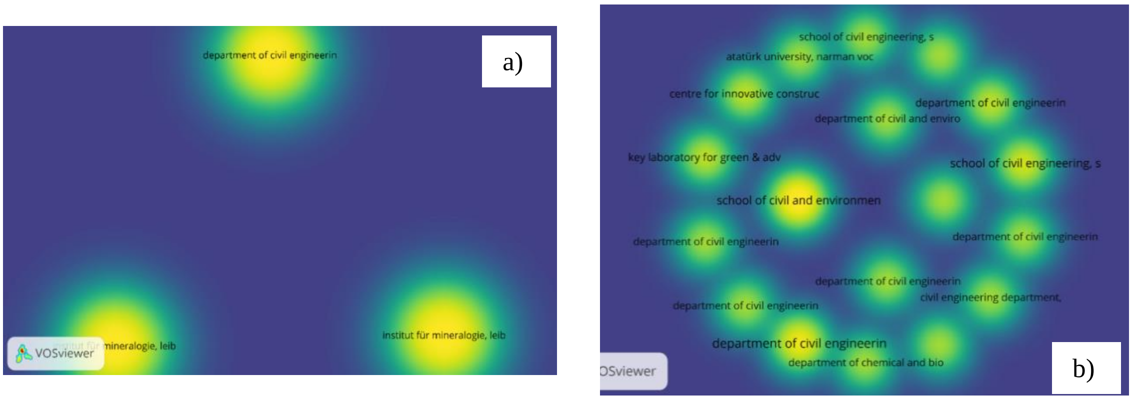

Figure 10. a) Image of scientific mapping using density model of rice husk ash in geopolymer concrete

b) Image of scientific mapping using density model of GGBFS in geopolymer concrete

Table 3. Name of institution concerning GGBFS in geopolymer concrete

Organization/Institution	Documents	Citations
Curtin University, Australia	5	1779
University of Melbourne, Australia	5	882
Key laboratory for Green & Advanced Civil Engineering Materials and Application Technology of Hunan province, China	6	217
School of Civil and Environmental Engineering, University of Technology, Sydney, Australia	7	214
Department of Civil Engineering, Indian Institute of Technology, Guwahati, India	9	184
School of Civil Engineering, Sastra University, Thanjavur, India	5	180
The University of New South Wales, Sydney, Australia	5	155
Centre for Innovative Construction Technology, Malaysia	6	155
School of Civil Engineering, Southwest Jiaotong University, Chengdu, China	7	150
Atatürk university, Turkey	5	126
Department of Civil Engineering, Hacettepe University, Ankara, Turkey	5	119
Department of Civil Engineering, Sri Jayachamarajendra College of Engineering, Mysore, India	5	79
University of the West Indies, Trinidad and Tobago	5	75
Department of Civil Engineering, Kütahya Dumlupınar University, Turkey	5	65
Department of Civil Engineering, University of Guilan, Rasht, Iran	6	52
Civil Engineering Department, Nigeria	5	43
Annamacharya Institute of Technology and Sciences, India	5	40
The Hong Kong Polytechnic University, Hong Kong	5	28
Atatürk University, Turkey	5	14

3.4. Countries

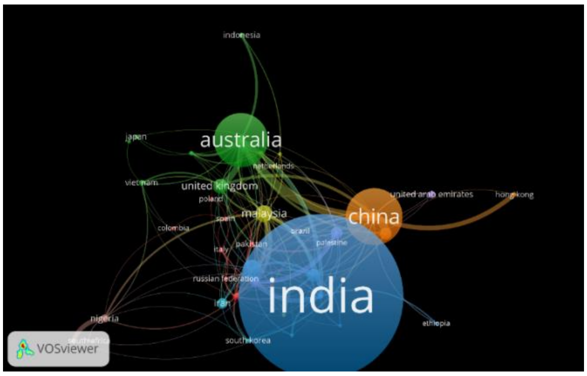

Figure 11. Image of scientific mapping using overlapping model for countries using GGBFS with geopolymer concrete

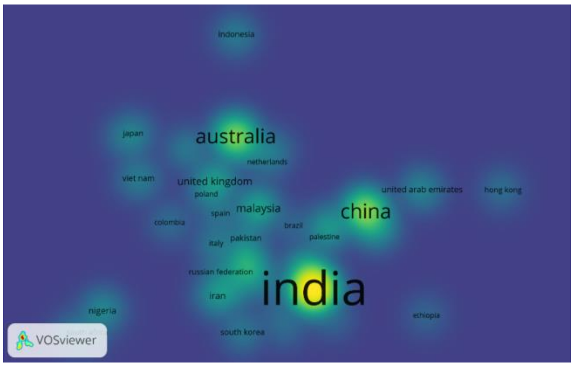

Figure 12. Image of scientific mapping using density model for countries using GGBFS with geopolymer concrete

Table 4. Name of country with respect to slag in geopolymer concrete

Country	Documents	Citations	Total link strength
Australia	173	11110	75
India	527	5242	52
China	182	4534	84
United Kingdom	47	3129	36
Malaysia	55	1986	60
United states	39	1556	32
Turkey	60	1206	28
Egypt	39	1022	27
Iraq	42	851	38
Saudi Arabia	32	733	52
Nigeria	27	426	24
Canada	23	371	38
Singapore	9	273	20
Pakistan	15	225	24

From Table 4, it can be visualized that Australia has the highest number of citations by just having 173 documents with a total link strength of 75, whereas India stands second in terms of citations having 5242 citations but has documents of 527 which is way higher than any other countries in the world. Hence, it is said that India has worked a lot more in slag-based geopolymer concrete than the rest of the world. However, China is having highest link strength, which is 84 which states that China is having a greater level of impact on other countries when it comes to geopolymer concrete with GGBFS as a source material. Countries having link strength above 20 were considered for mapping of the data. Figure 11 and Figure. 12 depicts the scientific mapping of slag in geopolymer concrete using an overlapping and density model.

3.5. Authors

The frequency with which two writers are referred together is tracked by the author co-citation network, which visualizes the intellectual structure of a specified knowledge subject. Knowledge is shared through authors, and spotting research collaboration can help in locating significant writers and assessing the state of the matter which in this case is the use of metakaolin in geopolymer concrete. Table 5 and Figure. 13 show a co-citation network, where each node represents a different author and different links represent on how the authors interact. Authors having citations above 100, are represented in Table 5. The lowest link strength taken for this study is 10. Table 6 and Figure. 14 depict the work done by various authors in the field of geopolymer concrete using fly ash as a source material. As a lot of work is done using fly ash, hence authors having citations above 400 are represented in Table 6.

Table 5. Name of authors working on metakaolin in geopolymer concrete

Author	Document	Citation	Total link strength
Rüscher C.H	21	714	49
Tchakouté H.K.	21	705	47
Leonelli C	19	662	43
Kamseu E	16	631	42
Abbas H	9	163	23
Al-salloum Y	9	163	23
Albidah A	9	163	23
Canpolat O	9	108	14

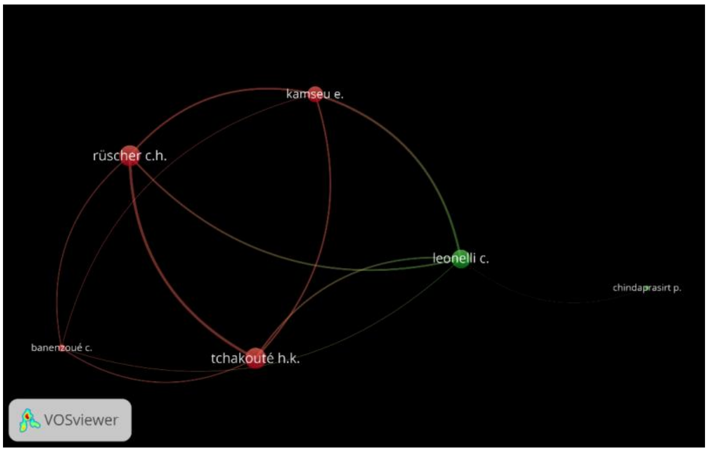

Figure 13. Image of scientific mapping using network model for authors working on metakaolin with geopolymer concrete

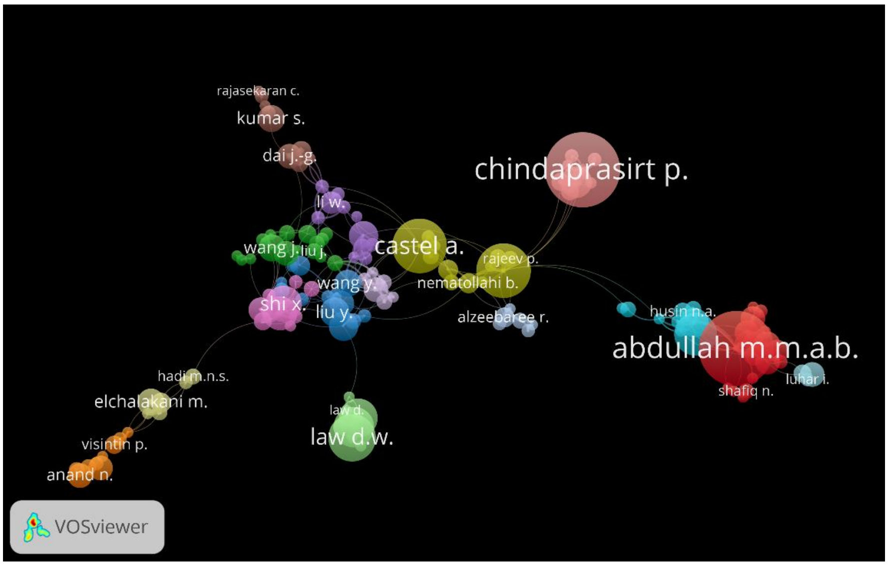

Figure 14. Image of scientific mapping using network model for authors working on fly ash with geopolymer concrete

Table 6. Name of authors working on fly ash in geopolymer concrete

Author	Documents	Citations	Total link strength
Castel A.	24	1326	28
Chindaprasirt P.	33	1036	49
Wang H.	11	934	16
Sata V.	14	838	34
Wang J.	12	772	19
Sanjayan J.	24	748	36
Zhang Z.	13	703	17
Setunge S.	17	690	34
Zhang M.	13	668	19
Gunasekara C.	18	662	38
Huang B.	8	619	19
Nuaklong P.	8	577	22
Jiang X.	5	525	17
Law D.W.	21	517	32
Shi X.	16	512	32
Wongsa A.	8	411	25

4. CONVENTIONAL REVIEW OF SOURCE MATERIALS USED IN GEOPOLYMER CONCRETE

Geopolymer concrete is manufactured from industrial by-products rich in silica and alumina ions. These ions when react with alkaline activators form a three-dimensional polymeric chain [16, 42 - 46]. The chain reaction is very fast and gives a steady structure and therefore has a lot of application in the civil engineering field. Generally, it is found that a high initial temperature is required for fast development of early strength, however, now a lot of parameters are varied and studied so that geopolymer concrete can be prepared at ambient curing [47 - 50].

Source materials have a pivotal role in developing the mechanical and durability properties of geopolymer concrete and they are discussed in detail below.

4.1. Fly ash

Fly ash is a by-product of the coal-fired power plant. In developed countries, as 70 % of power is produced by thermal power plants, hence enormous amount of fly ash is produced [51, 52]. Only about 25 - 30 % of the 780 million tonnes of fly ash produced gets utilized as per a survey report [53]. Fly ash is categorized as pozzolanic and cementitious depending on the Calcium Oxide content present in it and due to this reason, these are purchased by cement and concrete industries also utilized with soil [54]. In addition, a recent study demonstrates the use of fly ash in carbon nanotubes and aerogels [55]. Despite its extensive use in cement, the fly fly ash can only replace cement up to 35 % by mass which is a setback for the cement industry [56]. Because fly ash has a higher silica-to-alumina ratio and a low calcium content, it has been successfully used by many researchers to make geopolymer concrete with good strength and durability performance [57 - 60]. The inclusion of fly ash in geopolymer concrete depends upon the type of activators, curing conditions and particle size distribution [61, 62]. It is observed by many researchers that good mechanical properties are achieved when heat curing or steam curing is carried out when fly ash is used as source materials [63, 64]. The fly ash as source material in geopolymer concrete yields compressive strength in the range of 30 – 80 MPa when curing temperature varied from 60 to 80 ℃ for a period of 24 hrs to 72 hrs using activator to binder ratio in a range of 0.35 to 0.94 by various researchers. The range of flexural strength was from 4.9 to 12 MPa while the modulus of elasticity varied from 10.7 to 42 GPa [65 - 69]. Geopolymer concrete with fly ash as source material showed better durability properties as compared to OPC concrete. Better resistance to acid attack, sulphate attack, lower permeability carbonation and corrosion was observed by various researchers. The fly ash-based geopolymer concrete had pore refinement which led to longer durability at later ages [23, 69 - 73]. The fly ash-based geopolymer concrete showed excellent resistance to fire and very little reduction in compressive strength and spalling was observed [74 - 77]. The fly ash was also used with steel fibres to develop self-compacting fibre-reinforced geopolymer concrete having good compressive and tensile strength [78]. Some novel geopolymer composites have been developed using other waste materials like fly ash with polyethene terephthalate plastic bottles from packaging wastes [79]. Thus, the large use of fly ash as source material in geopolymer concrete can reduce risk to the environment, give better resistance in aggressive environments and enable better use of fly ash and bottom ash also [80, 81].

4.2. Ground granulated blast furnace slag

Geopolymer concrete with GGBFS can be produced at ambient temperature. The GGBFS when used as source material has higher compressive strength, higher flexural and shear strength and also high modulus of elasticity [82 - 84]. The GGBFS-based geopolymer concrete also has very good durability properties in terms of sulphate attack, acid resistance, carbonation and permeability of concrete compared to OPC concrete [82, 85 - 90].

4.3. Rice husk ash

Rice husk ash is obtained when the outer husk of rice is removed and burnt for the generation of power in boiler fuel. The RHA though contains a high amount of silica, most of it is in an amorphous state and hence it exhibits good compressive strength and durability properties. Compared to OPC, which has about 20 % silica, rice husk ash is a silica-rich aluminosilicate source with over 90 % SiO_2, ranking among the highest in silica content after silica fume and nano-silica. In contrast to the Al-O-Al and Si-O-Al bonds that are normally present in the combination, it has been observed that rice husk ash strengthens bonding in alkali-activated materials by creating Si-O-Si bonds, which lead to higher mechanical properties [91, 92]. Generally, lot of researchers have used rice husk ash with other industrial waste like fly ash, slag, metakaolin or other materials to obtain good mechanical and durability properties [93–96]. Generally, in geopolymer concrete rice husk ash can be used as an activator by dissolving it into sodium hydroxide or potassium hydroxide solution. This dissolved activator is then used to activate fly ash, slag, metakaolin or its combination. It was observed by the researchers that this activator gave higher compressive strength and also reduced density [97].

4.4. Metakaolin

Metakaolin is obtained when calcination of kaolin clay is carried out at a temperature between 600 – 900 ℃, which dehydrates the kaolin and transforms it into metakaolin. Metakaolin generally has 50 - 55 % silica and 40 - 45 % alumina ions and hence it possesses good zeolite properties thus possessing good mechanical and durability properties [98 - 101]. In order to maximise the Si/Al ratio of the binder, metakaolin is a crucial component, especially in low-calcium alkali-activated materials. It has been shown to greatly increase Class F fly ash's reactivity and speed up the polycondensation rate, which results in the creation of denser nano- and micro-structures. This produces better mechanical qualities when cured at high temperatures [102].

4.5. Silica fume

Silica fume is obtained as a byproduct in the production of ferrosilicon alloy. It is rich in silica ions and hence has high pozzolanic reactivity index. Silica fume is also included in geopolymer concrete with other industrial waste like fly ash, GGFBS or metakaolin yielding excellent mechanical and durability properties [103 - 106]. Alkali-activated mixes usually contain silica fume, a very pure silica substance, as a filler. Studies show that the mechanical strength and durability of alkali-activated materials are constantly improved by their tiny particle size. Silica's improved availability for subsequent reactions with aluminosilicate sources in the mixture and its function as a filler, which lessens the permeability of the hardened alkali activated materials (AAM), are the causes of this improvement [107, 108].

4.6. Minor alkali-activated materials

The type of precursor utilised determines the mixture's chemical makeup in AAM, and frequently, low reactivity calls for the application of particular strategies to increase the mixture's reactivity. Aluminosilicate-rich materials make up the majority of the precursors in AAMs, which react with alkaline solutions to form a solid binder that resembles cement. To increase the range of materials that can aid in geopolymerization, both natural and artificial pozzolans are occasionally included, such as GGBFS and volcanic ash. By reducing CO_2 emissions and using industrial by-products, these precursors provide an environmentally acceptable substitute for conventional Portland cement. In contrast to other popular supplemental cementitious materials, red mud, a byproduct of alumina manufacture, has a higher alkalinity and a lower Si/Al ratio. It predominantly comprises Fe, Al, and Si. Nevertheless, it can be used as a filler or as a partial precursor substitute in AAM in small concentrations (usually greater than 15 %) [109, 110].

When utilised in AAM, paper sludge, a microfiber-based byproduct of the papermaking process, has improved mechanical qualities, flowability, and drying shrinkage. The sludge's notable Fe to Si component ratio is partially to blame for these effects [111, 112].

One of the main waste materials that can be recycled indefinitely is glass, which is produced at a rate of between 50 and 100 Mt year. However, it is believed that between 30 and 70 percent of all glass produced ends up in landfills due to economic concerns. The main constituents of glass are Si, Na, and Ca. Due to its pozzolanic qualities, glass can be utilised as a precursor in the form of fine powder in AAM; it can also be employed as a filler or as a natural aggregate alternative. When employed as an aggregate, glass may exhibit expanding behaviour and raise the system's alkalinity, according to research [113 - 115]. Fly ash, coal bottom ash[116, 117], industrial slags, and silica fume [118 - 120] are examples of industrial waste materials that are byproducts of the burning of coal and the production of metal. These materials are suitable for concrete applications because they have properties similar to those of cement. In addition to these, siliceous minerals like opal, volcanic materials like pumice and pumicite, and both natural and artificial pozzolans add significant reactivity to concrete formulations. Furthermore, tailings-remaining materials from mining operations—are also successfully recycled into building projects [121, 122]. The composition of tailings from mining activities varies. It has been demonstrated that AAM have advantages such as a strong resistance to acids, a rapid increase of mechanical strength, and an ideal Si/Al ratio [123, 124].

Combustion plants produce ash from the incineration of municipal solid waste (MSW) and makes up roughly 10 - 15 % of the MSW's initial volume and 20 - 35 % of its initial weight. Ash from MSW incineration is renowned for having a very diverse makeup. Glass powder[125], sludge ash [126, 127], paper sludge[128], and recovered plastics are among the components found in municipal solid waste that can be used to make concrete. Garbage rubber [129], building debris, and incinerator ashes from municipal garbage (both fly ash and bottom ash) are also included in this category [130 - 133]. By reducing the need for new raw materials, adding these recycled components to concrete improves its qualities, such elasticity and durability, and encourages a more environmentally friendly building method. It has demonstrated encouraging outcomes when utilised in AAM, such as enhanced leaching performance and frequently better mechanical qualities in contrast to conventional supplemental cementitious materials [128, 131, 134].

5. CONCLUSION

As study in the area of geopolymer concrete grows, researchers are confronted with an abundance of information that could impede fruitful researcher efforts and inter-researcher collaboration. Hence, the methodology that enables the researcher to extract useful data from the most trustworthy databases must be found and adopted.

The uniqueness of this study depends on the following reasons: -

- Unlike previous studies, the outcome of this research is more comprehensive and conclusive and relies on quantitative analysis.
- This study maps the use of various source materials in geopolymer concrete in the construction industry with a holistic approach.

- This study clearly reveals the knowledge base, knowledge domain and knowledge evolution of varied source materials in geopolymer concrete.

Through the outcomes of this investigation, researchers and practitioners could comprehend the top countries, institutions, authors, journals and influential publications related to varied source materials in geopolymer concrete. Further, this investigation will be informative, a valuable reference and will be a guide to the upcoming budding innovative researchers of various countries willing to do research in the field of geopolymer concrete. Along with the scientometric review, a conventional review is also carried out to enable researchers to know the effect of various source materials on the mechanical and durability properties of geopolymer concrete.

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