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Review

A Bibliometric Review of Lightweight Aggregate Geopolymer Concrete

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Abstract: The increase in cement production has had a noteworthy impact on the emission of greenhouse gases. As a result, it is essential to develop geopolymer concrete innovations to mitigate the environmental consequences. However, conventional geopolymer concrete not only requires heavy machinery and an increase in the cross-sectional area of structural supports, but it also endangers the operating safety of workers. Therefore, in recent times, lightweight concrete has gained significant attention due to its many advantages and benefits to the structure and construction sectors. Thus, the aim of this study is to carry out a bibliometric analysis of the lightweight geopolymer concrete and assess its fundamental characteristics to determine the research gap in this area. This review paper will benefit researchers in identifying the ongoing trend in lightweight aggregate geopolymer concrete, identifying more areas for additional study. It will also act as a knowledge source for policymakers, journal editors, professionals, and research organizations.

Keywords: geopolymer concrete; lightweight aggregates; bibliometric analysis; mechanical properties

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1. Introduction

In the past two decades, developed countries have limited the use of natural building materials. This has led various government agencies and researchers worldwide to invest their efforts and resources in creating new eco-friendly materials with the potential to reduce the consumption of cement and other conventional components [1]. Therefore, in the last decades, the area of concrete technology has made significant discoveries with the objective of reducing or eliminating the usage of Portland cement. As an example, back in the 1950s, Glukhovsky put forward the concept of alkali-activated cementitious materials, often referred to as "soil silicates". Later, during the late 1970s, Davidovits introduced the term "inorganic aluminosilicate polymers", which has become widely known as "geopolymers". These inorganic polymers are regarded as environmentally friendly substitutes for Portland cement because of their minimal carbon footprint. Among those inventions and innovations, the geopolymer concept is one of the most widely used substitutes for producing concrete without cement.

Nonetheless, conventional geopolymer concrete is not viable for high-rise building projects. This is because it necessitates the use of heavy machinery, leading to an escalation in the overall construction expenses, and poses a safety risk to the personnel involved in the operation [2]. Therefore, in recent times, lightweight concrete has gained considerable attention due to its many advantages and benefits to the structure and construction sectors. According to Shafigh et al. (2010), lightweight concrete has been utilized since bygone days and is an extremely fascinating area of research due to its numerous advantages [3]. These benefits include improved heat insulation, fire and frost resistance, sound absorption, superior anti-condensation properties, and increased seismic damping. Additionally, lightweight concrete is known for its ability to reduce the self-weight of structures and sectional members, making construction more convenient [4]. Utilization of lightweight aggregates is an extremely trendy way of accomplishing lightweight concrete fabrication [5,6]. Therefore, this review employs a bibliometric analysis to depict the evolution of lightweight geopolymer concrete over the past few decades. It also delves into the ongoing discourse and research associated with this technology. The aim of this review is to provide a more comprehensive understanding of the existing body of knowledge, particularly within the construction and building materials domain, with an emphasis on fostering sustainability and dependability in construction practices.

2. Methodology

With the extensive number of research papers published by the scientific community, it is critical to know which databases to rely on when looking for information. Journals are ranked by Scopus and Web of Science (WoS) based on their visibility and citation number, which reflect their significance, standing, and influence. The database used in this study was constructed through an extensive search process using Scopus' advanced search option as the primary database. This choice was made due to its capacity to provide more than four times the number of documents related to lightweight aggregate geopolymer concrete per download compared to WoS, which had a limitation of approximately 500 publications per download. This larger dataset from Scopus facilitated the ease of conducting bibliometric analysis and visualization.

The search term used in Scopus was "lightweight aggregates geopolymer concrete", followed by a manual review of the titles, keywords, and abstract sections of the retrieved papers. We removed off-topic literature that focused on other subjects or was unrelated to lightweight aggregate geopolymer research throughout the successive filtration. Following that, all relevant papers were downloaded.

The examination was carried out using the VOSviewer program and Scopus analyzer. VOSviewer (version 1.6.19) is a free software program for creating maps from network data, as well as displaying and exploring them. Not only that, VOSviewer distinguishes itself from other bibliometric mapping tools by placing particular emphasis on the visual representation of bibliometric maps [7]. VOSviewer is primarily designed for bibliometric network analysis, but it may also be used to create, analyze, and explore maps based on any sort of network data [8]. VOSviewer can perform a variety of analyses, such as co-authorship, keyword co-occurrence, and co-citation of cited journals/authors/references. Furthermore, the Scopus core collection database was used to provide core data, such as yearly publishing and citation statistics, as well as different sorts of documents that may show the evolution of lightweight aggregate geopolymers through time and the leading institutions in a certain subject area. The initial Scopus dataset was subsequently processed using VOSviewer to present bibliometric distributions categorized by countries, cited sources, and the co-occurrence of author keywords.

3. Bibliometric Analysis

Figure 1 shows a graphic illustration of the various document types included in the data obtained from the Scopus database, as assessed by the Scopus analyzer. According to Figure 1, conference papers and journal articles comprise 21% and 62.9% of lightweight aggregate geopolymer concrete documents, respectively. Since conference papers and journal articles represent nearly 84% of the total data collected, the study and discussion will largely focus on them as sources of information.

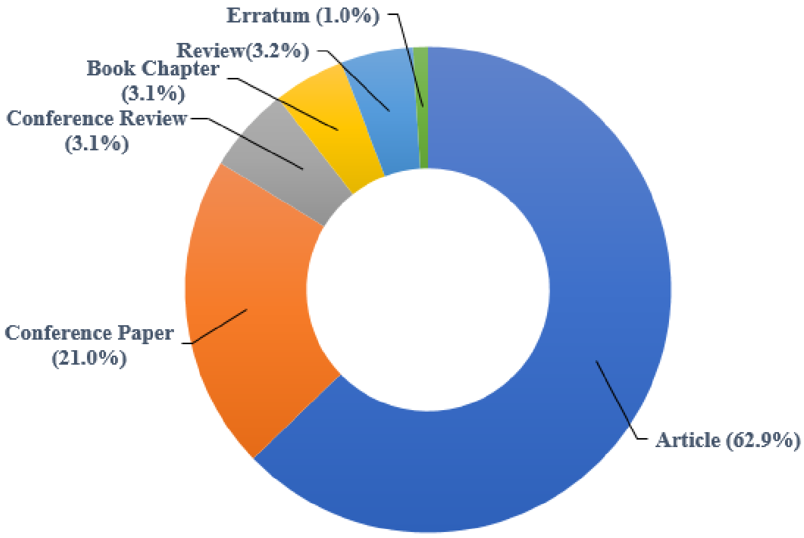

Figure 1. Types of documents available related to lightweight aggregate geopolymer concrete.

3.1. Literature Samples

Figure 2 displays the whole literature sample, with publication years ranging from 2008 to 2022. The first paper on lightweight aggregate geopolymers was discovered in 2008, and since then, academics have developed an interest in the field. Furthermore, the number of publications increased dramatically from 2012 to 2013 and fluctuated from 2013 to 2017. Next, the total number of publications increased significantly, starting from 5 publications in 2017 and reaching its peak of 16 publications in 2022. As a result, the number of publications was predicted to continue to rise in the future years.

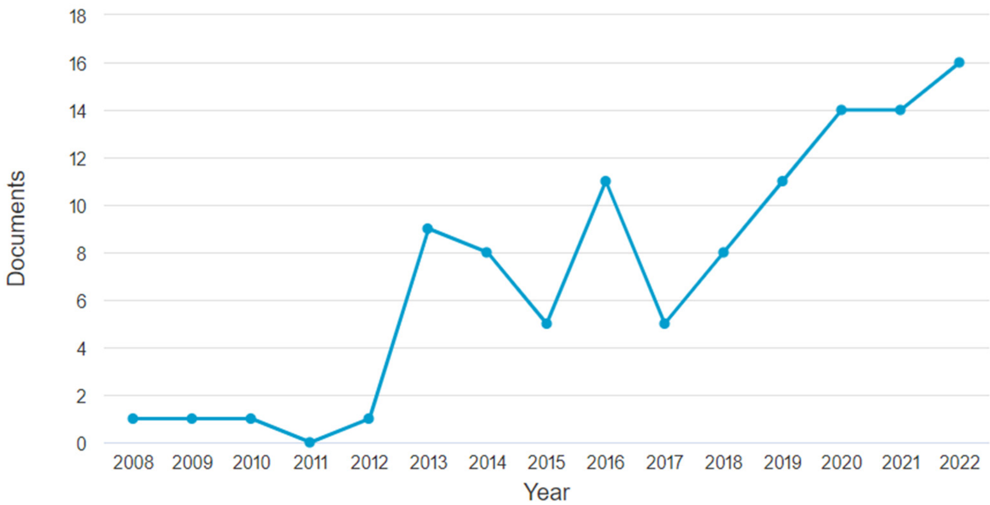

Figure 2. Publication years of literature on lightweight aggregate geopolymers.

3.2. Research Keywords

The fundamental content of literature is indicated by keywords defined by authors. As a result, applying keyword-related data to a body of literature on a certain topic might lead to helpful insights into the study domain's core focus [9]. The keywords having the most occurrences in the research papers selected for this investigation are listed in Table 1. The most commonly used terms in the studies were geopolymer and lightweight aggregates, with fly ash and lightweight geopolymer rounding out the top four. Figure 3 illustrates the visualization of author keyword co-occurrence and their connectedness to one another based on link strength. After adjusting the minimum occurrence to 2, 52 out of 239 author keywords are presented in 9 color-coded clusters. The size of the node represents how frequently terms are used. A keyword occurs more often as the size of a node grows. The most common term in the research of lightweight aggregate geopolymers is geopolymer, which appeared 55 times and had a total link strength of 130.

Table 1. Keywords used in the research articles.

S/N	Keyword	Occurrences	Total Link Strength
1	Geopolymer	55	130
2	Lightweight aggregate	21	56
3	Fly ash	16	48
4	Lightweight geopolymer	14	37
5	Compressive strength	11	29
6	Lightweight concrete	11	27
7	Alkali activation	10	33
8	Mechanical properties	10	25
9	Thermal conductivity	9	28
10	Artificial lightweight aggregate	8	22
11	Elevated temperature	7	22
12	Microstructure	7	25
13	SEM	5	20
14	Aggregate	3	6
15	Density	3	7
16	Durability	3	9
17	Expanded perlite	3	10
18	Expanded polystyrene	3	11
19	Lightweight	3	7
20	Metakaolin	3	11
21	Strength	3	7
22	Sustainability	3	9
23	Thermal insulation	3	8
24	Aggregate crushing value (acv)	2	7
25	Aggregate impact value	2	6
26	Composite	2	6
27	Construction materials	2	4
28	Expanded clay aggregate	2	7
29	Foamed concrete	2	6
30	Geopolymerization	2	4
31	GGBS	2	7
32	Glass powder	2	5

Table 1. *Cont.*

S/N	Keyword	Occurrences	Total Link Strength
33	Granulation	2	4
34	Inorganic polymer	2	4
35	Lightweight mortar	2	7
36	Microwave irradiation	2	3
37	NaOH	2	4
38	Oil palm shell	2	6
39	Palletizing	2	7
40	Palm oil clinker	2	4
41	Palm oil fuel ash	2	6
42	Passive fire protection	2	4
43	Physical and mechanical properties	2	2
44	Physico-mechanical performance	2	4
45	Recycled lightweight aggregate	2	4
46	Recycling	2	5
47	Thermal properties	2	5
48	Thermal shrinkage	2	8
49	Volcanic ash	2	7
50	Water absorption	2	7
51	XRD	2	8
52	XRF	2	8

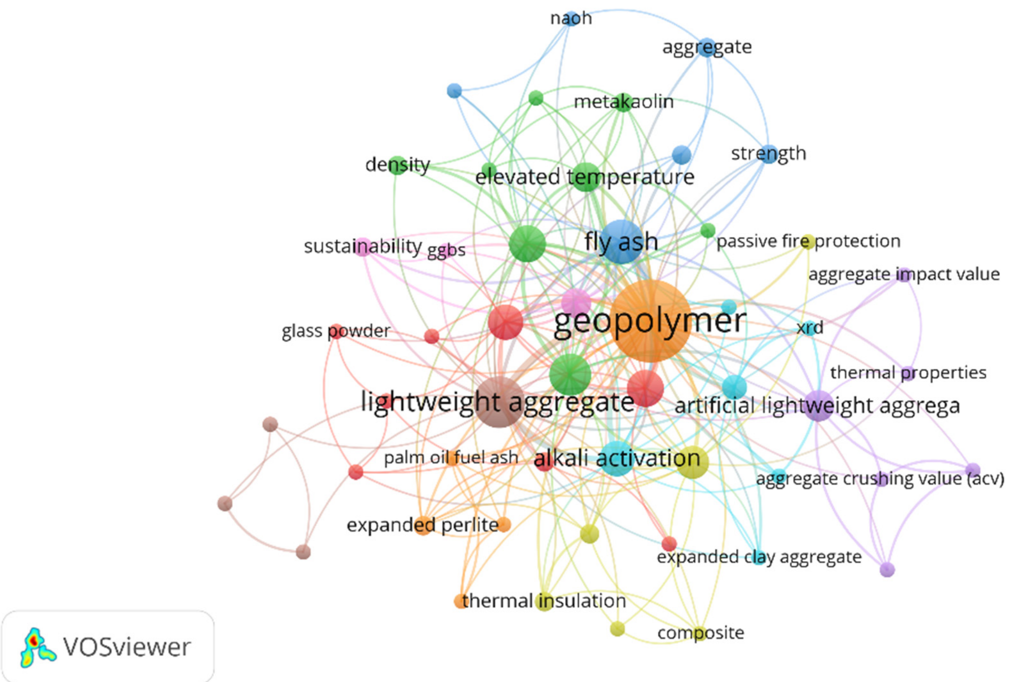

Figure 3. Visualization of co-occurrence of author keywords.

3.3. Sources of Documents

Table 2 displays the number of publications by various sources in the field of lightweight aggregate geopolymer research. *Construction and Building Materials* placed first in terms of effect in the ranking, with a total number of 22 publications. Figure 4 displays a breakdown of publications on lightweight aggregate geopolymers from 2008 to 2022, organized by source and year, as analyzed by Scopus. The graph indicates that *Construction and Building Materials* is the leading journal in terms of publishing literature on lightweight aggregate geopolymers. This might be due to the number of citations for Construction and Building Materials is the highest, which is 868 in the domain of research focusing on geopolymers incorporating lightweight aggregates.

Table 2. The number of documents on lightweight aggregate geopolymers published by various sources.

Rank	Journal	No. of Publications	No. of Citations	CiteScore (2022)	The Most Cited Article	Times Cited	Publisher
1	*Construction and Building Materials*	22 (21.0%)	868	12.3	[10]	162	Elsevier
2	*Key Engineering Materials*	7 (6.7%)	6	0.9	[11]	3	Trans Tech Publications Ltd.
3	*Advanced Materials Research*	6 (5.7%)	7	45.6	[12]	5	Trans Tech Publications Ltd.
4	*Journal of Building Engineering*	5 (4.8%)	68	8.2	[13]	28	Elsevier
5	*Cement and Concrete Composites*	4 (3.8%)	164	15.4	[14]	104	Elsevier

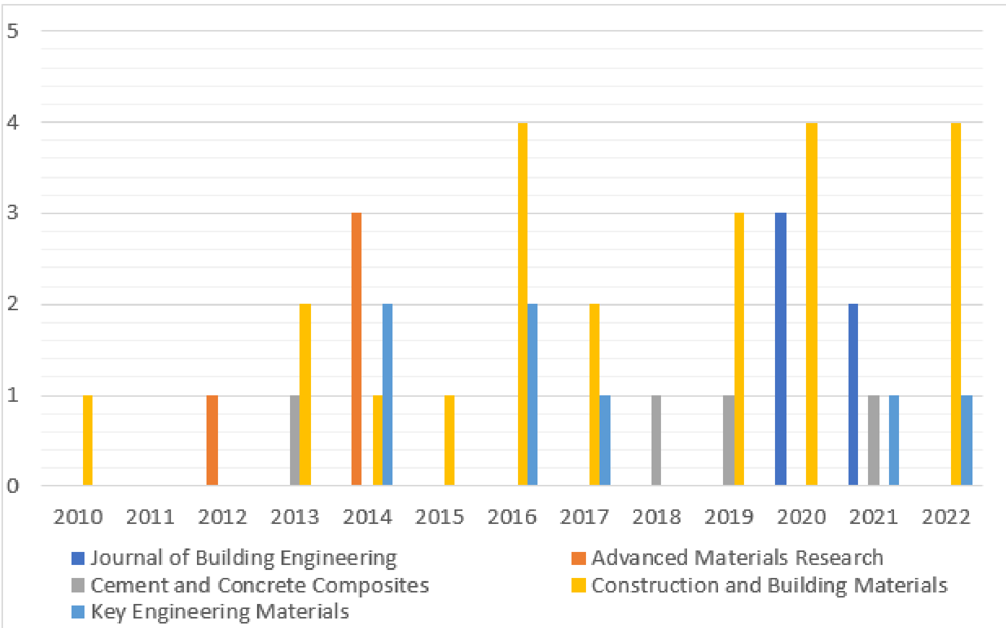

Figure 4. The number of documents on lightweight aggregate geopolymers published by source per year.

3.4. Publications by Author

Table 3 displays various authors' publications and total citations in the field of lightweight aggregate geopolymers, as gathered from the Scopus database. From the table below, it can be observed that Abdullah, Mohd Mustafa Al Bakri has 62 total citations and 8 publications, followed by Hussin, Kamarudin, who has seven publications. However, it can be observed that Alengaram, U. J. has the highest total citations, which is 313, with just five publications. Figure 5 illustrates authors who have published at least two papers in the field of lightweight aggregate geopolymers, along with the connections between their published articles and other authors in terms of article publication collaboration. According to the figure shown in the VOSviewer, Abdullah, Mohd Mustafa Al Bakri has the highest node size, indicating that he has the most publications.

Table 3. Number of publications on lightweight aggregate geopolymers and total citations per author.

Rank	Author	Scopus Author ID	Year of 1st Publication	Total Publication	h-Index	Total Citation	Current Affiliation and Country
1	Abdullah, Mohd Mustafa Al Bakri	53164519100	2008	8	41	62	Universiti Malaysia Perlis, Arau, Malaysia
2	Hussin, Kamarudin	16642513600	1994	7	41	62	Universiti Malaysia Perlis, Arau, Malaysia
3	Abdulkareem, O. A.	54393305300	2011	5	7	184	Louisiana Tech University, Ruston, LA, USA
4	Alengaram, U. J.	26533874300	2008	5	51	313	Universiti Malaya, Kuala Lumpur, Malaysia
5	Chindaprasirt, Prinya	8302542200	1980	5	70	192	Khon Kaen University, Khon Kaen, Thailand
6	Hardjito, Djwantoro	6508089898	1994	5	14	30	Universitas Kristen Petra, Surabaya, East Java, Indonesia
7	Ismail, Khairul Nizar	51161627800	2006	5	24	48	Universiti Malaysia Perlis, Arau, Malaysia
8	Rashid, Khuram	56725212400	2015	5	17	64	University of Engineering and Technology, Lahore, Lahore, Pakistan

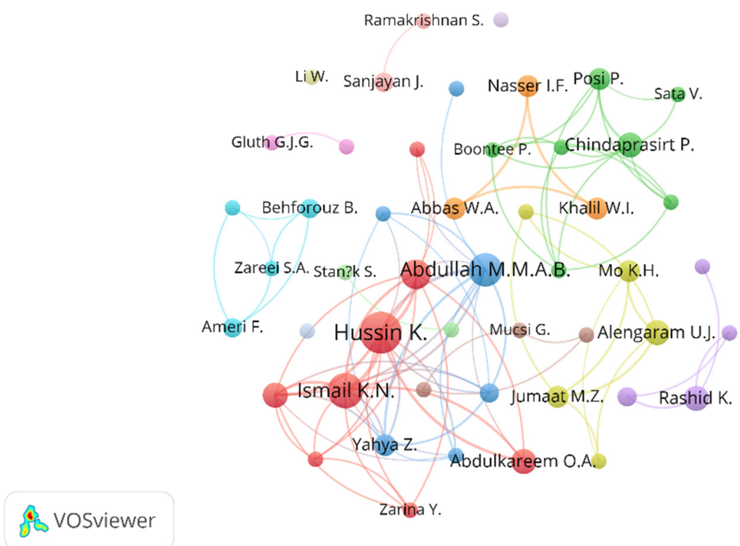

Figure 5. Visualization of authors with at least two published articles on lightweight aggregate geopolymers.

3.5. Research Institutions

Table 4 lists the research institutes that contributed the most to the study of lightweight aggregate geopolymers, as determined by Scopus. With 19 and 7 documents produced, respectively, the Universiti Malaysia Perlis (UniMAP) and University of Malaya (UM) have had the most impact on lightweight aggregate geopolymer research. The visualization of research institutes engaged in lightweight aggregate geopolymer research is shown in Figure 6. The greatest overall link strength is just 16 institutions, which are the Center of Excellence Geopolymer and Green Technology (CEGEOGTECH), School of Materials Engineering, Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia, indicating the necessity for ongoing collaboration amongst research institutes. Figure 7 shows a map with the location of the top 10 most productive academic institutions in lightweight aggregate geopolymer concrete.

Table 4. Research institutions with their number of publications on lightweight aggregate geopolymers and total citations.

S/N	Organization	Documents	Citations	Total Link Strength
1	Universiti Malaysia Perlis	19	380	8
2	University of Malaya	7	602	3
3	Khon Kaen University	5	301	3
4	Petra Christian University	5	47	6
5	University of Engineering and Technology	5	73	5
6	University of Technology	5	25	4
7	Curtin University	4	130	3
8	Islamic Azad University	4	160	5
9	Middle Technical University	4	23	4
10	Al Imam Mohammad Ibn Saud Islamic University	3	32	5
11	Rajamangala University of Technology Isan	3	82	3
12	Swinburne University of Technology	3	101	0
13	Universiti Sains Malaysia	3	34	4
14	University of Aveiro	3	78	1
15	University of Miskolc	3	30	0
16	Gaziantep University	2	21	0
17	Hunan University	2	133	1
18	Indian Institute of Technology Madras	2	131	1
19	King Saud University	2	27	4
20	Gheorghe Asachi Technical University	2	17	3
21	National Technical University of Athens	2	10	1
22	Sharif University of Technology	2	79	4
23	Texas State University	2	44	3
24	University Of Oulu	2	86	1
25	Bundesanstalt für Materialforschung	2	35	2

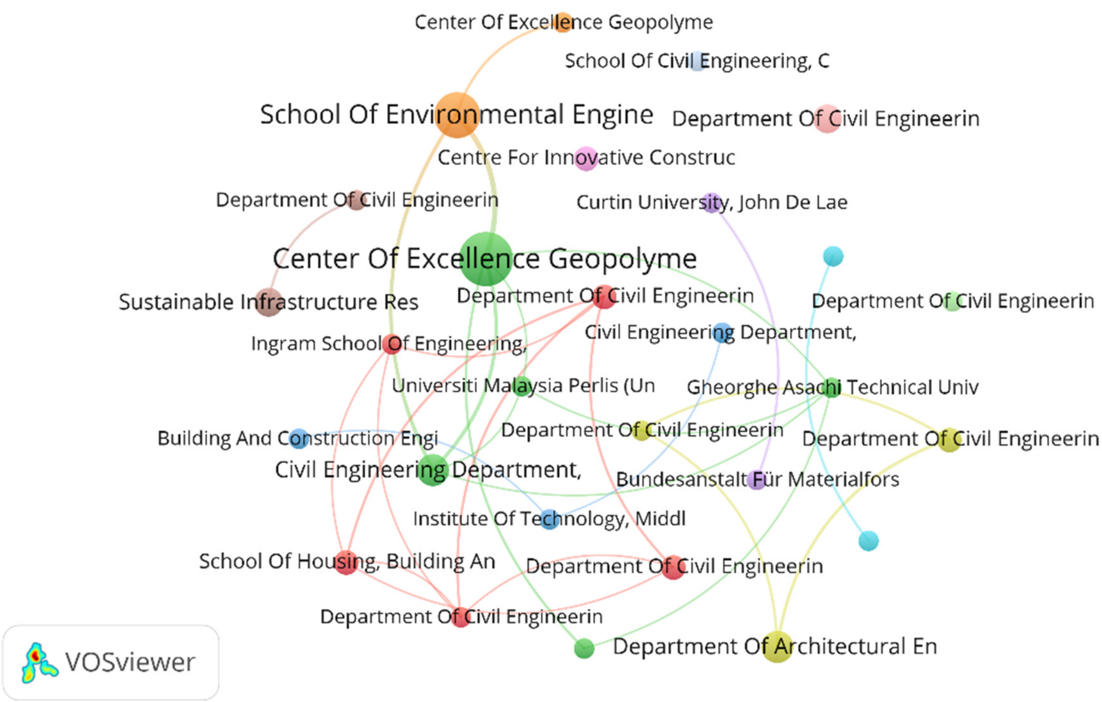

Figure 6. Visualization of the relationships between the published works on lightweight aggregate geopolymers and all research institutions.

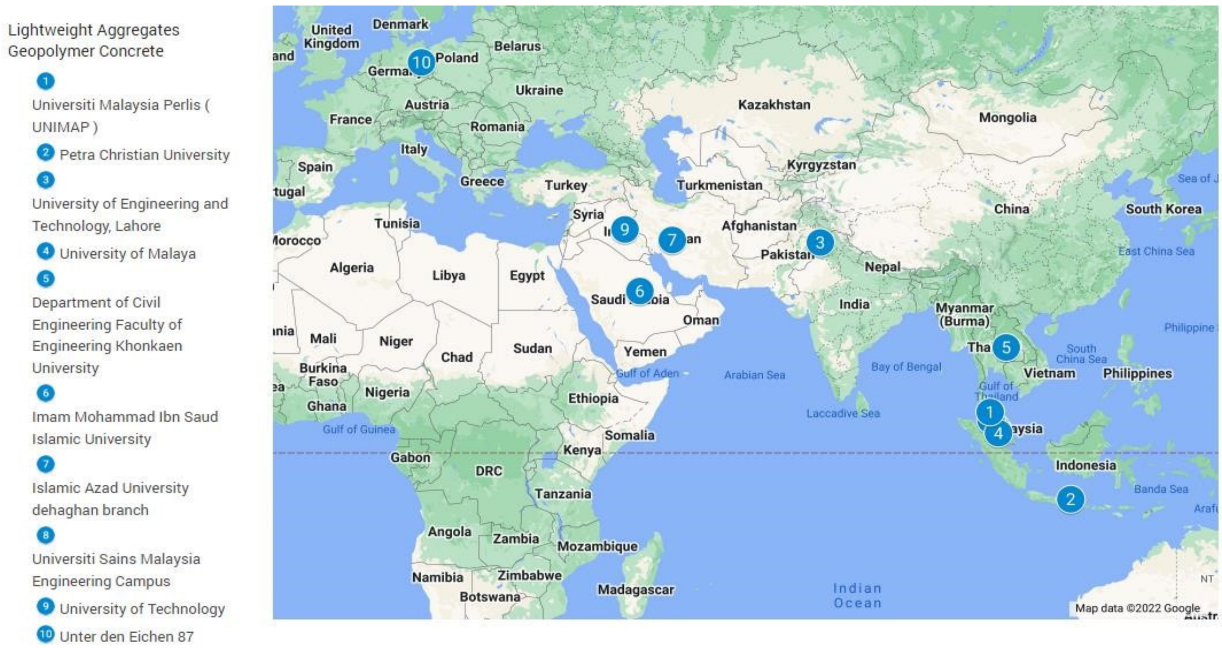

Figure 7. Location of the top 10 most productive academic institutions in lightweight aggregate geopolymer concrete research.

3.6. Countries

This study provided general bibliometric information and conducted a co-authorship analysis among different countries to ascertain the most prolific and influential nations, along with their collaborative network, within the domain of lightweight aggregate geopolymers. Table 5 shows the nations where the majority of lightweight aggregate geopolymer research was conducted. Malaysia has a commanding lead in the standings with the greatest number of publications and total citations, with 31 and 1016, respectively, followed by Australia with 11 publications and 412 total citations, respectively, making them the highest contributing countries on lightweight aggregate geopolymer research. In Figure 8, the VOSviewer was used to visualize the co-citation connection between the 36 nations that have published research on this topic. Through the cooperative network across all 36 nations, the VOSviewer identified 16 clusters in various colors. The presence of a link between two countries indicates that they have a cooperative relationship, and the stronger the link, the stronger their collaboration. As shown in the figure, Malaysia has the greatest overall link strength, with 22 total links. Figure 9 displays the total number of documents by nation analyzed by Scopus; similar to the results obtained in Table 5, Malaysia has the greatest number of publications, followed by Australia. This might be because Malaysia has intensified its efforts to promote sustainability by expanding funding opportunities and aligning research priorities with the United Nations' Sustainable Development Goals (SDGs), such as SDG 9 (Industry, Innovation, and Infrastructure) and SDG 13 (Climate Action). Therefore, Malaysia has the most financing, with a total of 10 publications sponsored by the UM and the Ministry of Higher Education, as shown in Figure 10.

Table 5. Influential countries with the number of publications on lightweight aggregate geopolymers and total citations.

S/N	Country	Documents	Citations	Total Link Strength
1	Malaysia	31	1016	22
2	Australia	11	412	11
3	Indonesia	9	61	13
4	Iraq	8	40	2
5	China	7	311	2
6	Saudi Arabia	6	79	9
7	Thailand	6	301	1
8	Turkey	6	114	5
9	India	5	164	5
10	Pakistan	5	73	4
11	Iran	4	160	4
12	Portugal	4	145	3
13	United States	4	114	3
14	Finland	3	86	2
15	Germany	3	35	3
16	Hungary	3	30	0
17	Italy	3	227	1
18	Romania	3	20	7
19	Brazil	2	29	1
20	Czech Republic	2	3	0
21	Greece	2	10	1
22	United Kingdom	2	185	2
23	Belgium	1	0	1
24	Bulgaria	1	0	0
25	Egypt	1	8	1
26	France	1	25	0
27	Hong Kong	1	32	0

Table 5. *Cont.*

S/N	Country	Documents	Citations	Total Link Strength
28	Jordan	1	11	0
29	Mexico	1	158	0
30	Netherlands	1	39	1
31	Nigeria	1	18	4
32	Poland	1	4	0
33	South Korea	1	5	2
34	Taiwan	1	21	0
35	Tunisia	1	18	4
36	United Arab Emirates	1	53	0

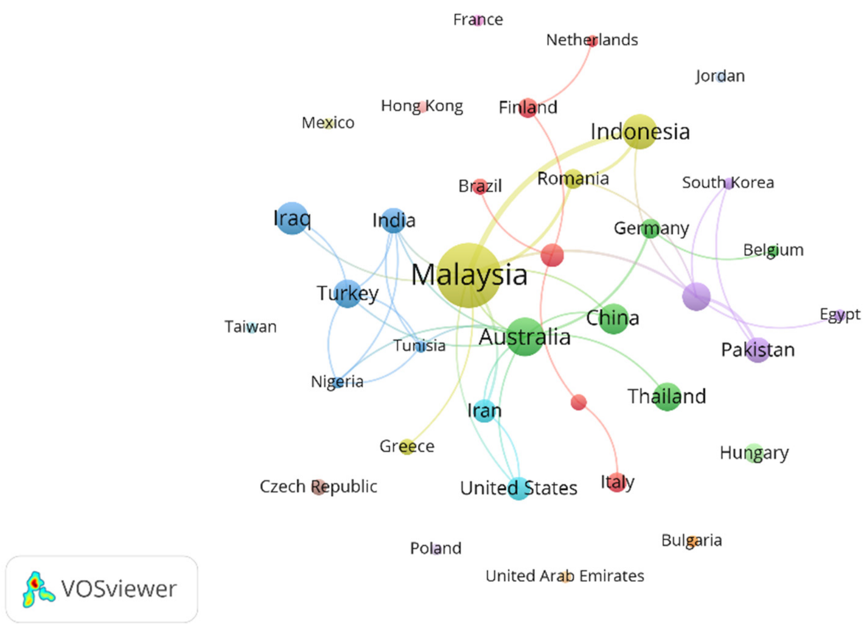

Figure 8. Graphical representation of co-citation relationship between countries.

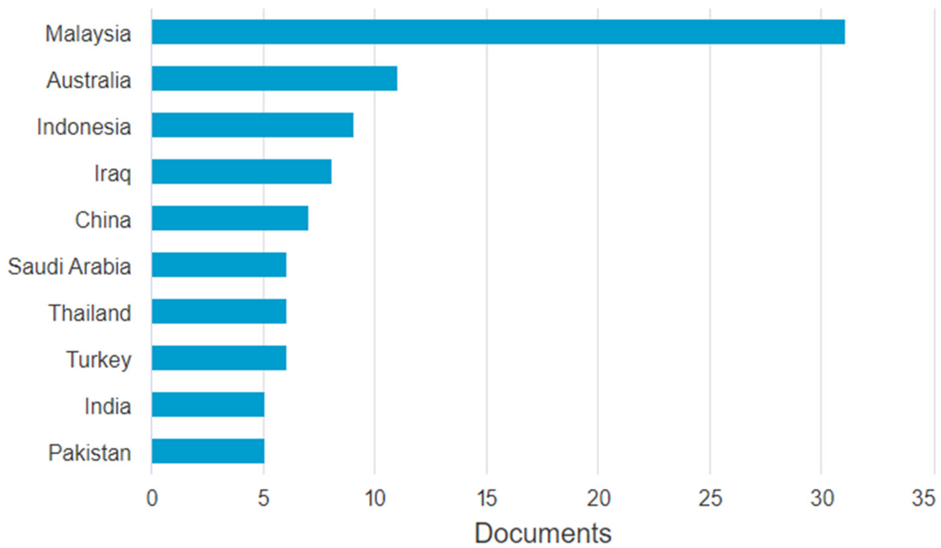

Figure 9. Number of published documents count per country.

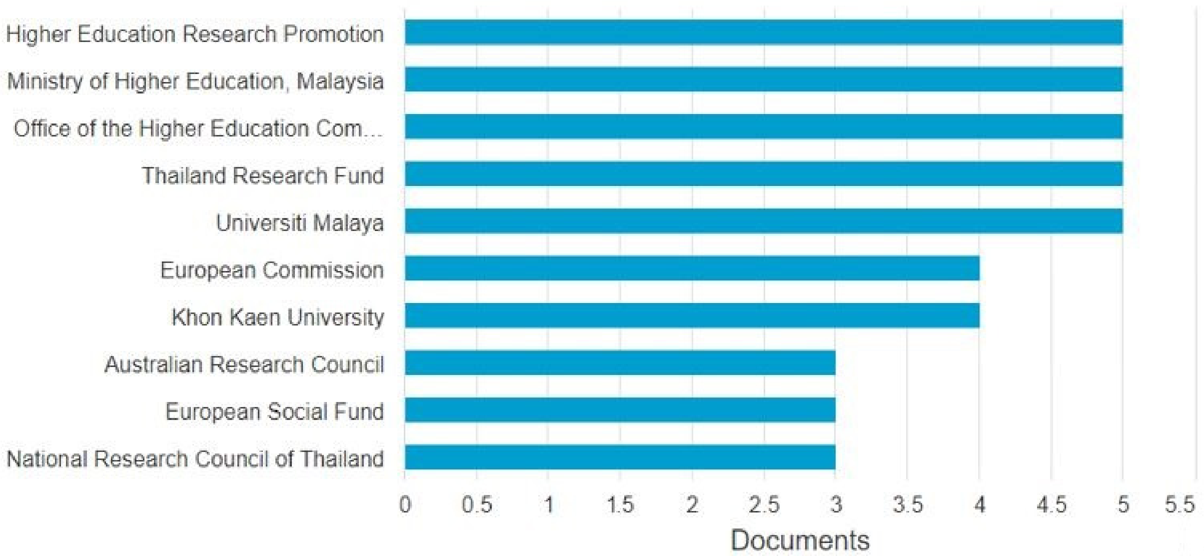

Figure 10. Number of documents that that have obtained funding from a sponsor.

4. Findings and Discussion

In this study, we used a bibliometric analysis of a large database for publications on lightweight aggregate geopolymer concrete, as well as a detailed discussion of the findings, to highlight the current state of lightweight aggregate geopolymer concrete. Despite the fact that lightweight aggregate geopolymer concrete has been studied for more than 10 years, it continues to provide significant opportunities for researchers. The source of publications, the trend of increase in publications in recent years, the keywords and their frequency of occurrence, as well as the main authors, most influential institutions, and countries that take part in lightweight aggregate geopolymer concrete research, were identified and visualized together with their link strength through the VOSviewer. The bibliometric analysis determined that there are still research gaps in the field of lightweight aggregate geopolymer concrete, serving as a source of information for future study. The key topics in the research of lightweight aggregate geopolymer concrete are succinctly examined in the subsequent sections.

4.1. Geopolymer Concrete

Internationally, the annual concrete utilization is above 25 billion tons and the estimated annual requirement for mixing material is approximately 9 billion tons in 2050 [15,16]. Nevertheless, there is ongoing debate regarding the environmental impact of concrete production, particularly regarding the significant energy consumption and carbon dioxide (CO_2) emissions associated with the manufacturing process. Therefore, geopolymers have developed as an outstanding substitute to the usage of Portland cement in recent years owing to their significantly lower environmental impact in terms of raw ingredients and exemplified lessening of CO_2 emissions [17,18]. According to Colangelo et al. (2018), geopolymers have the potential to replace conventional Portland cement in specific applications due to the fact that geopolymers are not only capable of reducing environmental impact but also have excellent mechanical properties [14]. The utilization of waste materials as precursors in geopolymerization has two major benefits for producing eco-friendly concrete: firstly, it enables the creation of zero-cement concrete mixtures, and secondly, it helps prevent the accumulation of waste materials in the environment.

Davidovits, a French professor, first coined the term "geopolymer", which refers to the network of inorganic molecules that were formed from the reaction between a thermally activated natural material, i.e., metakaolinite or industrial by-products, i.e., blast furnace slag or fly ash, and an alkaline activating solution [19]. It is agreed in the study of Gordon et al. (2011) that Joseph Davidovits is the one who originally introduced the concept of geopolymers as a novel material in 1978 [20]. Additionally, in the same year, Davidovits also proposed that novel concrete binders could be created by a polymeric reaction between silicon and aluminum-rich source materials of geographical sources, such as kaolin clay with alkaline liquids [21]. These combinations were termed as geopolymers, which have hardened properties similar to ordinary Portland cement (OPC). Next, Davidovits envisaged the geopolymer, which was developed by the reaction between source materials that have a high content of silica and alumina with a highly alkaline solution, with the characteristics of polymers, ceramics, and cement [22]. According to Hardjito et al. (2004), a geopolymer is defined as a type of concrete that does not require cement and can be produced through the reaction between alkaline solutions and silica-rich and alumina-rich solids, assisted by heat curing and drying [23]. Davidovits further defined the term "geopolymer" in 1978 as a diverse group of materials consisting of chains of inorganic molecules [24]. Singh et al. (2015) also described a geopolymer as a synthesized material that consists of the monomer of Si-O-Al-O [25]. Geopolymers are not only semi-crystalline aluminosilicates that are activated by alkali and developed through the reaction of aluminosilicates in alkaline environments but also a category of sustainable and eco-friendly inorganic aluminosilicate polymers [26–30]. In addition, it was found that the source of silicon and aluminum can be provided by the utilization of fly ash or slag. These materials are dissolved in an alkaline activating solution, leading to polymerization into molecular chains and networks that ultimately result in the formation of a hardened binder. Similarly, Mohseni et al. (2019) also agreed that geopolymers are aluminosilicate polymers fabricated by reacting an aluminosilicate powder, such as metakaolin, fly ashes, slags, or any source of silica and alumina with a highly concentrated alkaline environment [30]. A more detailed definition given by Pasupathy et al. (2020) mentioned that geopolymer binders are manufactured by activating industrial waste products, such as fly ash, slag, metakaolin, etc., using alkali activators, which are also known as hydroxide and silicate solutions, whereas Khalil et al. (2018a) also have the similar thought that geopolymers are formed by mixing geopolymer binders with alkaline solutions, which often include a sodium silicate solution (Na_2SiO_3) [28,29]. Furthermore, under a highly alkaline environment, the geopolymer binder is formed through a chemical reaction between silica and alumina components found in an active pozzolanic substance, for instance, fly ash [30]. As indicated by multiple researchers with various definitions, diverse raw materials, such as fly ash, slag, rice husk ash, metakaolin, and silica fume, can be employed as aluminosilicate sources in the production of geopolymer concrete.

According to Khale and Chaudhary (2007) and Zhang et al. (2004), geopolymer concretes exhibit not only remarkable strength and durability against chloride ion penetration and sulphate attacks but also boast advantages, such as rapid setting time, efficient protection of steel reinforcements against corrosion, water resistance, resistance to high temperatures, and the ability to encapsulate metal ions [31,32]. Furthermore, according to Alonso and Palomo, (2001), Dimas et al. (2009), and Zhang et al. (2010), geopolymers are also well known due to displaying fantastic characteristics including high compressive strength, high-temperature stability, low thermal conductivity, and high thermal engineering applications [33–35]. It is in line with the research results obtained by Chindaprasirt et al. (2013), Kumaravel and Girija (2013), Nasvi et al. (2014), and Mohseni (2018) in which geopolymers exhibit great characteristics, such as higher compressive strength, superior heat resistance, reduced permeability, and excellent resistance to acid and saline environments [36–39]. These attributes have led to extensive research on the properties of geopolymers. Additionally, this revolutionary binder also introduces other fascinating characteristics, including enhanced chemical resistance and thermal durability [40,41]. In addition, geopolymers have a wide variety of applications in the fields of transportation, emergency repairs, metallurgy, coatings, membrane materials, and nuclear waste disposal [42–47]. Moreover, geopolymers are gaining attention due to their environmentally friendly properties, as they have versatile applications as fireproof building materials, efficient sound and heat insulators, and materials suitable for encapsulating hazardous wastes, and they are known for their low energy consumption during the manufacturing process from raw materials, as mentioned by Richard E. Lyon et al. (1997) [48]. Geopolymer is an extremely gifted advanced material that replaced conventional Portland cement and can be utilized in every single field of industry [49–51].

4.2. Lightweight Concrete

Commonly, conventional concrete has a density ranging from 2200 kg/m^3 to 2600 kg/m^3, according to Priyanka et al. (2020) [52]. Therefore, concrete with an oven-dry density of 2000 kg/m^3 or less is characterized as lightweight concrete [53]. It is agreed by BS EN 206 (2013) that lightweight concrete possesses an oven-dry hardened concrete with a lower density range, typically varying from 800 kg/m^3 to 2000 kg/m^3 [54]. In comparison, normal-weight concrete has a density range of 2000 kg/m^3 to 2600 kg/m^3, while heavy-weight concrete has a density equal to or exceeding 2600 kg/m^3. Furthermore, Chen and Liu (2005) provide a similar definition, indicating that lightweight concrete typically possesses a density within the range of 1400 to 2000 kg/m^3, whereas normal weight concrete is distinguished by its higher density, approximately 2400 kg/m^3 [55]. Moreover, according to Owens and Newman (2003), it is possible to produce lightweight concretes with oven-dry densities ranging as low as 300–2000 kg/m^3, while maintaining equivalent cube compressive strengths ranging from nearly 1 to over 60 MPa and thermal conductivities ranging from 0.2 to 1.0 W/mK [56]. Furthermore, Arioz et al. (2008) give a more specific definition of structural lightweight concrete as a concrete with a density range from 1400 to 2000 kg/m^3 [57].

4.3. Binding Materials

Binding materials are one of the most vital ingredients in lightweight geopolymer concrete production. A binder in lightweight geopolymer concrete provides cohesion and structural integrity to the mixture by chemically binding the aggregate particles together. This binder is responsible for the hardening and setting of the concrete, ultimately giving it strength and durability. Various types of binders had been employed by researchers in their studies, such as fly ash, ground granulated blast furnace slag (GGBFS), metakaolin (MK), ceramic waste powder (CWP), clay brick waste powder (CBWP), pulverized fuel ash (PFA), palm oil fuel ash (POFA), rice husk ash (RHA), etc. Table 6 shows the chemical composition of different binders used in the studies of previous researchers.

Table 6. Chemical composition of binders used in previous studies.

Binding Materials	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	LOI
GGBFS [28]	43.23	32.19	12.53	0.43	5.69	0.29	0.26	4.02	0.39
MK [14]	0.17	52.90	41.90	1.60	0.19	0.77	-	-	-
RHA [27]	0.41	91.15	0.41	0.21	0.45	6.25	0.05	0.62	0.45

However, according to bibliometric analysis, fly ash is the most common binder to be used in lightweight geopolymer concrete production due to its attractive chemical composition and easy availability. Fly ash is a type of aluminum and silicon-rich material that can act as a binder in geopolymer concrete production. According to the American Concrete Institute Committee (ACI 116R-00), 2000, fly ash is a finely divided residue that is formed from the combustion of ground or powdered coal [58]. It is transported to the particle removal system by flue gases from the combustion zone. Fly ash is an industrial by-product that has been produced by coal-fired power plants all over the world. In the year 2016, approximately 6.8 million tons of fly ash were produced by Malaysia alone, mainly from the coal-fired power station, and the number will keep on rising due to the country's development [59]. It is clear that this industrial by-product, fly ash, is being produced in large amounts and then deposited in landfills, causing massive pollution to the environment. This is due to the fact that fly ash contains reactive oxide materials, such as alumina, silica, and ferric oxide, that will turn into hazardous material if not treated properly [60]. Hence, it is a wise decision to properly reuse this industrial by-product and turn it into a useful substance, such as replacing cement for concrete production. By doing so, greenhouse gas production will be lessened, and the amount of fly ash to be released to the landfill will be greatly reduced, resulting in a positive impact on the environment. Figure 11 shows the morphology of fly ash.

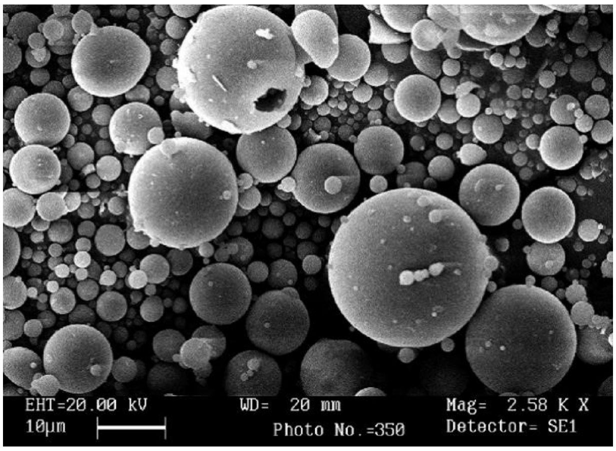

Figure 11. Morphology of fly ash [61].

According to ASTM C 618 (2015), fly ash can be classified into two categories based on its chemical composition [62]. If the total content of SiO_2, Al_2O_3, and Fe_2O_3 in fly ash is more than 70%, it is categorized as Class F. On the other hand, if the total content of SiO_2, Al_2O_3, and Fe_2O_3 falls within the range of 50% to 70%, it is classified as Class C. Class F fly ash, which has a low CaO content, possesses pozzolanic characteristics and is usually generated from burning bituminous or anthracite coals, whereas Class C fly ash, which contains up to 20% CaO content, possesses pozzolanic and some cementitious properties and is usually produced from sub-bituminous or lignite coals [63]. To differentiate these 2 classes of fly ash, the chemical constituents or oxides that make up the individual fly ashes must be identified. The most used type of analysis is the X-ray fluorescence (XRF) test. Table 7 shows the differences between Class F and Class C fly ash based on ASTM C618, whereas Table 8 illustrates the chemical composition of Class C fly ash from different researchers, which consists mainly of SiO_2, Al_2O_3, Fe_2O_3, and CaO and some impurities.

Table 7. Differences between Class F and Class C fly ash [62].

Chemical Composition	Class C	Class F
$SiO_2 + Al_2O_3 + Fe_2O_3$ (minimum %)	50.00	70.00
SO_3 (maximum %)	5.00	5.00
LOI (maximum %)	6.00	6.00
Moisture content (maximum %)	3.00	3.00

Table 8. Chemical composition of Class C fly ash from previous studies.

Oxides (%)	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	LOI
[64]	20.42	32.47	14.92	16.50	7.95	1.32	2.92	1.88	0.43
[65]	27.39	38.71	16.46	6.21	1.34	1.55	0.22	3.30	10.17
[66]	15.10	46.38	13.90	8.26	6.68	2.78	2.13	4.26	0.22
[67]	36.56	31.94	13.50	4.09	1.42	0.94	1.10	3.86	2.99

Table 8. *Cont.*

Oxides (%)	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	LOI
[68]	15.10	46.38	13.90	8.26	6.68	2.78	2.13	4.26	0.22
[69]	12.15	45.69	24.59	11.26	2.87	2.66	0.07	1.57	1.23
[70]	15.50	45.23	19.95	13.15	2.02	2.15	0.52	0.30	0.88
[71]	14.50	39.4	20.80	11.50	2.20	2.40	-	4.20	1.50

It can be observed that the CaO content of Class C fly ash varies from 12.15 to 36.56%, whereas the SiO_2 content of fly ash ranges between 31.94 and 46.38%. From Table 8, it is also noticed that the Al_2O_3 and Fe_2O_3 contents of high calcium fly ash fluctuate between 13.5 and 24.59% and between 4.09 and 16.50%, respectively. The high amount of calcium in Class C fly ash has a higher probability to interfere with the polymerization process and produce an impact on the microstructure of the geopolymer [72].

Table 9 indicates the studies conducted using fly ash as a precursor for geopolymer concrete production. From the table, it clearly shows that only a very small number of researchers utilize Class C fly ash as the binder to manufacture geopolymer concrete, while plenty of them use low calcium content fly ash as the binder to manufacture geopolymer concrete. This may be due to the short setting time of geopolymer concrete if Class C fly ash is employed. However, according to Yildirim et al. (2011), Class C fly ash not only enhances the workability of concrete marginally and decreases the water necessity of the concrete, but is also commonly the reason for the higher compressive strength as Class C fly ash has a higher calcium amount compared to Class F fly ash [66].

Table 9. Type of fly ash used in previous studies.

Refs.	Class C	Class F	SiO_2	Al_2O_3	Fe_2O_3
[73]		✔	59.56	29.33	3.36
[74]		✔	35.70	15.40	19.91
[75]		✔	52.30	25.90	10.52
[19]		✔	-	-	-
[76]	✔		34.60	10.30	0.73
[77]		✔	-	-	-
[78]	✔		32.10	19.90	16.91
[79]		✔	58.30	22.50	8.00
[80]		✔	53.71	27.20	11.17
[81]	✔		-	-	-
[82]	✔		-	-	-
[83]		✔	62.20	27.50	3.92
[84]		✔	53.36	26.49	10.86
[85]		✔	-	-	-
[86]		✔	45.23	19.95	13.15
[87]		✔	59.56	29.33	3.36
[88]		✔	59.56	29.33	3.36
[89]		✔	48.80	27.00	10.20
[90]		✔	57.60	28.90	5.80
[72]		✔	-	-	-
[91]		✔	-	-	-

Table 9. *Cont.*

Refs.	Class C	Class F	SiO_2	Al_2O_3	Fe_2O_3
[92]		✔	52.30	25.90	10.52
[93]	✔		32.62	31.23	8.48
[94]		✔	-	-	-
[95]		✔	50.50	26.57	13.77
[28]		✔	56.74	24.89	6.87
[70]	✔		45.23	19.94	13.15
[52]		✔	58.25	25.10	4.60
[96]		✔	-	-	-
[97]		✔	56.34	23.08	1.70
[98]		✔	55.30	25.80	5.50
[99]		✔	55.20	24.10	5.50
[71]	✔		39.40	20.80	11.50
[100]		✔	62.34	21.13	7.16

4.4. Lightweight Aggregates

Lightweight aggregates can be categorized into two main categories, which are natural lightweight aggregates and manufactured lightweight aggregates. The main natural lightweight aggregates are diatomite, pumice, scoria, volcanic cinders, and tuff, whereas the manufactured aggregates are expanded clay, shale, slate, perlite, vermiculite, and industrial by-products, such as crushed clay bricks, glass, sintered slate and colliery waste, and foamed or expanded polystyrene. Several lightweight aggregates have been utilized by researchers to produce lightweight geopolymer concrete, such as expanded perlite, pumice, palm oil clinker, artificial lightweight aggregates, and expanded vermiculite [28,29,73,79,99,101–112]. The use of lightweight aggregates in construction has been proven to be economical due to its reduction of construction cost [57,113–124]. Lightweight aggregate can also improve thermal and acoustical insulating properties due to the pores and voids that exist in it [125–130]. According to the database collected, the favorable lightweight aggregates to be employed to produce lightweight geopolymer concretes are acidic pumice [99], expanded perlite [28,99], coconut shell [129], bottom ash [71], expanded vermiculite [103], palm oil clinker [79,102], artificial aggregates [73,87] etc. Table 10 notes the chemical composition, while Table 11 displays the physical properties of different lightweight aggregates used in the studies of previous researchers. The use of low-water absorption lightweight aggregates in geopolymer concrete enables a lower water-to-cement ratio, leading to higher strength, while their low density reduces the overall concrete weight, which makes lightweight geopolymer concrete advantageous for various construction applications, especially where weight reduction is crucial.

Table 10. Chemical composition of lightweight aggregates utilized in previous studies.

Chemical Composition	SiO_2	Al_2O_3	Fe_2O_3	K_2O	MgO	CaO	Na_2O	P_2O_5	SO_3	SrO	TiO_2	MnO	LOI
Acidic pumice [99]	69.70	13.64	2.34	4.07	-	3.15	0.40	-	0.07	0.03	0.15	-	3.65
Expanded perlite [99]	75.16	14.50	1.04	5.98	-	1.01	-	-	-	0.03	0.14	-	1.35
Expanded perlite [28]	74.93	12.88	0.70	4.42	0.04	0.70	3.85	0.01	0.02	-	0.07	0.07	2.06
Coconut shell [129]	20.70	5.75	2.5	0.15	1.89	63.11	0.60	0.05	2.75	-	-	0.20	2.30
Bottom ash [71]	31.80	12.10	18.00	2.50	2.40	25.30	-	0.30	3.70	-	0.50	-	3.20
Expanded vermiculite [103]	41.00	10.00	9.50	7.00	24.00	5.00	-	-	-	-	1.50	-	-

Table 11. Physical properties of lightweight aggregates utilized in previous studies.

Physical Properties	Specific Gravity	Water Absorption (%)	Bulk Density (kg/m^3)	Dry Density (kg/m^3)	Fineness Modulus	Porosity (%)
Palm oil clinker [79]	1.92	3.30	-	-	3.52	-
Palm oil clinker [102]	1.87	14.65 (24h)	-	1096	-	-
Coconut shell [129]	1.15	10.02	695	-	6.11	38
Artificial aggregates [87]	1.63	11.50	-	773	-	-
Artificial aggregates [73]	1.63	11.50	-	769	-	-
Recycled lightweight concrete aggregates [70]	1.42	76.00	360	-	5.75	-
Bottom ash [71]	2.47	3.32	1116	-	6.00	-

However, there is a lack of research using LECA as a lightweight aggregate in lightweight aggregate geopolymer concrete. According to bibliometric analysis, there are only three studies that utilized LECA as a lightweight aggregate in their geopolymer concrete [52,75,101]. This may be attributed to the high costs associated with its production and manufacturing, as the manufacturing process of LECA involves heating clay at high temperatures (1100–1300 °C), which is energy-intensive and costly. Lightweight expanded clay aggregate (LECA) is a type of lightweight aggregate that has risen in popularity in the construction industry. LECA is made from a unique plastic clay that contains very little to no lime component [104]. LECA is a spherical pellet with an interconnected hole or vesicular texture when burst apart, as seen in Figure 12. LECA comes in a variety of colors based on its source and chemical makeup, but it is usually dark brown or grey (Figure 13).

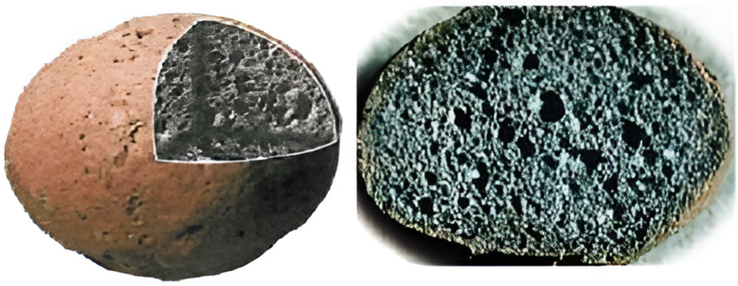

Figure 12. Air-filled cavities and interconnected holes of different sizes in LECA [104].

Figure 13. Variety colors of LECA from different sources [104].

Table 12 shows the chemical composition of lightweight expanded clay aggregates (LECAs) reported by different researchers. The main chemical components of LECA are SiO_2, Al_2O_3, Fe_2O_3, CaO, and some alkalis, such as Na_2O and K_2O. The content of SiO_2 in the total composition varied from 53.3% to 66.05%, while the Al_2O_3 content varied from 15.05% to 18.51%. The Fe_2O_3 content ranged from 6.1% to 7.85%, and the CaO content varied from 1.8% to 3.92%, except in the study of Arioz et al. (2008), where the Fe_2O_3 and CaO content of LECA were 1% and 0.2%, respectively [57].

Table 12. Chemical properties of LECA from previous studies.

Composition	SiO_2	Al_2O_3	Fe_2O_3	K_2O	MgO	CaO	Na_2O	P_2O_5	SO_3	SrO	TiO_2	MnO	Others	LOI
[105]	62	18	7	4	3	3	2							1.36
[106]	66.05	16.57	7.1	2.69	1.99	2.46	0.69	0.21	0.03					0.84
[57]	58	27	1	2.3	0.4	0.2	0.3				1.3			
[107]	53.3	16.6	6.2		2.8	2								
[108]	61.67	18.51	6.14	3.18	3.97	3.5	1.54	0.19	0.23	0.13	0.65			
[109]	61.05	15.74	6.1	2.67	2.52	3.92	5.62	0.21	0.03				0.84	0.75
[4]	66.05	16.57	7.1	2.69	1.99	2.46	0.69							
[110]	66.2	16	6.4	4		1.8	1.8		0.1			2.7		0.1
[111]	60.1	17.7	7.85	4	2.95	2.1	1.75	0.2	0.55		0.9	0.1		1.8
[112]	64.83	15.05	7.45	2.55	3.67	2.98	1.1	0.13			0.63	0.13		1.37

Table 13 demonstrates the physical characteristics of LECA obtained from various research studies, which consist of specific gravity, water absorption, fineness modulus, porosity, bulk, and dry density. It can be noticed that the specific gravity of LECA fluctuated between 0.44 and 2.65, whereas the water absorption of LECA for 24 h fluctuated between 12.3% and 27%. Additionally, the bulk density of LECA differed from 273 to 750 kg/m^3,except the study of Ramanjaneyulu et al. (2018) describes that the bulk density of LECA is 1442 kg/m^3 [121]. The various densities of LECA can be regarded as one benefit as they allow for the use of the material in both structural and non-structural lightweight concretes.

Table 13. Physical properties of LECA in previous studies.

Properties	Specific Gravity	Water Absorption (%)	Bulk Density (kg/m^3)	Dry Density (kg/m^3)	Fineness Modulus	Porosity (%)
[113]	-	24.1 (24 h)	279	503	-	-
[105]	-	-	750	1600	-	-
[114]	1.23	40 (4 h)	650	600	-	-
[115]	-	15.8 (24 h)	624	1076	-	40.7 (24 h)
[116]	-	12.3 (24 h)	613	1068	-	60 total
[117]	-	12.3 (24 h)	613	1068	-	60 total
[118]	-	26.2	358	-	5.77	-
[119]	-	23.2 (24 h)	681	1092	-	-
[120]	-	-	562	1060	-	59 total
[121]	2.65	-	1442	-	7.16	-
[6]	0.80	27 (24 h)	-	-	-	-
[122]	0.44	10	357	-	5.99	-
[123]	0.66	26.5 (24 h)	273	-	5.96	-
[52]	2.1	-	560	-	-	-

4.5. Alkaline Solution

Geopolymer production is generally achieved by combining an alkaline solution, which commonly consists of concentrated aqueous alkali silicate and hydroxide where the alkali metals are usually sodium or potassium, with a reactive aluminosilicate precursor. The silicon (Si) and aluminum (Al) atoms from the aluminosilicate material will be extracted and activated by the aqueous solution, forming a binder similar to that of CSH gel [91]. The pH values of the alkaline solution play an essential component in geopolymerization reactions, as they affect the dissolution of the aluminosilicate material and the level of polymerization of silicate elements. The higher the pH value of the alkali hydroxide, the greater the dissolution and polymerization [31,124]. At high pH values, the geopolymer paste becomes more viscous, while at low pH values, the viscosity decreases, leading to an increase in workability [31]. In addition, high concentrations of hydroxide solutions that exhibit the corrosive nature not only will corrode the steel reinforcement in the concrete but also will shorten the design working life of the structure [125]. Furthermore, when the concentration of NaOH increases, the lightweight geopolymer concrete properties produced, like its compressive strength, increase [91]. According to research done by Priyanka et al. (2020), a mixture of 8 molarity of sodium hydroxide and sodium silicate was used as an alkali activator to investigate the strength of fly ash-based lightweight geopolymer concrete produced with LECA [52]. By comparison, a 10 molarity mixture of sodium hydroxide was combined with sodium silicate to produce geopolymetric paste in the studies of Posi et al. (2016); Wongsa et al. (2016); Ameri et al. (2019), (2020); Mohseni et al. (2019); Novais et al. (2019); Rehman et al. (2020); Swaminathan et al. (2020) and Udvardi et al. (2020) [27,70,71,101,126–130]. In addition, Abdullah et al. (2018) and Ming et al. (2019) reported the use of 12M sodium hydroxide and sodium silicate as the alkali activators in their research to manufacture lightweight geopolymer concrete [75,92]. Then, a sodium hydroxide concentration of 14 was used in the study of Ariffin et al. (2011) and Liu et al. (2016), while 16 molarity sodium hydroxide along with sodium silicate was employed in the research of Khalil et al. (2018b) and Nasser et al. (2020) to develop lightweight geopolymer composites [87,90,94,131]. In the literature, most of the lightweight geopolymer concretes are synthesized by using sodium hydroxide concentrations between 8M and 16M. In short, the use of low-molarity of alkaline solutions was not discussed in the development of lightweight geopolymer concrete.

4.6. Alkaline-to-Binder Ratio

The ratio of alkaline activator-to-fly ash of the study done by Abdullah et al. (2017) was 0.33, while the most appropriate ratio of the activator solution to fly ash in the study of Abbas et al. (2018) was 0.35 [73,75]. In addition, the activator to fly ash ratio of 0.4 was employed by Khalil et al. (2018b); Ming et al. (2019); and Nasser et al. (2020) [87,92,94]. Whilst according to Abdullah et al. (2018), Darvish et al. (2020), and Priyanka et al. (2020), the mass ratio of alkaline activator solution to binder of 0.5 was used in all the lightweight mixes [52,75,79]. Furthermore, a ratio of alkaline activator to binder of 0.55 was also employed in the research of Liu et al. (2016) [90]. In addition, in the studies of Posi et al. (2016) and Colangelo et al. (2018), a solid binder to liquid alkaline solution ratio of 0.7 by weight was utilized in the production of lightweight geopolymer concretes [14,70]. In addition, in the study of Priyanka et al. (2020), which investigated the characteristics of lightweight geopolymer concrete with alkaline-to-binder ratios of 0.5 and 0.6, they discovered that the strength of the geopolymer concrete is higher at the 0.5 alkaline-to-binder ratio compared to 0.6 [52]. It is in line with the research of Abbas et al. (2018) that a lower alkaline to binder ratio results in higher compressive strength, as the highest compressive strength at 7 days of 29.7 MPa was observed with a 0.4 alkaline-to-binder ratio [73]. In short, the ratio of binder-to-alkaline solution of 0.45 was employed by most of the researchers in their studies to produce lightweight geopolymer concrete. Table 10 shows the alkaline-to-binder ratio employed by other previous researchers in their studies.

4.7. Sodium Silicate to Sodium Hydroxide Ratio

The mass ratio of sodium hydroxide to sodium silicate in the studies of Darvish et al. (2020) and Rehman et al. (2020) is maintained at 1:1.5, whereas according to Posi et al. (2016), a sodium silicate to sodium hydroxide ratio of 1.0 is the most suitable ratio to produce an alkaline solution with high compressive strength [70,79,128]. Next, the sodium silicate to sodium hydroxide ratio is fixed as 2.0 for the study of Priyanka et al. (2020) [52]. In addition, the 1:2.5 ratio of sodium hydroxide to sodium silicate is the most commonly used in the fabrication of alkaline solutions, as shown in the research of Liu et al. (2016); Abdullah et al. (2017), (2018); Abbas et al. (2018); Khalil et al. (2018a), (2018b); Ameri et al. (2019), (2020); Ming et al. (2019); Mohseni et al. (2019); Nasser et al. (2020); Swaminathan et al. (2020); and Ariffin et al. (2011) [27,29,73–75,87,90,92,94,101,126,129,131]. Furthermore, Top et al. (2020) [99] discovered that increasing the concentration of sodium silicate results in a rise in the compressive strength value of the lightweight geopolymer concretes. Posi et al. (2016) showed that the strength of lightweight geopolymer concrete will increase with an increment of the sodium silicate to sodium hydroxide ratio [70]. In addition to the study by Ariffin et al. (2011), who showed that lightweight geopolymer concrete demonstrates superior compressive strength at a sodium silicate to sodium hydroxide ratio of 2.5, similar results were obtained by Younis et al. (2021), who demonstrated that the compressive strength of a lightweight geopolymer concrete increased until the $Na_2SiO_3/NaOH$ ratio of 2.5 before dropping [100,131]. In short, a 1:2.5 sodium hydroxide to sodium silicate ratio was commonly employed by researchers in producing lightweight geopolymer concrete. Table 14 showed the sodium silicate to sodium hydroxide ratio employed by other previous researchers in their studies.

Table 14. Literature review on alkaline-to-binder ratio and sodium silicate to sodium hydroxide ratio of previous research.

Previous Research and Studies	FA/AAS Ratio	$Na_2SiO_3/NaOH$ Ratio
[77]	2.22–3.33	-
[72]	2.83	2.50
[96]	2.83	2.50
[84]	2.83	2.50
[95]	2.50–3.33	1.50–2.50
[98]	2.00	1.00
[132]	2.00	2.50
[133]	1.81	1.00–2.50
[134]	2.00–2.80	1.00–3.00

4.8. Superplasticizer

The addition of a superplasticizer, which is a type of water-reducing agent, is to enhance the workability of the fresh lightweight geopolymer concrete without leading to any segregation and deprivation in the compressive strength of the concrete [89]. There are several types of superplasticizers available commercially, and they can be applied to lightweight geopolymer concrete production as well because lightweight geopolymer concrete has a relatively stiff consistency in the fresh state. Based on Singh et al. (2015), a naphthalene-based superplasticizer can increase the relative slump of fresh lightweight geopolymer concrete by 136% while not affecting its compressive strength. In contrast, a modified polycarboxylate-based superplasticizer can increase the workability of fresh concrete while having a 29% decrease in compressive strength [25]. In the study of Nematollahi and Sanjayan (2014), only 1% dosage by mass of fly ash of superplasticizer was included in the fresh mixtures [135]. Whilst according to Hardjito et al. (2004), the proportion of the superplasticizer to the mass of fly ash was 1.5% [23]. Moreover, the inclusion of superplasticizer with 2% of the binder has exhibited a significant increase in the workability of the concrete [136]. In addition, the study of Pacheco-Torgal et al. (2011) deduced that the utilization of 3% of superplasticizer enhances the mortar flow from fewer than 50% to more than 90% while preserving a great compressive and flexural strength [137]. However, the superplasticizer contents of 3–12% by weight of fly ash were applied in accordance with the study of Chindaprasirt et al. (2007) [138]. It is in line with the research of Ghosh and Ghosh (2012) that the extremely high flow diameter of 270 ± 11 mm achieved at 4% plasticizer dosage [139]. Additionally, the study of McLellan et al. (2011) stated that the percentage of superplasticizer to the mass of binder utilized was 6% [18]. However, a study by Hardjito and Rangan (2005) shows that adding superplasticizer exceeding 2.5% of the mass of fly ash in the mix of fly ash-based lightweight geopolymer concrete will likely cause a decrease in compressive strength of the hardened geopolymer concrete, as shown in Figure 14 [84].

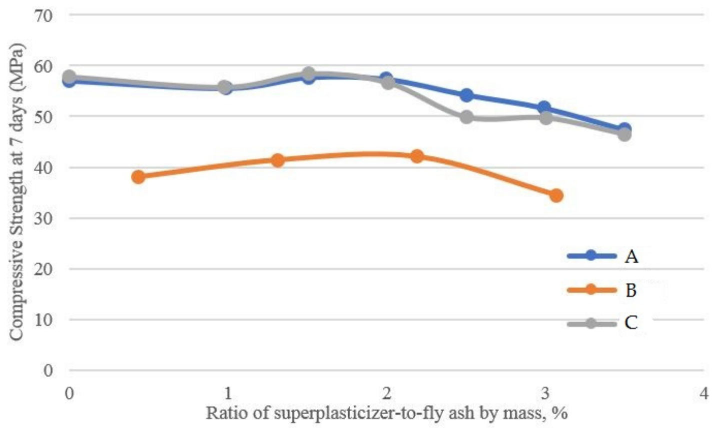

Figure 14. Effect of superplasticizer on compressive strength of lightweight aggregate geopolymer concrete, A [83], B [136], C [22].

4.9. Setting Time

The setting time of geopolymers is a critical factor that greatly affects their handling, transportation, compaction, and pouring, making it a major influence on their overall performance [79]. Firstly, according to Cheng and Chiu (2003), Na_2O content plays an important role; increasing concentration of alkaline solution increases the setting time of lightweight geopolymer concrete [140]. Phoo-ngernkham et al. (2016) have also indicated that the setting time of geopolymer mortars can be extended by increasing the molarity of sodium hydroxide used in the mix [141]. However, these statements differ from research by Saloma et al. (2016), who showed that the increasing concentration of sodium hydroxide can surprisingly shorten the initial setting time and reduce the final setting time of geopolymer mortars [142]. The geopolymer mortar mixtures that were prepared with low sodium hydroxide molarity took substantially longer to set due to the low content of Na_2O and the slow rate of the geopolymerization reaction at low ambient temperatures [139,143–145]. These results are in line with the research done by Malkawi et al. (2016), which determined that the sodium content is the key factor influencing the setting time while the ratio of sodium to silicate can be modified by the altering of sodium hydroxide molarity [133]. Next, in the study of Hardjito et al. (2008), the amount of aluminum available for the geopolymerization reaction seems to have a leading effect in influencing setting time [146]. Hence, the extension of setting time is discovered to increase with an increase in the SiO_2/Al_2O_3 ratio. Similarly, an increase in the water-binder ratio was found to also lead to longer setting times [147].

Moreover, one of the noticeable weaknesses of geopolymer is its low reactivity during the initial setting stages at room temperature [148,149]. Therefore, Sindhunata et al. (2006), who investigated the impact of curing temperature on geopolymerization, determined that raising the temperature from 30 to 50 °C will accelerate the nucleation rates and polycondensation of lightweight geopolymer and thus decrease the setting time [150]. Nguyễn et al.

(2008) mentioned that the setting time of Class F fly ash-based lightweight geopolymer concrete decreases with increases in curing temperature [151]. When cured at 65 °C and 80 °C, they can be manipulated for up to 2 h, in accordance with Hardjito et al. (2008) [146]. The rate of geopolymerization increases with an increase in temperature, resulting in faster setting times at higher temperatures [152]. In short, the setting time of Class F lightweight geopolymer concrete is significantly influenced by the curing temperature. Furthermore, the setting times of lightweight geopolymer concretes are significantly affected by the calcium content. For instance, in situations where large amounts of Class F fly ash are utilized in the precast industry, a longer setting time can delay the demolding cycle. Thus, fly ash with higher calcium content can be used to achieve shorter initial and final setting times [144]. According to Antoni et al. (2017), a higher replacement ratio with Class F fly ash increases the setting time at a higher rate [64]. This physical effect was further detected by Lee and Van Deventer (2002), who discovered that the addition of a small amount of soluble calcium to a Class F fly ash-based lightweight geopolymer results in a reduction in setting time as measured by yield stress [153]. Moreover, the use of chemical admixture, such as superplasticizer, was recommended to address issues related to low workability and rapid setting time in lightweight geopolymer concrete, in accordance with Parthiban et al. (2013) [136]. In short, superplasticizer is benefiting both in-situ and precast applications. In on-site construction, they extend setting time and enhance workability, allowing for easier placement and finishing. For precast elements, superplasticizers improve flowability and enable better control over the casting process, resulting in higher-quality finished products.

4.10. Workability

One important factor in identifying the quality of concrete is examining its workability. Workability is the quality of fresh concrete, which is determined by the ease and flowability to be mixed, compacted, delivered, and finished [154]. In other words, to ensure ease of transfer, placement, smooth surface finish, and cost-effectiveness, the mixture should possess sufficient workability [155,156]. Generally, concrete made with hydraulic cement shows higher workability than lightweight geopolymer concrete in the fresh state; this is due to the fact that higher viscosity liquids were used in lightweight geopolymer concrete instead of normal water [80,157]. According to Davidovits (2020), fly ash particles are hollow and spherical in shape, with a smooth surface texture, which can contribute to improved workability of the resulting geopolymer mixture [1]. As mentioned in the studies of Abbas et al. (2018), Khalil et al. (2018a), and Khalil et al. (2019), the use of fly ash in geopolymer concrete results in a concrete mix with good workability, as evidenced by a slump value of 245 mm and a fresh density of 1951 kg/m^3 [29,73,88].

However, lightweight geopolymer concrete mixes incorporating various types of artificial, fine, lightweight aggregates exhibit reduced workability and fresh density compared to conventional geopolymer concrete. This is primarily due to the lower specific gravity of the artificial lightweight fine aggregates, which consequently causes a decrease in fresh density. Similarly, Posi et al. (2016) found that a decrease in fly ash content and an increase in ordinary Portland cement content reduced the workability of the mixture and caused complexities in casting and compacting as well [70].

In addition, the workability of the lightweight geopolymer concrete reduces with an increase in the concentration of sodium hydroxide due to a more viscous alkaline activator solution at a higher concentration of sodium hydroxide [133,138,158,159]. It is also reported in the study of Koutník et al. (2020) that an increase in water content leads to a decrease in the viscosity of the geopolymer [160]. Furthermore, at the same liquid-to-ash ratio, the slump value of lightweight geopolymer concretes was reduced due to the increasing sodium silicate to sodium hydroxide ratio. This is because the high viscosity of sodium silicate will reduce the flow of composites [138]. Furthermore, an increase in the liquid-to-ash ratio leads to an increase in the slump values, indicating an improvement in the workability properties of fresh lightweight geopolymer concrete. This is attributed to the higher amount of liquid alkali activators present in the mix. Whilst for aggregates-to-binder ratio, it can be observed in the research done by Top et al. (2020) that increasing the ratio of acidic pumice to fly ash during sample preparation processes led to an increase in the workability of the mixtures [99].

According to the observations carried out by Rehman et al. (2020), the slump value was higher for aggregates with lower porosity because they absorb less liquid [128]. It can be proved in the results obtained through the research done by Wongsa et al. (2016) [71]. The slump values of lightweight geopolymer concretes were around 88 to 198 mm, which were lower than the slump values of control geopolymer concretes, which were around 190 to 205 mm. The reason for the reduction in workability of fresh concrete containing bottom ash compared to natural aggregates is attributed to the high porosity, rough surface texture, and irregular shape of bottom ash. This leads to increased friction between bottom ash particles, as reported by Lee et al. (2010) and Singh and Siddique (2013) [161,162]. Furthermore, the high porosity and rough surface of bottom ash particles will also decrease the amount of paste for lubrication between aggregates [163]. However, in the observation from the Novais et al. (2019) study, the workability of the mixtures is strongly affected when the amount of cork exceeds 92 vol.%, causing a significant decrease [127]. Moreover, in the study of Ameri et al. (2020), concretes prepared using pumice as lightweight aggregates showed lower workability than those that used LECA as lightweight aggregates [101]. This is because pumice aggregates have a rough and porous surface, which leads to an increased adhesion between the aggregates and fresh paste, reducing the workability of the mixture [164,165]. The rough and porous surface of pumice aggregates allows the fresh paste to infiltrate the surface pores, providing mechanical anchorage and increasing the interlocking capability between the aggregates and the paste. Additionally, the surface pores increase the water absorption capacity of pumice aggregates, leading to an increased water demand in composites incorporating pumice lightweight aggregates [165–167]. Based on the literature review carried out by Rashad (2018), 78% of previous research was shown to have a positive impact on the workability of fresh concrete when they replaced a certain amount of aggregates with LECA [103]. Similar findings were also discovered by Priyanka et al. (2020) that the workability of concrete increases as the amount of LECA is increased due to the smooth and round shape of aggregates, while a 0.5 alkaline solution-to-binder ratio provides great workability and thus provides excellent strength [52].

4.11. Compressive Strength

Concretes are known for their properties to resist compressive forces due to their exceptional compressive strength. Huiskes et al. (2016) researched the performance of ultra-lightweight fly ash-based geopolymer concrete and obtained a 28-day compressive strength of 10 MPa with the use of highly porous glass lightweight aggregates, making it more suitable to be used as a non-structural element [86]. According to the study done by Top et al. (2020), lightweight geopolymer concrete manufacturing that utilizes expanded perlite as lightweight aggregates exhibits low hardened density, which is 1250 kg/m^3, and uniaxial cube strength of 10 to 50 MPa [99]. However, the research of Pasupathy et al. (2020), in which expanded perlite was also used as lightweight aggregates to manufacture lightweight geopolymer concrete, shows opposite results [28]. They found out that 20% of expanded perlite replacement shows the best outcome, which is a 1.38 MPa compressive strength for 28 days. Next, according to Darvish et al. (2020) findings, fully replacing conventional sand with palm oil clinker produces lightweight geopolymer mortar with a 28-day compressive strength of 53 MPa, whereas palm oil clinker has also been used in the research of Malkawi et al. (2020) as a source for lightweight aggregates, and the result shows that the optimum palm oil clinker content was 75% replacement as a volume percentage from total aggregates, which have a compressive strength of more than 30 MPa [79,102].

Additionally, the use of manufactured sand and coconut shell as a 100% replacement of fine aggregates and coarse aggregates, respectively, produces a lightweight geopolymer concrete with an average compressive strength of 40.40 MPa [129]. While, according to Mohseni et al. (2019), incorporating scoria particles as coarse lightweight aggregates in concrete resulted in a decrease of the 28-day compressive strength of the samples [27]. Specifically, when natural aggregates were replaced by 10% and 20% of scoria by volume of the total aggregates, the compressive strength was reduced by up to 3.8% and 6.5%, respectively, compared to the original strength. Furthermore, in the study of Novais et al. (2019), cork was employed as a lightweight aggregate in the creation of ultralightweight geopolymer composites, and they found that the addition of cork resulted in a significant reduction in compressive strength, ranging from 2.86 MPa to 0.23 MPa, compared to the control inorganic polymer matrix, which reached compressive strength of 14 MPa after 28 days [127].

Artificial aggregates have also been used to produce lightweight geopolymer aggregates in a few studies. According to research conducted by Khalil et al. (2018a), artificial coarse aggregate replacement will decrease the compressive strength from 32.60 to 28.73 MPa when the replacement ratio ranges from 25% to 100% [29]. In contrast, in the study of Abbas et al. (2018), lightweight geopolymer concrete fabricated using artificial coarse lightweight aggregate as 100% replacement of natural coarse aggregates found that the compressive strength of lightweight geopolymer concrete tends to increase with age, with values of 35.8 MPa at 28 days [73]. Moreover, recycled lightweight concrete aggregates were also explored as lightweight aggregate replacement by Posi et al. (2016), and they observed that lightweight geopolymer concretes with densities between 1200 and 1500 kg/m^3 obtained 28-day compressive strengths of 4.5 and 17.5 MPa, respectively. In contrast, Wongsa et al. (2016) used bottom ash as lightweight aggregate to produce lightweight geopolymer concrete, and they noticed that the density of lightweight geopolymer concrete fabricated ranged between 1661 and 1688 kg/m^3 with a 28-day compressive strength varied between 14.3 and 18.1 MPa [70,71].

According to research carried out by Medri et al. (2015), lightweight geopolymer composite panels manufactured using expanded vermiculite as a lightweight aggregate [103] produced lightweight geopolymer composite panels with a density that ranged between 700 and 900 kg/m^3 and an average strength of about 2 MPa. However, LECA, which was employed as coarse aggregate replacement in this research, has also been used as a lightweight aggregate by a few researchers. In the study of Ameri et al. (2020), they found out that the higher density and rougher surface texture of pumice aggregates compared to LECA resulted in lower workability but higher mechanical strength of the concrete, as pumice aggregates have better bonding with the paste [101]. In contrast, a density of 2000 kg/m^3 and a maximum compressive strength of 48M Pa geopolymer lightweight aggregate concrete was fabricated with 20% replacement of LECA in the study of Priyanka et al. (2020) [52]. Furthermore, in the study of Abdullah et al. (2018), expanded clay aggregates and sand were utilized as coarse and fine aggregates, respectively, with the proportion fixed at 60% and 40%, respectively, to produce a lightweight geopolymer concrete. The results found that 70% of the total aggregate content relative to the geopolymer paste obtained the highest strength of 60.4 MPa [75]. In addition, Raj et al. (2018) carried out research studying the effect of replacing aggregate using lightweight aggregates such as LECA; the compressive strength obtained was 23.53 MPa, 21.53 MPa, 20.80 MPa, and 21.06 MPa for 5%, 10%, 15%, and 20% LECA replacement, respectively [168]. Table 15 shows the summaries of compressive strength of lightweight geopolymer concrete using different lightweight aggregates.

Table 15. Compressive strength of geopolymer concrete from previous research.

Refs.	Lightweight Aggregates	Age, Day	Compressive Strength, MPa
[86]	Porous glass	28	10
[99]	Expanded perlite	28	50
[28]	Expanded perlite	28	1.38
[79]	Palm oil clinker	28	53

Table 15. *Cont.*

Refs.	Lightweight Aggregates	Age, Day	Compressive Strength, MPa
[129]	Coconut shell	28	40.4
[73]	Artificial aggregates	28	35.8
[70]	Recycled lightweight concrete aggregates	28	17.5
[71]	Bottom ash	28	18.1
[103]	Expanded vermiculite	28	2.0
[52]	LECA	28	48
[75]	LECA	28	60.4
[168]	LECA	28	23.53

4.12. Splitting Tensile Strength

The tensile strength of concrete has been estimated to be approximately 10% of its compressive strength. This mechanical property of concrete is important for us to identify the vulnerability of the specific concrete towards tensile cracking since cracking in concrete is also termed tensile failure. Several tests can identify the tensile strength of concrete, namely the direct tensile strength test, splitting tensile test, and flexure test. Based on the literature reviewed, the splitting tensile test is the most used due to its simplicity of execution [80]. Brittle failure will occur on fly ash-based geopolymer concrete due to its weak fracture toughness and tensile strength [169]. Ryu et al. (2013) obtained a 28-day splitting tensile strength of 2.5 to 2.6 MPa for fly ash-based geopolymer concrete with its corresponding compressive strength of 30.0 to 31.2 MPa, respectively [98]. Deb et al. (2014), on the other hand, used a blend of fly ash and ground blast-furnace slag as the aluminosilicate material for the formation of geopolymer concrete and obtained a 28-day spitting tensile strength of between 2.12 and 4.81 MPa with its corresponding compressive strength of 22 to 51 MPa, respectively [80]. In addition, according to Rehman et al. (2020), the maximum split tensile strength of 3.21 MPa for geopolymer concrete consists of 20% cement share specimens [128]. The aggregates and matrix are divided separately by tension forces during tensile loading, and thus, the strength of the interfacial transition zone (ITZ) becomes critical in determining the strength of concrete. Hence, geopolymer concrete specimens revealed a stronger bond between paste and aggregates and indicate the strong ITZ compared to Portland cement concrete.

In the study of Nasser et al. (2020), geopolymer concrete made of lightweight aggregates displays a low split tensile strength of 0.9 MPa at 28 days because fine aggregates, which would fill in the pores within the concrete structure with geopolymer matrix, were not available [94]. Furthermore, researchers deduced that an increase in the fine locally artificial lightweight aggregate content leads to a reduction in the splitting tensile strength of lightweight geopolymer concrete due to the reduction in density and the strength of the locally artificial lightweight aggregates used [29]. In addition, in the study of Abbas et al. (2018), the splitting tensile strengths at 7, 28, and 56 days of lightweight geopolymer concrete utilizing artificial coarse lightweight aggregates as aggregate replacement were 2.22, 2.59, and 2.8 MPa, respectively [73]. Commonly, the splitting tensile strength improves with age. The percentage increases are 16.7% and 26% at 28 and 56 days, respectively, comparable to that at 7 days. Furthermore, it is proved that the replacement of both coarse bottom ash and fine bottom ash decreased the mechanical properties in the study of Wongsa et al. (2016) [71]. The splitting tensile strengths of lightweight geopolymer concretes were 1.2–2.0 MPa compared with 2.2–2.7 MPa of control geopolymer concretes due to the low density and high porosity of bottom ash particles. The lightweight geopolymer concretes with bottom ash replacement also revealed higher hollow spaces and porosity than control geopolymer concretes. Additionally, the splitting tensile strength of lightweight geopolymer concretes and control geopolymer concretes reduced with an increase in the sodium silicate to sodium hydroxide ratio. For lightweight geopolymer concretes with fixed solution-to-binder ratio, the splitting tensile strength declined from 1.5 to 1.2 MPa with the subsequent increases in sodium silicate to sodium hydroxide ratios from 0.5 to 1.5. Among the literature, there is a lack of research on the splitting tensile strength of geopolymer concrete incorporating LECA as lightweight aggregates.

4.13. Modulus of Elasticity

The modulus of elasticity, or Young's modulus, is one of the hardened concrete properties that is the ratio of axial stress to the interrelated strain of tensile or compressive stress before reaching the proportional limit of the material [58]. The modulus of elasticity of fly ash-based geopolymer concrete is much lower than that of hydraulic cement concrete [170]. Olivia and Nikraz (2012) further proved the statement with their findings regarding the modulus of elasticity of fly ash-based geopolymer concrete, which is 15–29% lower than hydraulic cement concrete [95]. Hardjito and Rangan (2005) reported that whenever the compressive strength of a fly ash-based geopolymer increases, the modulus of elasticity also increases [84]. Posi et al. (2013) reported that the modulus of elasticity of a lightweight geopolymer concrete increases linearly to the square root of the respective compressive strength with the equation shown in Equation (1).

$$E = 1.1673\, fc'^{0.8673}, \quad (1)$$

where E is the modulus of elasticity in GPa and fc' is the compressive strength in MPa [134]. Table 16 indicates the correlation of modulus of elasticity and compressive strength of fly-ash based geopolymer concrete.

Table 16. Correlation of the modulus of elasticity and compressive strength of fly ash-based geopolymer concrete.

Refs	Mean Compressive Strength, MPa	Age, Day	Modulus of Elasticity, GPa
[84]	89	90	30.8
[84]	68	90	27.3
[84]	55	90	26.1
[84]	44	90	23.0
[95]	57	91	27.2
[95]	59	91	28.0
[95]	63	91	26.8
[170]	60	28	18.4
[170]	55	28	11.7

According to Swaminathan et al. (2020), who used coconut shell to replace conventional coarse aggregates to produce lightweight geopolymer concrete in their study, found that as the replacement percentages of coconut shell as coarse aggregates increased, the modulus of elasticity of geopolymer concrete decreased. This is because of the lower stiffness of coconut shell in geopolymer concrete mix [129]. The same result was detected in the study of Khalil et al. (2019) [88]. They were investigating the use of locally artificial lightweight aggregates to produce lightweight geopolymer concrete. They also found out that the replacement of locally artificial lightweight aggregate content will reduce the modulus of elasticity of lightweight geopolymer concrete for unreinforced mixes because the locally artificial lightweight aggregates have a lower modulus of elasticity compared to natural aggregates. In addition, Kabir et al. (2017) discovered that using waste materials, such as oil palm clinker and palm oil shell, as a coarse aggregate to produce geopolymer concrete reduced the modulus of elasticity as the volume of lightweight aggregates increased. This is because the lower stiffness of the lightweight aggregates contributes to lower the stiffness of the geopolymer concrete [171]. Similarly, Posi et al. (2013) investigated the characteristics of geopolymer concrete incorporating aggregates from recycled lightweight blocks and found that as the volume of lightweight aggregates increased, the modulus of elasticity of geopolymer concrete decreased [134]. However, the increase in the amount of fine aggregates in the geopolymer concrete increases the modulus of elasticity of the geopolymer concrete as the fine aggregates will fill up the pores in the mix and, thus, the geopolymer concrete will become more compact and dense. Additionally, they also found that as the volcanic pumice aggregate content in geopolymer concrete increased, the modulus of elasticity of the geopolymer concrete decreased, as pumice aggregates are weaker than crushed granite, according to the finding of Wongsa et al. (2018) [172].

4.14. Flexural Strength

Novais et al. (2019) showed that the inclusion of cork triggers a sharp decrease in the flexural strength of concrete, varying from 1.55 MPa to 0.29 MPa after 28 days, whereas Khalil et al. (2018b) found that the flexural strength of lightweight geopolymer concrete utilizing fine locally artificial lightweight aggregates is reduced as the fine locally artificial lightweight aggregates content increases [87,127]. The percentage declination is 17.6% at 28 days for lightweight geopolymer concrete containing 100% fine locally artificial lightweight aggregates compared to control lightweight geopolymer concrete containing sand. Additionally, according to the study done by Abbas et al. (2018), the 28-day flexural strength of the lightweight geopolymer concrete containing artificial coarse lightweight aggregate that is manufactured from bentonite clays is 5.5 MPa [73]. It is common for the flexural strength of concrete to increase with age due to the ongoing hydration process and the development of internal bonds between the cementitious materials and aggregates. Therefore, it is not surprising that the percentage increase in flexural strength is higher at 28 and 56 days compared to 7 days. Furthermore, in the research of Colangelo et al. (2018), the flexural strength ranged from 0.32 MPa for geopolymer concrete to 0.6 MPa for composite mix with marble powder for 65% expanded polystyrene content [14]. However, only a minimal increment in the flexural strength with the supplement of marble powder and epoxy resin varied from 0.22 to 0.33 MPa with more expanded polystyrene content. It could be claimed that with too much expanded polystyrene content in the samples, the very poor mechanical characteristics and high compressibility performance of polystyrene particles counteract the advantageous outcome on the mechanical properties with the addition of epoxy resin and marble powder by creating microcracks at the interface between the geopolymer matrix and the expanded polystyrene particles. Moreover, according to Medri et al. (2015), the higher flexural strength of 2.4 MPa for sample using a smaller dimension of type 2 expanded vermiculite aggregate with a 3mm mean grain size associated with metakaolin (V2–Mk) was comparable to the flexural strength of 1.2 MPa for sample type 4 expanded vermiculite aggregate with a 10mm mean grain size associated with metakaolin (V4–Mk) [103]. This could be due to the fact that the V2–Mk sample has lower porosity and a more homogenous structure. By comparison, a mix prepared with LECA and ceramic powder as binder had the highest flexural strength of 6.81 MPa after 28 days, which was approximately 7% greater than the flexural strength of the corresponding Portland cement mix, which was 6.34 MPa [101]. Peng et al. (2019) showed that the utilization of SiO_2 content that is available in aluminosilicate sources during the geopolymerization process triggered the development of sodium-aluminum-silicate-hydrate (N-A-S-H) gel, leading to the densification of the microstructure [173].

4.15. Elevated Temperature

In contrast to Portland cement concrete, the strength of geopolymer concrete can either increase or decrease after being exposed to elevated temperatures [174]. A similar result was obtained by Pan et al. (2009), who deduced that geopolymer mortars may exhibit either an increase or a decrease in strength when subjected to elevated temperatures of up to 800 °C [175]. This variability in performance can be explained through the relationship of two opposite procedures when exposed to high temperatures. The first process is sintering and/or additional geopolymerization under high temperature and triggers the increasing of the strength, while the second process is the defects due to thermal incompatibility, which causes the reduction in strength. In addition, Kuenzel et al. (2013) examined the impact of high temperature exposure on the mechanical characteristics of metakaolin-based geopolymer mortar [176]. The results found that the microstructure, porosity, and strength of the mortars were not significantly affected by the temperature up to 800 °C. However, the utilization of silica sand enhanced the mechanical performance of the geopolymer mortar when exposed to temperatures as high as 1000 °C. In contrast, in the study of Ranjbar et al. (2014), it is deduced that as the temperature of exposure increased, there was a reduction in both the bulk density and compressive strength no matter what replacement rate of fly ash by palm oil fuel ash in geopolymer mortar [177]. The outcomes obtained from the research of Abdulkareem et al. (2014) also indicated that as the exposure temperature increased from 400 °C to 800 °C, there was a progressive reduction in the residual compressive strength of the geopolymer mortars [11]. It is in line with the study of Zhang et al. (2016), who assessed the mechanical characteristics, comprising compressive strength, tensile strength, bending strength, and bonding strength, of the geopolymer mortars after exposure to extreme temperature levels [169]. Nevertheless, according to the study of Hussin et al. (2015) the strength of blended ash geopolymer concrete increased when temperature increased, while peak strength reached at 600 °C [178]. In short, their findings suggest that geopolymer mortar is only suitable for construction in environments with temperatures below 300 °C, as the mechanical characteristics of the mortar were significantly affected at higher temperatures.

5. Conclusions

This research presents an overview of the latest developments in lightweight aggregate geopolymer concretes using a comprehensive data mining approach for bibliometric analysis and detailed discussion. To completely comprehend the possibilities of lightweight aggregate geopolymer concrete in the building industry, further research partnerships and investigations are urgently needed amongst academics, institutions, and nations. Consequently, there is a need for devising and implementing a strategy that facilitates researchers in accessing crucial data from the most reliable sources. To mitigate the inherent subjective biases in literature reviews, the use of bibliometric techniques aids in addressing this gap through computational tools. This study aimed to perform a bibliometric analysis using extensive bibliographic data sourced from the Scopus database on lightweight aggregate geopolymer concretes. During the bibliometric investigation, it unveiled the primary sources of publication, the keywords most commonly utilized in the literature, the authors and papers that received extensive citations, and the regions with the most prolific publication output.

Additionally, this study emphasized and explored several crucial areas of research, such as geopolymer concrete, lightweight concrete, binding materials, lightweight aggregates, and engineering properties of lightweight aggregate geopolymer concrete. From the results reported in the literature, the workability, strength performance, and resistance to aggressive environments of lightweight geopolymer concrete are significantly influenced by the type of lightweight aggregates, binder chemical and physical properties, type and dosage of alkaline activator solution and superplasticizer, ratios of solution-to-binder, and binder-to-aggregate content.

Lastly, future studies should explore the impact of novel waste materials or industrial by-products as binders and aggregate replacements on the properties of lightweight geopolymer concrete, alongside investigating the potential structural application of lightweight aggregate geopolymer concrete in construction, including beams, columns, and slabs, as well as assessing the long-term performance of lightweight geopolymer concrete under various aggressive conditions.

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