Review Article

Raheel Arif, Muhammad Faisal Javed*, Raheel Asghar, Ammar Iqtidar, Bilal Ahmed*, Rayed Alyousef, and Mohsin Ali Khan

A scientometric review on the utilization of copper slag as a substitute constituent of ordinary Portland cement concrete

https://doi.org/10.1515/rams-2024-0082
received May 06, 2024; accepted December 19, 2024

Abstract: This article presents a scientometric review on the utilization of copper slag (CS) as a substitute constituent in ordinary Portland cement concrete, with a greater focus on analyzing CS as a supplementary cementitious material (SCM). The review was conducted through a comprehensive scientometric analysis of literature using Scopus and VOSviewer, examining publication trends, document types, subject areas, leading contributors, and the overall progression of research on CS concrete. The analysis revealed a substantial increase in publications between 2015 and 2022, with the journal "Construction and Building Materials" and the country "India" identified as the most influential in the field. The methodology involved filtering relevant documents to focus on the most impactful research, which was then critically analyzed to assess the fresh and hardened properties of CS concrete. The findings indicate that incorporating 5–10% of CS as an SCM can significantly enhance the mechanical properties and durability of concrete. CS was also found to improve concrete durability by imparting a micro-filler effect, thereby densifying the structure. Additionally, CS contributes to ecological benefits by incorporating heavy metals into the concrete matrix, preventing their leaching, and aiding in environmental conservation. Despite these promising results, the review acknowledges that the long-term performance of CS concrete remains a critical area that needs further investigation.

Keywords: publication trend, subject areas, articles, environmental impact, mechanical properties, durability properties

*** Corresponding author: Muhammad Faisal Javed,** Department of Civil Engineering, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi, Swabi, Khyber Pakhtunkhwa, 23640, Pakistan; Department of Technical Science, Western Caspian University, Baku, Azerbaijan, e-mail: arbabfaisal@giki.edu.pk

*** Corresponding author: Bilal Ahmed,** Faculty of Transport and Aviation Engineering, Silesian University of Technology, Katowice, Poland, e-mail: Bilal.Ahmed@polsl.pl

Raheel Arif, Raheel Asghar, Ammar Iqtidar: Department of Civil Engineering, COMSATS University Islamabad, Abbottabad Campus, Abbottabad, 22060, Pakistan

Rayed Alyousef: Department of Civil Engineering, College of Engineering in Al-Kharj, Prince Sattam bin Abdulaziz University, Al-Kharj, 11942, Saudi Arabia

Mohsin Ali Khan: Department of Civil, Construction, and Environmental Engineering, North Dakota State University, Fargo, ND 58102, United States of America

1 Introduction

The construction industry plays a fundamental role in any economy, and concrete is a widely used construction material [1]. The properties of concrete enable it to have a long service life. Although concrete has a lot of advantages, it may also have several harmful effects like carbon dioxide (CO_2) emissions [2], which leads to the greenhouse effect [3]. It can be seen in Figure 1 that building construction materials and building operations contribute greatly toward increasing CO_2 emissions [4]. The use of concrete is increasing to fulfill the demands of the growing population [5–7]. It is being used for the construction of reinforced concrete frame structures [8–10], bridge structures, and their structural elements, *e.g.*, slabs, beams [11], and columns [12–18], *etc*. So, there is a need to pay special attention to the constituent elements of concrete. Concrete is a heterogeneous mixture of different elements like aggregate, binder, and water. Concrete is composed of 55%–88% aggregate, so the rapid use of aggregate in concrete leads to the depletion of our natural resources day by day [19]. Also, cement is prepared at a very high temperature of about 1,500°C; again resources are required to provide such a high temperature [20]. These resources include fossil fuels which again produce CO_2. Thus, the increase in demand and utilization of concrete for different projects leads to more production and use of concrete. And it in turn increases the CO_2 emissions, further degrading the quality of environment.

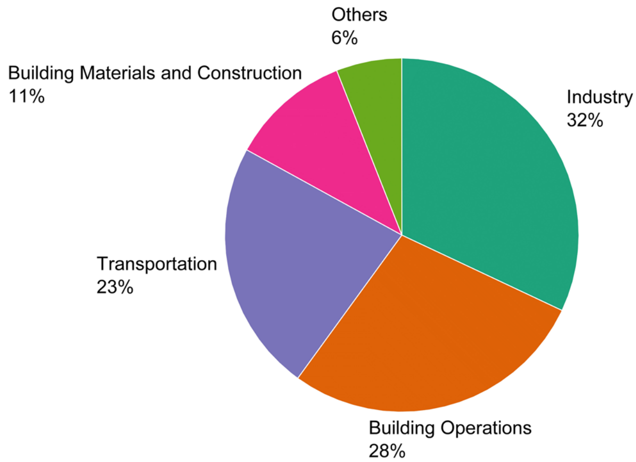

Figure 1: Sources of CO_2 emissions.

To overcome the damaging effects related to concrete usage, feasible alternatives can be used for the replacement of concrete ingredients [21–24]. By looking at some past decades, it can be assessed that there is a rapid increase in the use of waste material as a replacement for concrete ingredients [25–29]. Ejection of different types of waste directly into the environment leads to serious ecological problems by contaminating the water [30], soil [31], and air [32]. As industrialization increases [33,34], although it is beneficial, it also has considerable harmful effects on the environment by disposing of different slags [35–37]. An enormous quantity of solid waste is generated by several operations including mining [38], power generation, agricultural waste, and electrical stock [39]. Some of these wastes are flammable, reactive, contagious, and corrosive; their production has resulted in serious threats to the environment [40]. Keeping in view all these problems, concrete ingredients replacement's philosophy is currently triggered through either replacing ordinary Portland cement (OPC) with different waste or using waste as aggregate in concrete [41–43]. The replacement of cement with these wastes not only solves the problem of suitable disposal but also reduces CO_2 emissions [44]. Not every replacement leads to useful results, but researchers are always working to find suitable replacements. Most studies have shown that the application of this waste is economical and environmentally friendly [45]. The basic purpose of this strategy is to utilize the waste product beneficially and to bring down the cost of construction materials [46,47]. Many agricultural and industrial wastes which are not properly disposed of are pollutive [48]. These waste materials require proper disposal. Several research studies have shown that there is a potential for the replacement of concrete ingredients with these waste materials [49–51]. The researchers have successfully introduced a lot of replacements in concrete by using industrial waste and agricultural wastes [52–55]. The copper slag (CS) is a by-product of the copper mining industry [56,57]. It is produced during the smelting of copper ore to obtain pure copper [58]. CS is a by-product generated during the pyrometallurgical extraction of copper from its ores. This process involves high-temperature smelting, where copper sulfide ores are heated to separate the metal from impurities. The resulting slag primarily consists of iron silicates and other oxides, and it is produced in large quantities – approximately 2.2–3 tons of slag for every ton of copper produced, leading to an estimated global production of around 24.6 million tons annually [59]. CS poses environmental challenges, particularly due to its accumulation in landfills and the potential leaching of heavy metals into the soil and groundwater. However, studies have shown that CS is generally non-hazardous and can be classified as a "special waste" under various environmental regulations, including those set by the United Nations and the US Environmental Protection Agency [60]. Recent research studies have shown that copper can be used as a pozzolanic material in the production of green concrete [61–63]. Hence, it is necessary to summarize the use of CS as a replacement for cement constituent.

This article reviews the use of CS as a replacement constituent in concrete. CS is considered one of the waste materials that has a promising future in the construction industry as a replacement for concrete ingredients [64]. CS is the by-product of copper distillation by melting. Each ton of copper produces almost 2.5 tons of CS [65]. A huge quantity of CS is produced every day, so proper use of CS in the construction industry leads to a reduction in the cost of dumping and minimizing air pollution. Japan and the US produce almost six million tons of CS per year [66]. In the current era, CS finds wide application in roofing granules, cutting tools, road-base construction, railroad ballast, asphalt pavement, as well as the cement and concrete industry [67]. Several advantages of employing CS in the construction industry are given in Figure 2. As cement production is an energy-intensive process [68,69], a considerable amount of energy can be reduced by using CS, as it only requires grinding [70]. A maximum amount of CS can be utilized by using it replacement of aggregate, as 70 % of concrete is composed of fine and coarse aggregate [70]. The addition of CS improves the quality of concrete [71,72] and leads to increased longevity of the structure and decreased expenses associated with renovations [73]. Furthermore, utilizing CS in concrete significantly decreases the quantity of cement required, thereby achieving the objective of resource conservation and cost-effectiveness [66,67]. Numerous researchers have explored substituting CS for both fine and coarse aggregate, examining its impact on various properties such as freshness, mechanical strength, and durability [74,75]. These studies have shown several positive effects of these replacements but there were some undesirable results like setting time, freezing–thawing, and bleeding problems, especially when CS was used as fine aggregate [76]. The lime content of CS is very low, *i.e.* about 15%, and results in strength reduction, but a higher density (3.37) of CS compensates for strength problems [77]. Previous research has demonstrated that substituting cement and fine aggregate with CS can enhance the strength and long-term durability of high-strength and high-performance concrete [78–80].

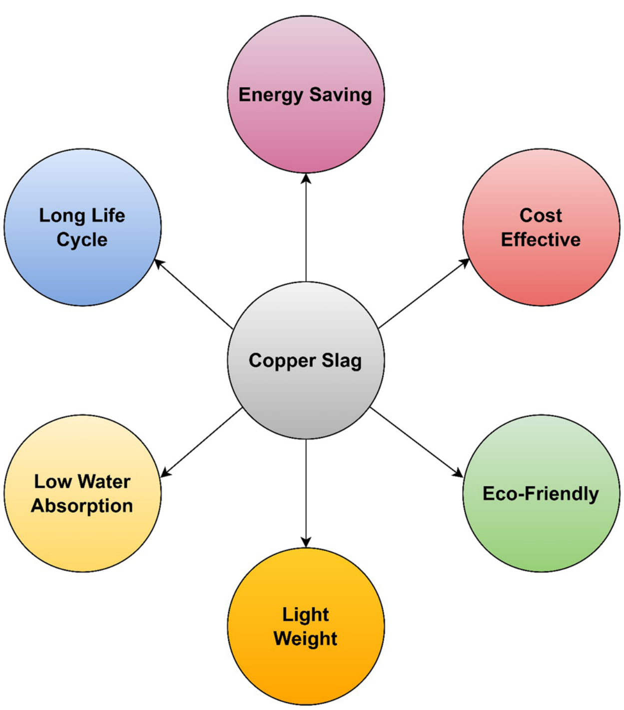

Figure 2: Benefits of employing CS in the construction sector.

This study aims to address these knowledge gaps by providing a comprehensive analysis of how CS affects various properties of concrete. By evaluating factors such as replacement ratios, particle size, and the impact on durability, this research contributes valuable insights into the practical applications of CS in concrete. The findings have the potential to improve the sustainability of construction materials, offering both environmental benefits by recycling industrial by-products and economic advantages by enhancing the performance of concrete.

2 Methods

There is always a chance of errors in studies and reviews when they are accomplished manually. A scientometric analysis involves quantitatively examining science, which includes studying communication within the scientific community and informing science policy decisions. This analysis involves assessing research impact, exploring the influence of academic journals and research institutions within a specific field of knowledge, and applying techniques to analyze citation interrelationships. In recent studies within the construction domain, including construction engineering and management and building information modeling, scientometric methods are being employed [81–91]. So, this review study was conducted through scientometric analysis to avoid the irrationality and essence of personal standpoint [92–100] about the use of CS in the construction industry. This study encompasses all the research done in the past on the abovementioned topic. The linkage between the research is used to evaluate the progress by utilizing different maps. It helped in the quantitative analysis of the data.

A substantial literature database exists regarding the use of CS in construction. However, the most notable data can be accessed through platforms like Web of Science or Scopus. Among these, Scopus was selected as the primary database for scientometric analysis due to its comprehensive and extensive coverage of the literature [52,101]. While Web of Science is recognized for indexing journals with impact factors, Scopus offers a broader and more up-to-date collection of articles, particularly in the fields related to construction and materials science. This wider scope was essential for ensuring that the analysis included the most recent and relevant studies on the utilization of CS in concrete. Furthermore, Scopus provides detailed citation data and a wider range of document types, including conference papers and book chapters, in addition to journal articles. This diversity was crucial for capturing the full spectrum of research activities related to CS. The larger database size and the inclusion of a broader range of sources allowed for a more comprehensive scientometric analysis. The keyword used to search for data was "CS concrete." The scientometric analysis was conducted on February 21, 2023, and it yielded a total of 503 documents on the above-stated topic. Furthermore, filters were used to refine the research to only relevant topics like "article" was selected as document type. Similarly, the source filter was set to "journal" and the language was set to "English." The documents on CS based concrete were found to be between the years 1983 and 2023. To narrow down the research the filters were set to obtain articles from the fields related to the construction industry. The search was conducted after applying filters. The obtained data were stored using Microsoft Excel's comma-separated file, CSV. Now, software was required to conduct scientometric analysis. A befitting analysis software by the name of VOSviewer was used to conduct the scientometric analysis. VOSviewer is an open-licensed software that is used to visualize the research literature in every field of research. It can import data from various sources (including Scopus), create network visualization (identifying patterns, trends, and clusters), create density visualization (identifying areas of high research activity), group-related entities based on co-occurrence (identifying thematic clusters), and conduct time-based analysis (enabling researchers to track changes in the research landscape over time). In this study, VOSviewer was used to analyze different parameters of the sources, articles, keywords, authors, organizations, and countries associated with CS concrete literature. A graphical illustration of the methodology is shown in Figure 3.

3 Results

The obtained data from Scopus was used in VOSviewer to analyze and visualize different trends. These obtained trends and maps are presented and discussed below.

3.1 Publication trend

The annual publication trend over the past four decades has been found on the topic of the use of CS in the construction industry. This publication trend is illustrated in Figure 4. The number of publications has been low and high from year 1983 to year 2008. However, it can be seen from the spike in the trend that the number of publications increased in the past few years and did not go down again. The fact is obvious that global warming and climate change are turning into reality quickly and more and more research is being conducted to slow down the effects of this phenomenon. Remarkably, research is being conducted on green concrete and sustainable construction materials. This research is significant because this research will be used as a basis for further future research on this topic. Furthermore, recent research did not focus on mapping the scientific details of the research. They rather focus on manual reviewing.

3.2 Document types

Document types have also been analyzed on the topic. Out of all the documents analyzed, the maximum number of

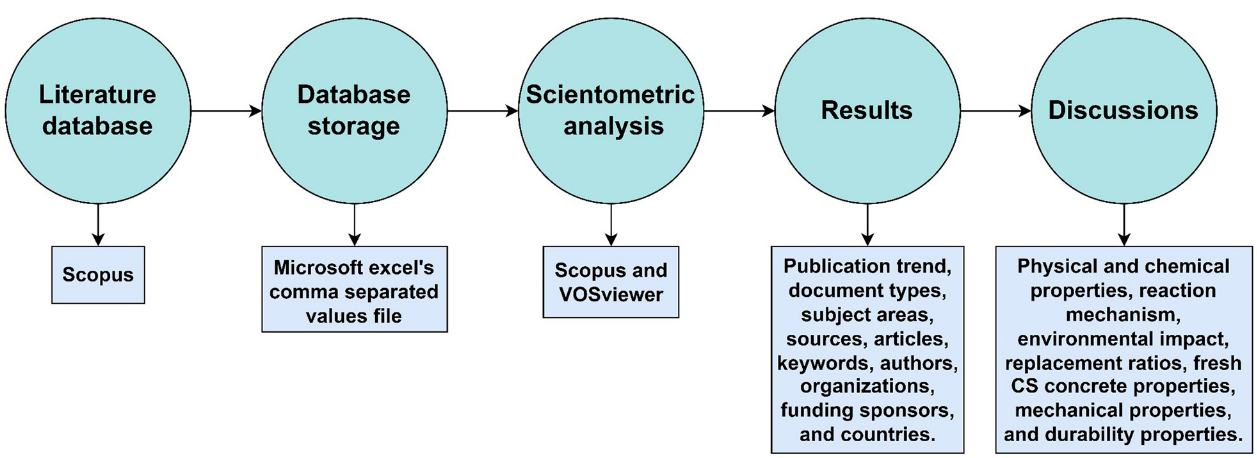

Figure 3: Review methodology.

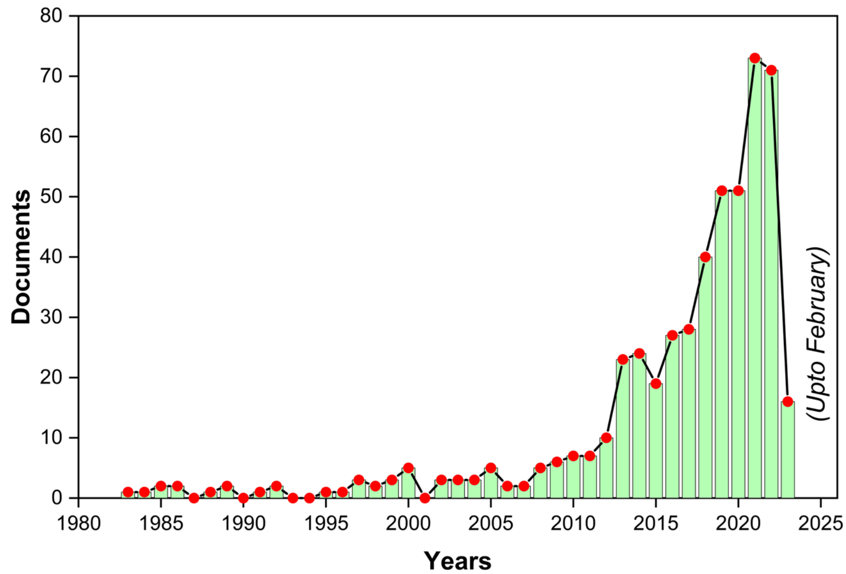

Figure 4: Annual publication trend of analyzed documents.

documents were articles published in different journals. These articles contributed largely to the database, with a total of 64.2%. Next in the database for scientometric review were conference papers from different conference proceedings. These conference papers contribute 19.3% to the scientometric database. Then, the conference reviews on the topic of CS in the construction industry occupied 8.9% of the database. Then, reviews claimed 5.6% of the database. The review papers were followed by book chapters by 1.6% and then books which took 0.4% of the database. The results showed that most of the published work on the topic under consideration was in the form of articles. The results of the analysis of document types are presented in Figure 5.

3.3 Subject areas

The Scopus analyzer was utilized to find out the relevant field of studies for CS. It can be seen from the analysis results in Figure 6 that several fields came out to be relevant to the topic of CS. However, among all these fields, engineering came out on top with 37.9% relevancy. The field of materials science stood second with a total of 22%. The field of environmental science followed these two fields with 10.6%. Hence, these three fields account for 70.5% of the total documents available on the topic of CS. The documents regarding CS are also presented in the fields of chemistry, energy, chemical engineering, *etc.* Remarkably, research is currently underway in the fields of engineering and environmental sciences to explore the adoption of CS as a substitute for the conventionally used OPC.

3.4 Sources

The mapping of publication sources helps in visualizing innovation and development. In this study, the sources were mapped using the VOSviewer on the database of publications. In the parameter settings, the "kind of analysis" was configured as "bibliographical coupling," and the "analysis unit" was selected as "sources." A minimum threshold of "5" published documents was selected. A total of 20 sources met the set-out criteria. Table 1 represents these

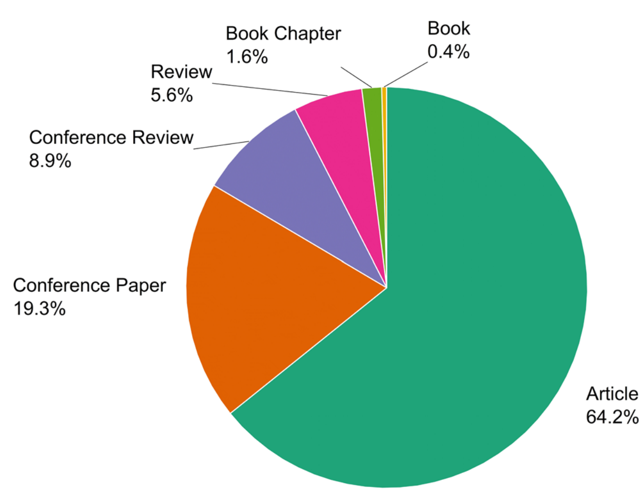

Figure 5: Types of analyzed documents.

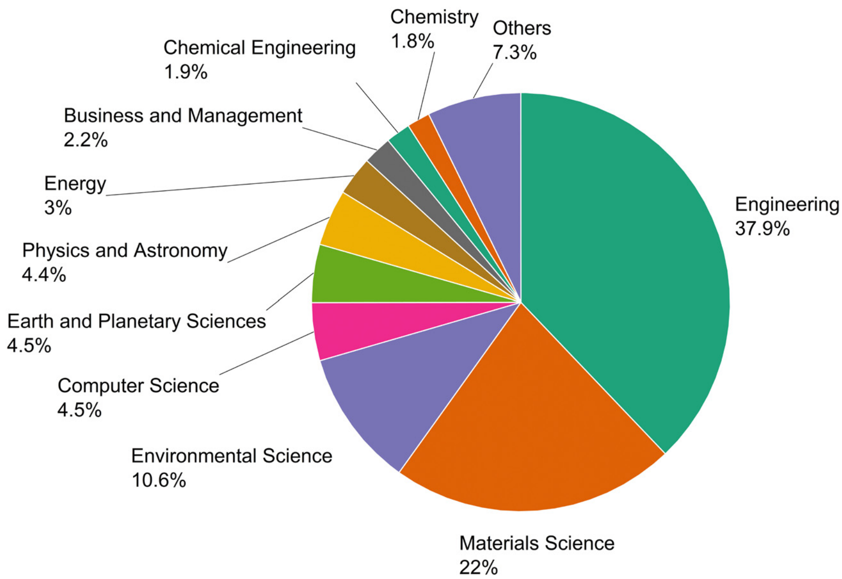

Figure 6: Subject areas of analyzed documents.

20 sources along with total documents, citations, and total link strength. A scientific journal by the name of "Construction and Building Materials" came to be the top source with 32 documents, 302 citations, and a total link strength of 686. It is followed by "Materials Today: Proceedings" with a document count of 32, 61 citations, and a total link strength of 338. Then, the Advanced Materials Research, American Concrete Institute, and Journal of Cleaner Production are some other honorable mentions on the list. All these journals are related to engineering and environmental science mostly.

The annual trend of these top publishing sources is presented in Figure 7. It is evident that Construction and Building Materials have been actively involved since the early 2000s, and even before that Journal of Materials in Civil Engineering was publishing articles on the concerned

Table 1: Top 20 sources of the analyzed documents of CS concrete

S. no	Source	Documents	Citations	Total link strength
1	Construction and Building Materials	32	302	686
2	Materials Today: Proceedings	31	61	338
3	Advanced Materials Research	17	0	0
4	American Concrete Institute, ACI Special Publication	12	2	0
5	Journal of Cleaner Production	12	35	608
6	International Journal of Innovative Technology and Exploring Engineering	10	11	0
7	Journal of Materials in Civil Engineering	9	147	535
8	IOP Conference Series: Materials Science and Engineering	8	5	0
9	Journal of Building Engineering	8	2	507
10	International Journal of Civil Engineering and Technology	7	4	1
11	Materials	7	8	223
12	Applied Mechanics and Materials	6	9	0
13	International Journal of Applied Engineering Research	6	3	0
14	IOP Conference Series: Earth and Environmental Science	6	0	82
15	Journal of Structural Engineering (India)	6	118	3
16	AIP Conference Proceedings	5	23	164
17	ARPN Journal of Engineering and Applied Sciences	5	0	0
18	Asian Journal of Civil Engineering	5	5	29
19	Cement and Concrete Composites	5	80	44
20	Journal of Environmental Management	5	871	103

topic. However, the contribution of Journal of Materials in Civil Engineering is linear, while that of Construction and Building Materials follows a zig-zag trajectory since 2012 and then gets a hike in its contribution. Similarly, Materials Today: Proceedings took a start in 2016 and 2017, and its contribution spiked and never came down since. Other journals like the Journal of Cleaner Production also contributed to the topic over recent years when research started on minimizing the carbon footprint of the construction industry.

Similarly, Figure 8 illustrates the visual network map of journals with at least five published articles on the relevant topic. The larger size of the node indicates a greater number of published articles [102]. In the figure, it is evident that Construction and Building Materials have the most prominent node in the whole map since it has the greatest number of articles published. Then, the most noteworthy node is that of Materials Today: Proceedings because it has the second most number of published articles on the concerned topic. Further, VOSviewer has also represented clusters of different colors. These clusters are set up based on common research scopes and the frequency with which they are cited together in a journal [103]. For example, Construction and Building Materials, Journal of Cleaner Production, and Journal of Building Engineering appear to be in green clusters. It can be inferred that these journals are co-cited in articles several times. The number of links shows how many times two journals are cited together in a research article [104]. The distance between the clusters shows their strength of relationship with each other [105]. For instance, the Journal of Cleaner Production exhibits closer proximity to Construction and Building Materials compared to Materials Today: Proceedings. It shows that there is a strong relationship between Construction and Building Materials and Journal of Cleaner Production. Along with all these parameters, density mapping is also shown in Figure 9. Various colors depict the varying contributions of journals in the research. A red color denotes the high density of research, a yellow color denotes moderate density, green is an

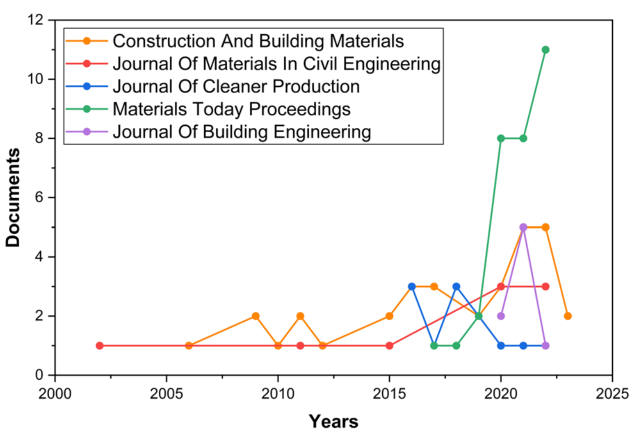

Figure 7: Annual publication trend of some top sources of the analyzed documents of CS concrete.

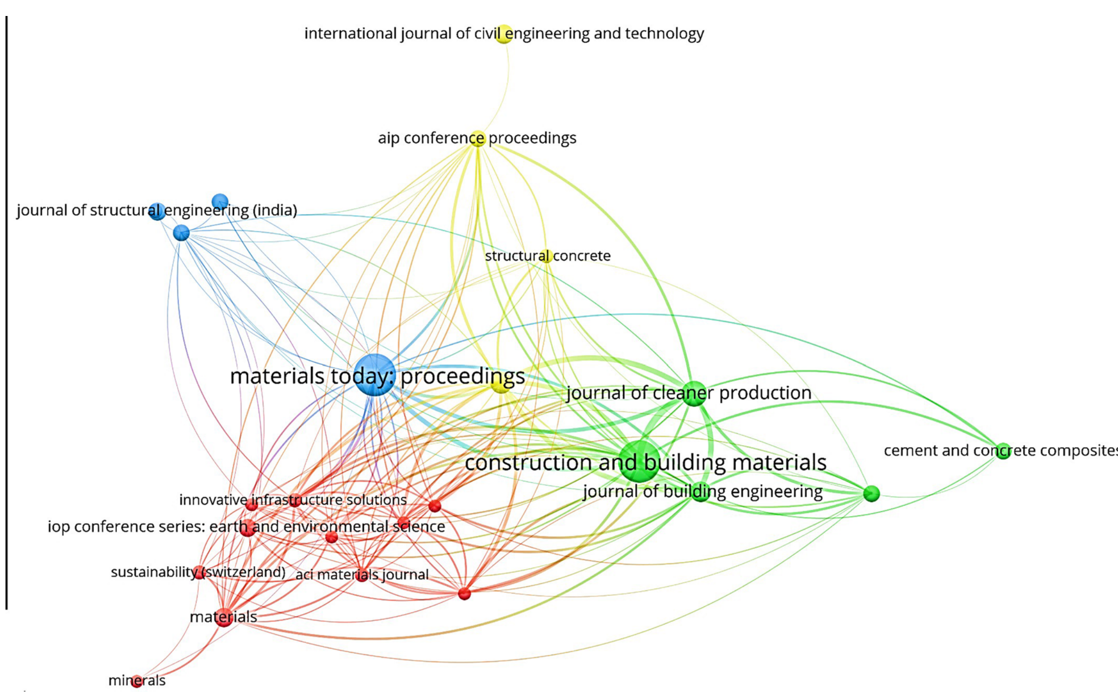

Figure 8: Network mapping of the sources of analyzed documents of CS concrete.

indicator of low density, and blue is then lowest density [106]. As evident from Figure 9, Construction and Building Materials have the greatest density or in other words greatest contribution to research on the topic of CS in the construction industry. Following this, the sequence continues with the Journal of Building Engineering, Materials Today: Proceedings, and finally, the Journal of Cleaner Production.

3.5 Articles

The influence of articles within a specific field of research is gauged by the number of citations they receive. Articles with the highest number of citations serve as beacons for further research on that topic. VOSviewer was employed to identify articles with the highest number of citations on the topic of the use of CS in the construction industry. The search parameters in VOSviewer were configured with "Bibliographic coupling" selected as the "type of analysis" and "document" was set as "unit of analysis." The minimum number of citations was set to one hundred. The analysis program returned various results. Out of these results, the top 20 articles with the most citations are presented in Table 2. The article "Characteristics and utilisation of CS – A review" by Gorai *et al.*, topped the list with 594 citations. It was followed by "High-performance cementing materials from industrial slags – A review" by Shi C and Qian J with 499 citations. These citations show the shifting of research toward finding more suitable materials to use as alternatives for conventional cement. Figure 10 illustrates the network mapping of the top-cited connected articles. It can be seen through nodes and links that different articles on CS concrete are closely related and cited. Figure 11 presents the density mapping of the articles on CS concrete. From the illustration, it can be inferred that articles authored by Chithra *et al.* have made the most significant contribution to the current field of study.

3.6 Keywords

Keywords are used to depict the domain of research's fundamental field; hence, they are important for this study. For the assessment of keywords, the "kind of analysis" was configured as "co-occurrence," and the "unit of analysis" was set as "all keywords." The minimum number of occurrences was set as five. The top 20 keywords that occurred

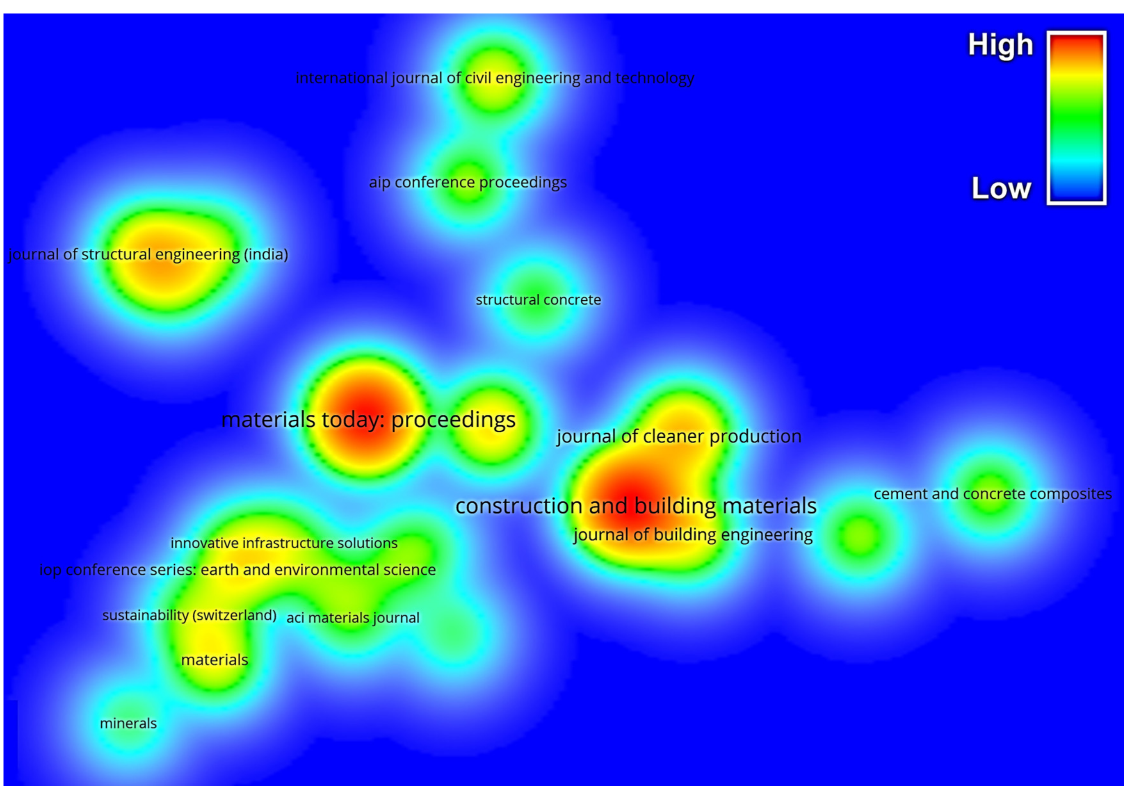

Figure 9: Density mapping of the sources of analyzed documents of CS concrete.

Table 2: Top 20 articles of CS concrete

S. no	Document	Ref.	Citations	Total link strength
1	Characteristics and utilization of copper slag – A review (Gorai B.; Jana R.K.; Premchand – 2003)	[107]	594	2
2	High performance cementing materials from industrial slags – A review (Shi C.; Qian J. – 2000)	[108]	499	0
3	Utilization of copper slag in cement and concrete (Shi C.; Meyer C.; Behnood A. – 2008)	[109]	370	1
4	Copper slag as sand replacement for high performance concrete (Al-Jabri K.S.; Hisada M.; Al-oraimi S.K.; Al-saidy A.H. – 2009)	[57]	232	15
5	Effect of copper slag as a fine aggregate on the properties of cement mortars and concrete (Al-Jabri K.S.; Al-saidy A.H.; Taha R. – 2011)	[75]	223	9
6	The effect of colloidal nano-silica on workability, mechanical, and durability properties of high performance concrete with copper slag as partial fine aggregate (Chithra S.; Senthil Kumar s.r.r.; Chinnaraju K. – 2016)	[110]	198	1
7	Optimum content of copper slag as a fine aggregate in high-strength concrete (Wu W.; Zhang W.; Ma G. – 2010b)	[111]	184	1
8	A comparative study on the compressive strength prediction models for high performance concrete containing nano silica and copper slag using regression analysis and artificial neural networks (Chithra S.; Kumar S.R.R.S.; Chinnaraju K.; Alfin Ashmita F. – 2016)	[112]	183	8
9	Performance of alkali activated slag concrete mixes incorporating copper slag as fine aggregate (Mithun b.m.; Narasimhan m.c. – 2016)	[113]	170	0
10	Experimental evaluation of high performance base course and road base asphalt concrete with electric arc furnace steel slags (Pasetto M.; Baldo N. – 2010)	[114]	155	0
11	Mechanical properties of high-strength concrete incorporating copper slag as coarse aggregate (khanzadi m.; behnood a. – 2009)	[115]	150	2
12	Immobilization of heavy metals (Pb, Cu, Cr, Zn, Cd, Mn) in the mineral additions containing concrete composites (Giergiczny Z.; Król A. – 2008)	[116]	147	0
13	Sustainable use of industrial-waste as partial replacement of fine aggregate for preparation of concrete – A review (Dash M.K.; Patro S.K.; Rath A.K. – 2016)	[117]	142	20
14	Studies on ultra high performance concrete incorporating copper slag as fine aggregate (Ambily P.S.; Umarani C.; Ravisankar K.; Prem P.R.; Bharatkumar b.h.; Iyer N.R. – 2015)	[118]	138	2
15	Use of waste copper slag, a sustainable material (Murari K.; Siddique R.; Jain K.K. – 2015)	[56]	136	0
16	Preparation of autoclaved aerated concrete using copper tailings and blast furnace slag (Huang x.-y.; ni w.; Cui w.-h.; wang z.-j.; Zhu l.-p. – 2012)	[119]	136	0
17	Sustainable use of copper slag in self-compacting concrete containing supplementary cementitious materials (Sharma R.; Khan R.A. – 2017a)	[120]	131	43
18	Performance of high-strength concrete made with copper slag as a fine aggregate (Al-Jabri K.S.; Hisada M.; Al-Saidy A.H.; Al-Oraimi S.K. – 2009)	[121]	130	15
19	Effect of copper slag and cement by-pass dust addition on mechanical properties of concrete (Al-jabri K.S.; Taha R.A.; Al-Hashmi A.; Al-Harthy A.S. – 2006)	[122]	124	1
20	Durability of copper slag contained concrete exposed to sulfate attack (Najimi N.; Sobhani J.; Pourkhorshidi A.R. – 2011)	[123]	119	8

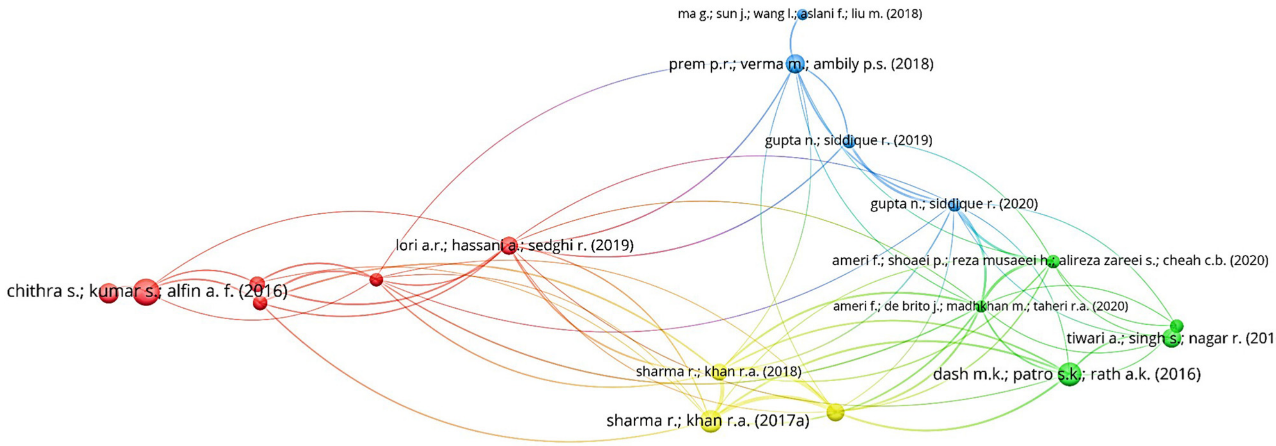

Figure 10: Network mapping of the articles of CS concrete.

in documents related to CS concrete are presented in Table 3. According to the analysis conducted by VOSviewer, the top three keywords with the most occurrences are CS, compressive strength, and concrete with 226, 74, and 69 occurrences, respectively. Figure 12 represents the nodes of keywords based on the frequency of their occurrence. The greatest node is CS. It is followed by compressive strength and then concrete. Hence, these keywords represent the most significant terms searched in the field of utilizing CS in concrete. The close links between the nodes show their strong relation and co-citation in different articles. Figure 13 represents the density visualization of the keywords. The varying colors from red to blue show the denser to lowest denser areas. It is evident from Figure 13 that the keyword CS has the greatest density, that is, red color in the density visualization map. It means that the greatest number of articles have CS as a keyword in them. Furthermore, the density of compressive strength, concrete, and fly ash has shown that these keywords are often used in combination with the CS. It can act as a guide for future authors so that they may use these words as keywords in their articles so that their articles can be found easily.

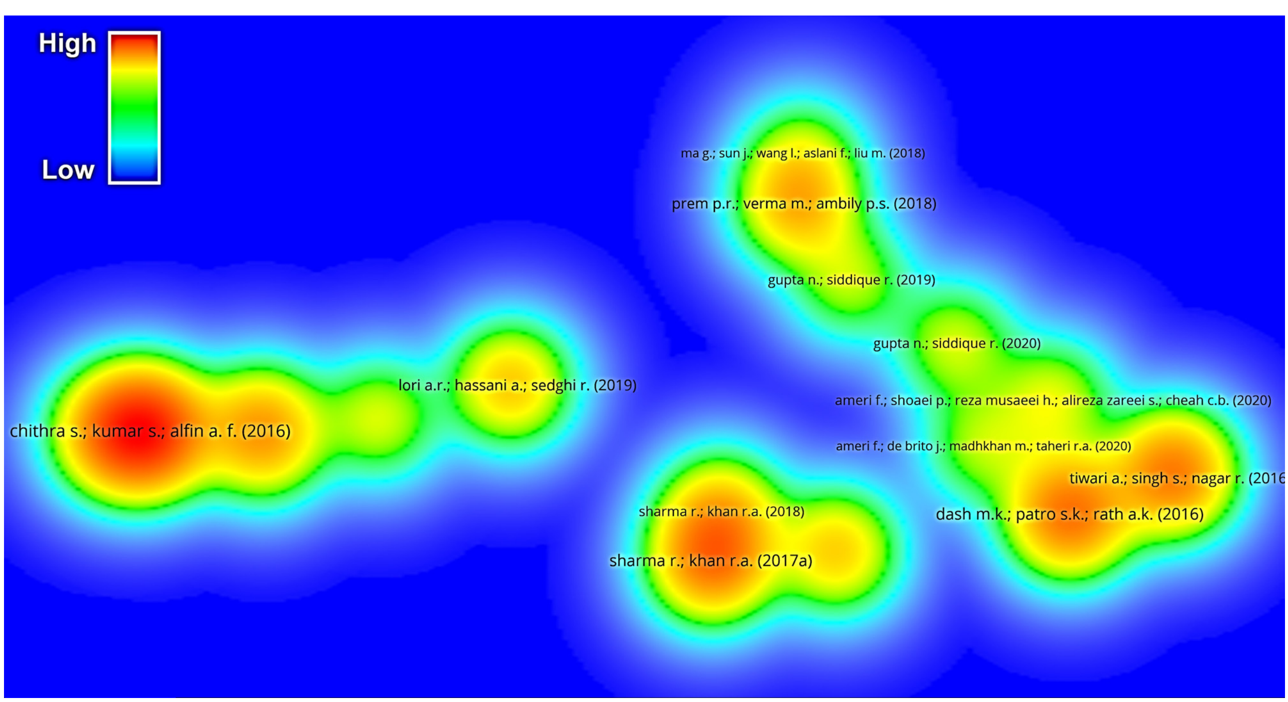

Figure 11: Density mapping of the articles of CS concrete.

Table 3: Top 20 keywords used in the analyzed documents of CS concrete

S. no	Keyword	Occurrences	Total link strength
1	CS	226	432
2	Compressive strength	74	172
3	Concrete	69	150
4	Fly ash	48	119
5	Durability	38	101
6	Strength	32	88
7	Mechanical properties	27	66
8	Flexural strength	20	58
9	Fine aggregate	19	53
10	Geopolymer concrete	17	29
11	Workability	17	55
12	Self-compacting concrete	16	35
13	Split tensile strength	14	41
14	Slag	11	23
15	Waste copper slag	11	19
16	Cement	10	32
17	ggbs	10	24
18	Silica fume	10	30
19	Fresh properties	9	20
20	Metakaolin	9	29

The top 20 keywords identified, including “CS,” “compressive strength,” “concrete,” and “durability,” align well with the focus of the articles published predominantly in civil engineering journals. The prominence of terms like “compressive strength,” “mechanical properties,” and “flexural strength” indicates a significant emphasis on evaluating the structural performance of concrete incorporating CS. Keywords such as “fly ash,” “ggbs,” “silica fume,” and “metakaolin” suggest a comparative analysis or combination of CS with other supplementary cementitious materials (SCMs), reflecting a broader interest in optimizing concrete mixes. The presence of “geopolymer concrete” and “self-compacting concrete” highlights the exploration of innovative and sustainable concrete technologies within the research community. Moreover, the keyword “waste copper slag” underscores the environmental angle, aligning with the growing trend of utilizing industrial by-products to promote sustainability in construction. This focus on sustainability and material efficiency is further evidenced by the recurring mention of “durability” and “fresh properties.” Overall, the keyword analysis reveals a strong alignment with the publication trends discussed in previous sections, confirming that the

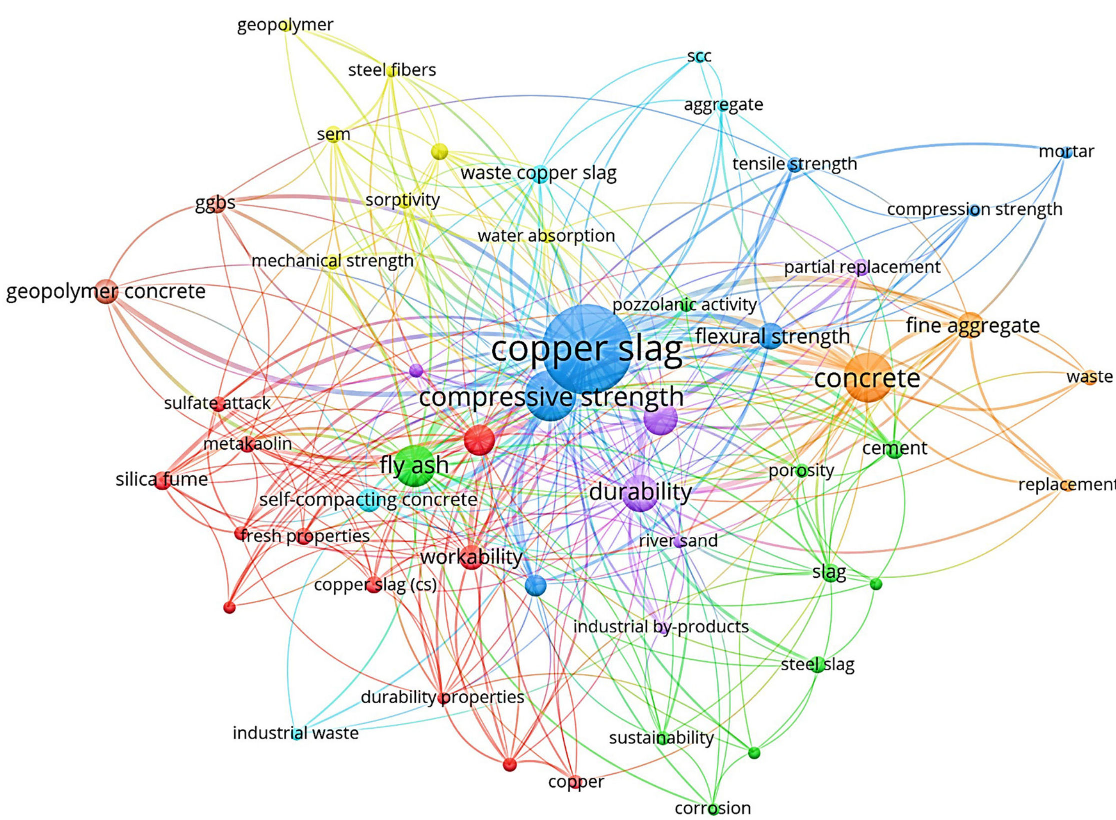

Figure 12: Network mapping of keywords used in the analyzed documents of CS concrete.

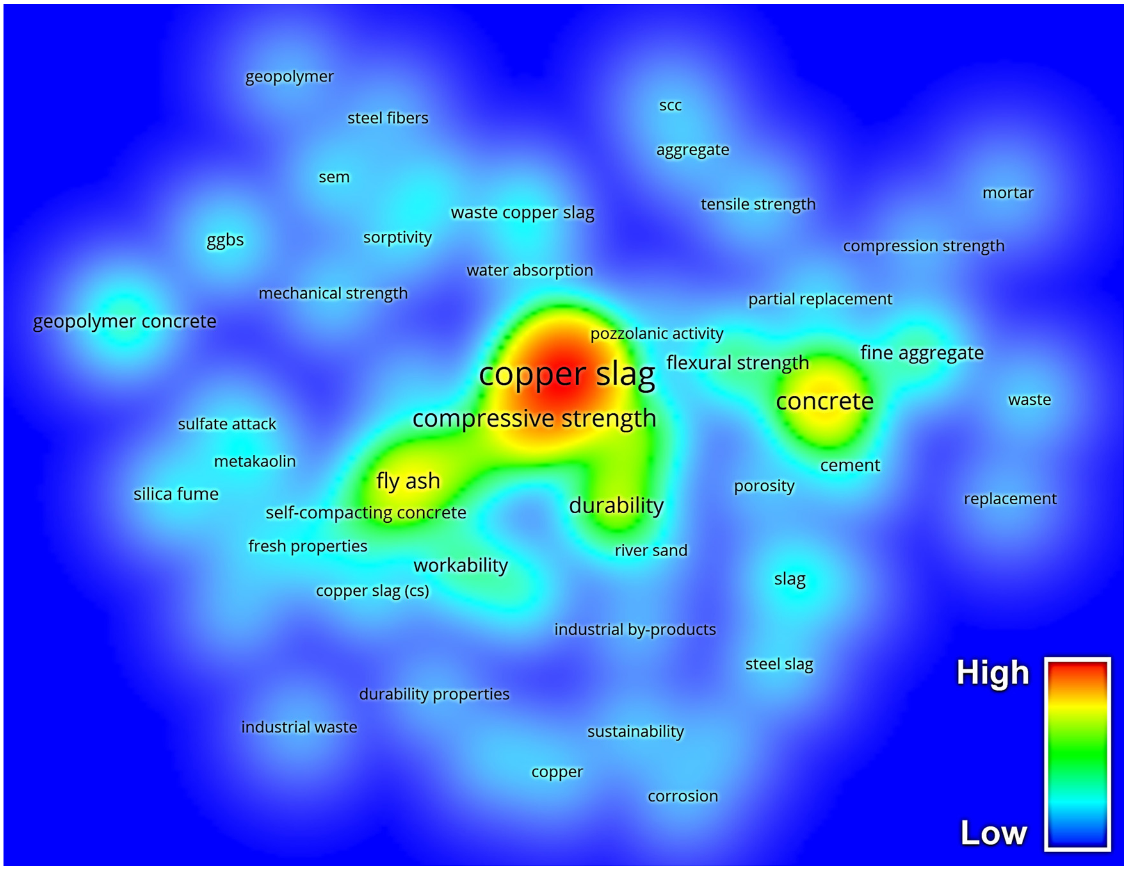

Figure 13: Density mapping of keywords used in the analyzed documents of CS concrete.

research is geared toward improving the performance and sustainability of CS concrete, particularly within the domain of civil engineering.

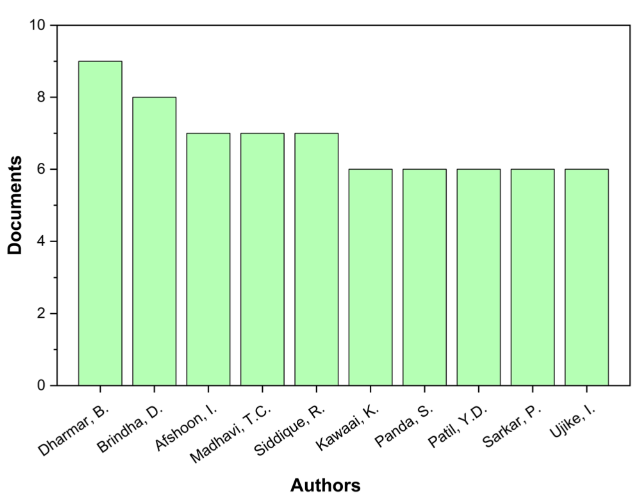

Figure 14: Contribution of some top authors of the analyzed documents of CS concrete.

3.7 Authors

A researcher's impact on his research field can be assessed by the number of citations he receives. Figure 14 illustrates some of the top authors who have contributed articles on the topic of CS concrete. The evaluation of authors on the study topic was performed using "co-citation" as the "kind of analysis" and "cited authors" as the "unit of analysis." Since it is difficult to assess any author's contribution by analyzing only one article with top citations, the total number of citations was divided by the total number of published articles on the topic. The minimum threshold for the average number of citations was set at 10. The analysis returned the results, out of which the top twenty authors are represented in Table 4. Siddique has the most citations with 119 citations and a total link strength of 4,654. He is followed by Al Jabri with 116 average citations and then Al Saidy with 83 average citations. Figure 15 represents the network mapping of the authors. The size of the node corresponds to the number of citations an author received on the topic of CS in concrete. It can be seen that the greatest node belongs to Siddique, then Al Jabri and Al Saidy.

Table 4: Top 20 authors of the analyzed documents of CS concrete based on number of citations

S. no	Author	Citations	Total link strength
1	Siddique, R.	119	4,654
2	Al-Jabri, K.S.	116	3,760
3	Al-Saidy, A.H.	83	3,333
4	Sharma, R.	78	3,353
5	Khan, R.A.	69	3,304
6	Hisada, M.	61	2,309
7	Behnood, A.	54	2,231
8	Zhang, W.	54	2,156
9	Al-oraimi, S.K.	53	2,250
10	Ambily, P.S.	53	2,203
11	Wu, W.	53	2,057
12	Ma, G.	50	2,072
13	Prem, P.R.	47	2,339
14	Sharifi, Y.	45	2,469
15	Shi, C.	44	1,379
16	Afshoon, I.	43	2,388
17	De brito, J.	40	1,717
18	Gorai, B.	40	1,070
19	Taha, R.	38	1,568
20	Ameri, F.	33	1,668

However, it is also noteworthy that authors belonging to different countries or territories do not have strong correlations. The density mapping of the authors is also conducted in Figure 16. The density represents the total number of citations received by an author. It can be seen that the red color density belongs to Al Jabri, Al Saidy, and Siddique. Hence, these authors have made significant contributions to research on the utilization of CS in the construction industry.

The co-citation analysis conducted in this study highlights the key contributors to research on the utilization of CS in concrete. Citations serve as a proxy for the influence and relevance of an author's work within the scientific community. Siddique's 119 citations and Al Jabri's 116 citations demonstrate their pivotal roles in advancing the understanding of CS in concrete. The high total link strength of these authors, particularly Siddique's 4654, suggests that their work is not only widely recognized but also forms a critical foundation upon which subsequent research is built. This indicates their studies are frequently referenced in the literature, contributing to the development of new insights and methodologies in the field. While

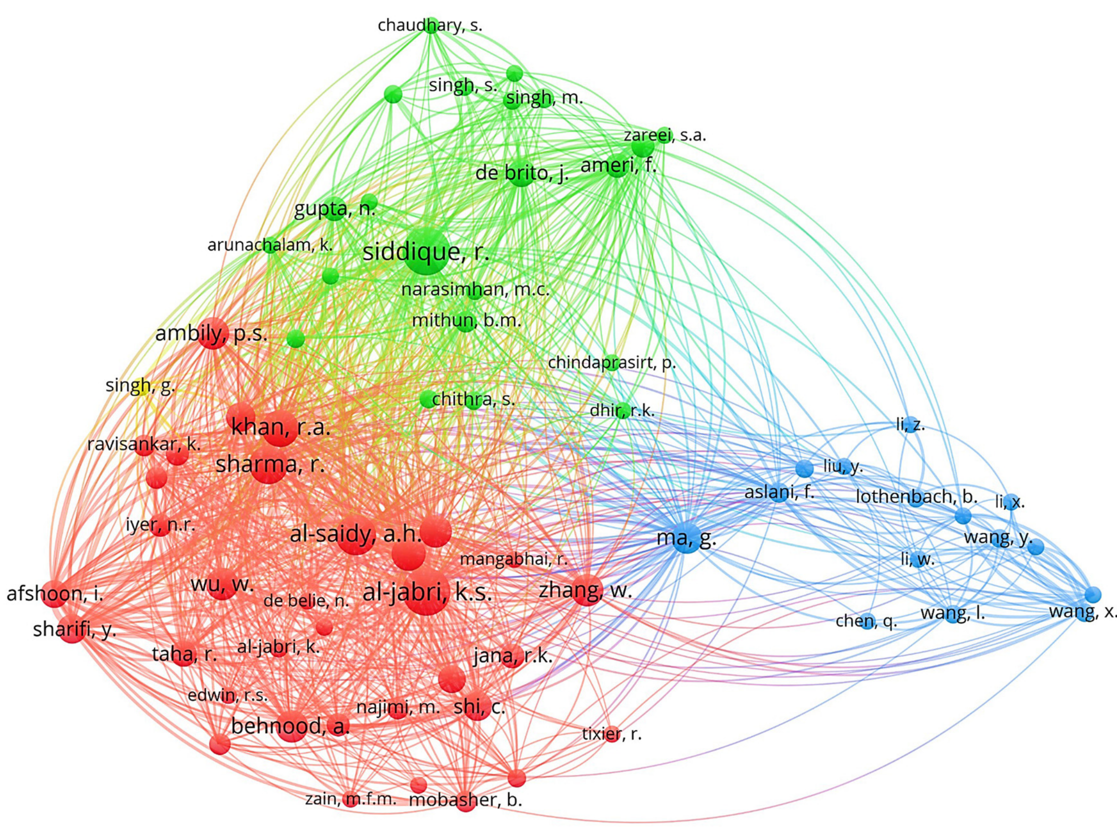

Figure 15: Network mapping of the authors of analyzed documents of CS concrete.

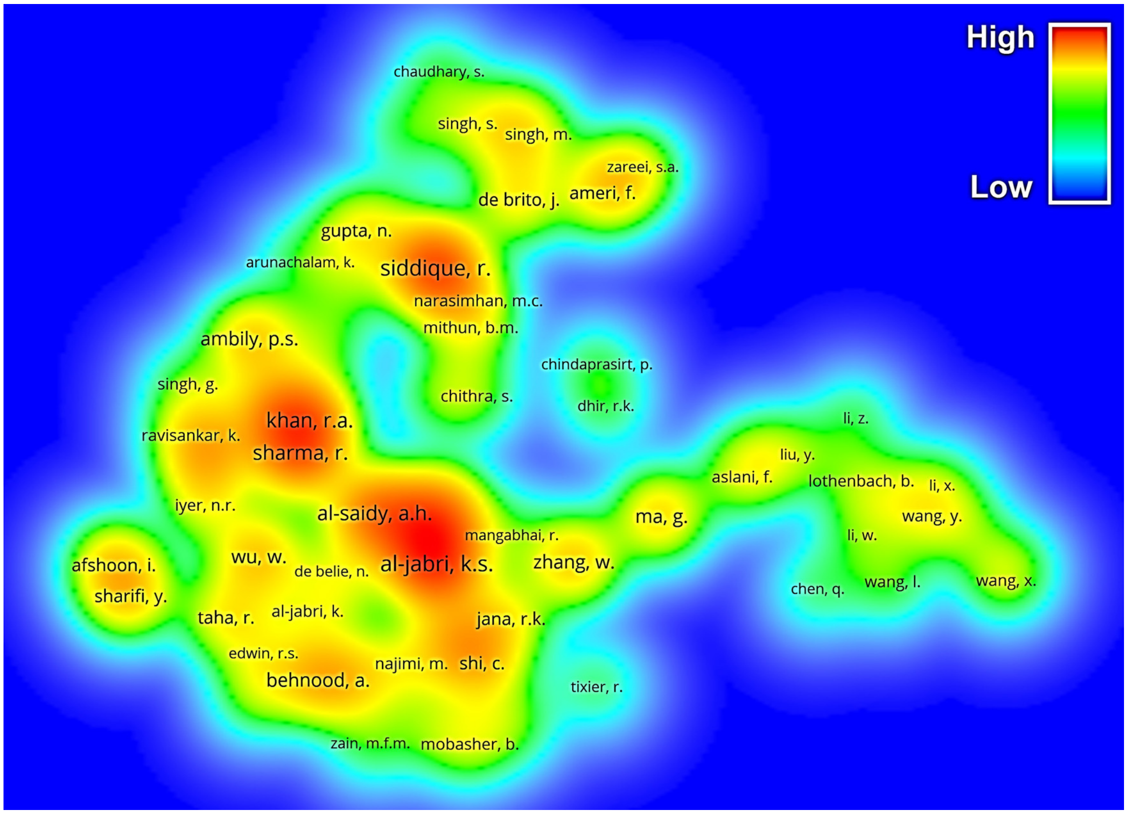

Figure 16: Density mapping of the authors of analyzed documents of CS concrete.

Siddique leads in citations, it is important to consider the breadth of his contributions compared to others. Al Jabri and Al Saidy, with slightly fewer citations, also show substantial impact, indicating that their research has been instrumental in exploring specific aspects of CS concrete. For instance, Al Jabri's work might be more specialized in certain applications or geographical contexts, which could explain his high citation density despite having fewer overall citations than Siddique. The network mapping reveals the collaborative landscape of CS research. The prominent nodes belonging to Siddique, Al Jabri, and Al Saidy indicate their central roles in the research network. However, the weak correlations between authors from different countries suggest that CS research might be somewhat fragmented, with limited cross-border collaboration. This could point to opportunities for enhancing global research efforts by fostering more international partnerships and knowledge sharing, which could lead to a more cohesive and accelerated advancement of the field. The density mapping showing the concentration of citations around Al Jabri, Al Saidy, and Siddique further underscores their significant contributions. The red color density highlights areas where research on CS in concrete is most active and influential. This concentration could indicate that these authors have focused on high-impact areas of research, such as optimizing CS content in concrete or investigating its environmental benefits. Understanding the specific themes these authors have explored could provide insights into current research priorities and gaps in literature. The dominance of a few key authors in this field suggests that while there are leading voices driving the research forward, there may be a need to diversify contributions to incorporate a wider range of perspectives and innovations. Encouraging emerging researchers to engage in this field and promoting collaboration between established and new researchers could help in addressing the complex challenges associated with CS concrete, such as long-term durability and environmental impacts.

3.8 Organizations

Organizations and institutions play a leading role in conducting and funding research in specific fields. These organizations and institutions encourage research on a certain topic. Hence, to find out such top organizations and institutions, an analysis was conducted using the available database on CS concrete. VOSviewer was utilized to find the top

Table 5: Top 20 organizations linked with the research on CS concrete

S. no	Organization	Documents	Citations	Total link strength
1	Thiagarajar College of Engineering	20	212	394.28
2	Anna University	14	607	385.25
3	Dr. B R Ambedkar National Institute of Technology	12	259	124.33
4	Sultan Qaboos University	11	874	79.67
5	Islamic Azad university	10	112	252.81
6	Alagappa Chettiar Government College of Engineering and Technology	10	41	283.67
7	S V National Institute of Technology	8	64	79
8	Structural Engineering Research Center India	8	381	118
9	Annamalai University	7	13	167.35
10	Thapar Institute of Engineering and Technology	7	98	132.33
11	Jawaharlal Nehru Technological University Anantapur	7	14	51
12	Peter the Great St. Petersburg Polytechnic University	5	25	390.32
13	Amran University	4	39	321.19
14	Far Eastern Federal University	4	39	321.19
15	Prince Sattam bin Abdulaziz University	4	39	321.19
16	Kongu Engineering College	3	7	21
17	Wuhan University of Technology	3	4	0
18	SRM University	3	1	14
19	Agni College of Technology	2	381	118
20	Nanyang Technological University	2	279	26

organizations and institutions. In VOSviewer, the “type of analysis” was set to “bibliographic coupling,” and “organizations” were chosen as the “unit of analysis.” The minimum threshold for publications was set to 1, while the rest of the values were left at their default settings. The results of the analysis are presented in Table 5. It can be observed that Thiagarajar College of Engineering topped the list in terms of both documents (20) and citations (212). While Anna University followed it closely with 14 documents and 607 citations. Organizations and their contributions to research on CS concrete can also be seen in Figure 17. It is also evident from Figure 17 that Thiagarajar College of Engineering and Anna University are the highest contributors to the research of CS concrete. Visual maps of organization contribution were also made and can be seen in Figure 18. The greatest node of Thiagarajar College of Engineering represents its greatest contribution to the research. It can also be seen that the node of Anna University is also visible and greater than the rest of the smaller nodes. However, long links show a weak correlation between the highest contributors and the rest of the organizations. It is also noteworthy through close links in clusters that institutions that are located in the same region have strong relations between them. Additionally, Figure 19 shows the density mapping of the contributory organizations. The red color density of Thiagarajar College of Engineering and Anna University show their greater contribution to the field of CS concrete research.

The institutions listed, such as Thiagarajar College of Engineering, Anna University, and Sultan Qaboos University, represent leading academic and research entities in the field of civil engineering, particularly in the study of CS concrete. Several of these organizations are located in regions with significant industrial activities, particularly related to metal production and processing, which naturally aligns with research on the utilization of industrial by-products like CS. For example, institutions such as

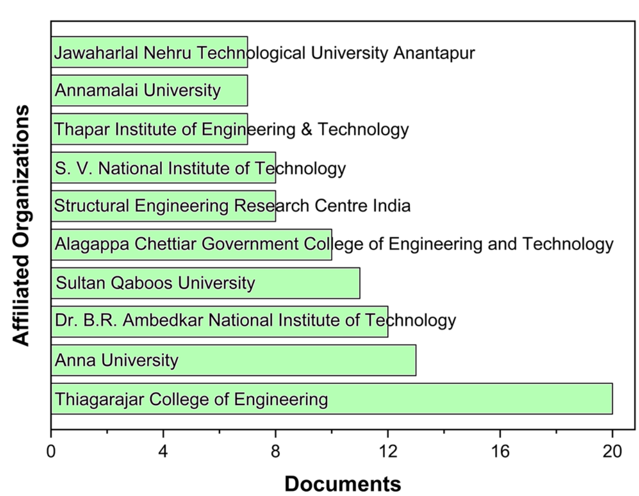

Figure 17: Contribution of some top organizations linked with the research on CS concrete.

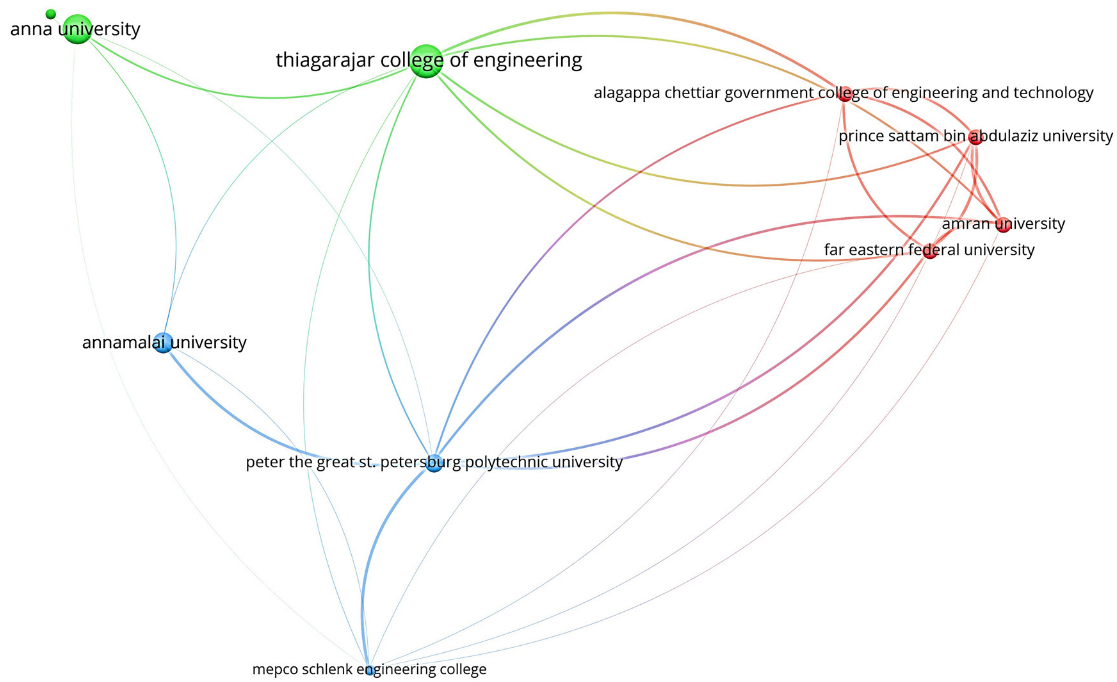

Figure 18: Network mapping of the organizations linked with the research on CS concrete.

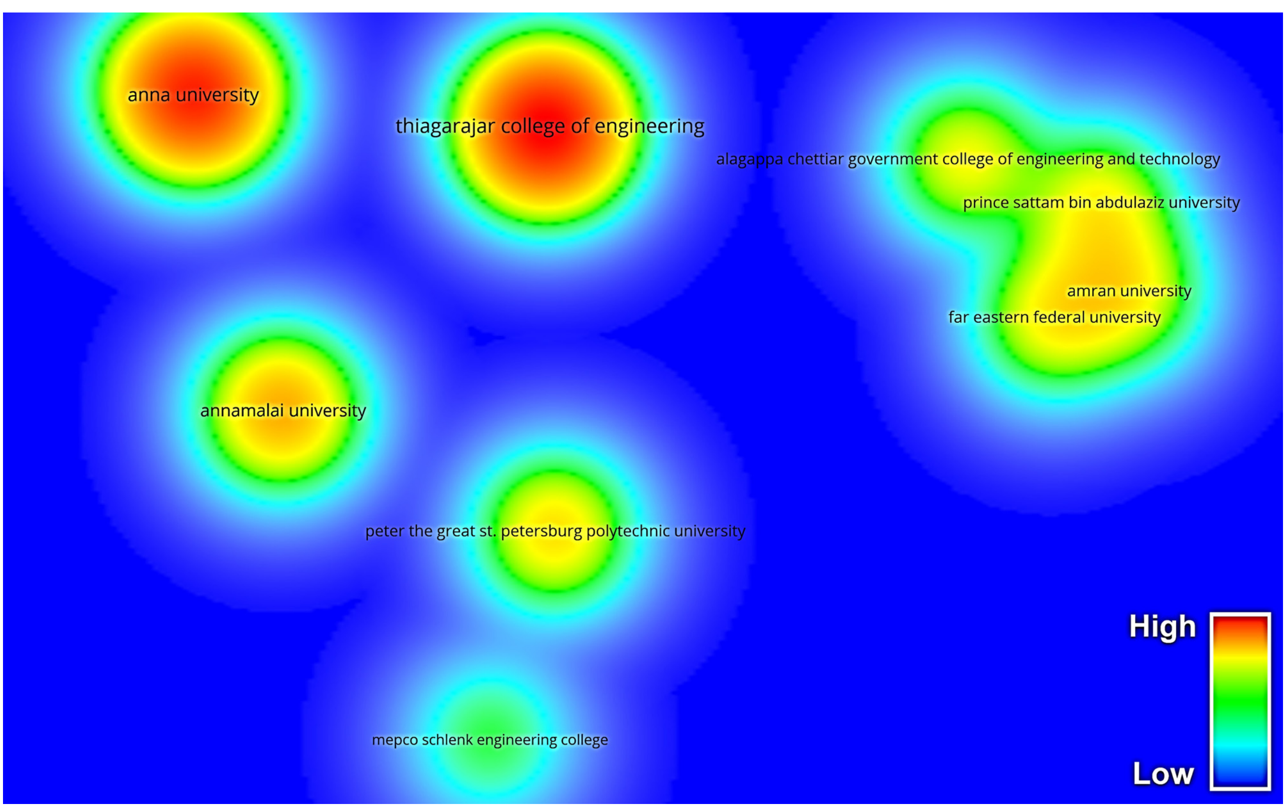

Figure 19: Density mapping of the organizations linked with the research on CS concrete.

Anna University and the Structural Engineering Research Center in India are at the forefront of research on sustainable construction materials, likely driven by national priorities on waste management and sustainable development. The high level of research output from these organizations suggests that they actively promote and perhaps prioritize studies on the utilization of industrial waste in construction, reflecting broader national or regional sustainability goals. Many of these institutions may have specific research guidelines or initiatives that encourage studies on the reuse of industrial by-products in construction materials. For instance, research funding from national bodies or collaborations with industry may steer these institutions toward exploring environmentally friendly construction practices. In countries like India and China, where rapid urbanization is accompanied by environmental concerns, academic and research institutions often focus on materials that can mitigate environmental impact. This focus is aligned with global sustainability initiatives such as the United Nations Sustainable Development Goals, particularly those related to sustainable cities and communities, responsible consumption and production, and climate action.

3.9 Funding sponsors

Funding sponsors is an important aspect of research. Funding greatly affects the productivity and scope of the research. Funding makes it possible for research to reach a maximum number of audiences. Funding can make research work approachable for the audience. Hence, this study presents the top ten funding sponsors for CS concrete research in Figure 20. To find these leading sponsors an analysis was performed using Scopus. It is evident from the figure that the primary funding sponsor for research on CS concrete is the National Nature Science Foundation of China, then the Ministry of Education and Science of the Russian Federation, and then Sultan Qaboos University. Remarkably, all these funding sponsors are paving the path for a better and sustainable future.

The top funding sponsors for research on CS concrete reveal significant insights into how research is being shaped and directed in this field. These sponsors play crucial roles in promoting and funding research with a focus on sustainability, innovation, and practical applications. The funding sponsors, including the National Natural Science Foundation of China, Horizon 2020, and the Department of Science and Technology, Ministry of Science and Technology, India, play a critical role in shaping the research landscape. These sponsors support projects that align with their priorities, such as sustainability, technological advancement, and addressing environmental challenges. National Natural Science Foundation of China and Horizon 2020 are prominent for their support of large-scale, high-impact research that advances innovative technologies and sustainable practices. Their funding often supports research that aligns with national and

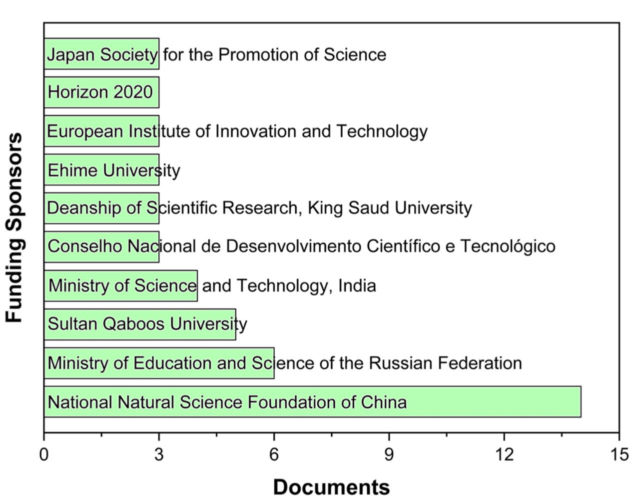

Figure 20: Contribution of some top funding sponsors toward the research on CS concrete.

Table 6: Top 20 countries linked with the research on CS concrete

S. no	Country	Documents	Citations	Total link strength
1	India	242	3,311	6,685
2	China	39	1,264	2,332
3	Iran	26	1,159	1,395
4	Japan	20	557	405
5	Russian Federation	13	60	2,209
6	United States	13	605	413
7	Indonesia	12	73	1,356
8	Oman	11	916	155
9	United Kingdom	11	313	1,499
10	Poland	10	168	323
11	Belgium	9	99	472
12	Brazil	9	220	117
13	Singapore	9	485	717
14	Australia	8	279	985
15	Chile	7	81	1,922
16	Canada	6	522	174
17	South Korea	6	61	409
18	Ethiopia	5	12	374
19	Germany	5	44	129
20	Saudi Arabia	5	49	1,915

international goals for environmental conservation and material efficiency. Department of Science and Technology, Ministry of Science and Technology, India and Sultan Qaboos University focus on regional needs and practical applications, supporting research that has direct implications for infrastructure development and environmental management in their respective regions. Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Deanship of Scientific Research, King Saud University contribute to research with a focus on technological innovation and societal benefits, emphasizing the importance of practical applications in construction. Ehime University, European Institute of Innovation and Technology, and Japan Society for the Promotion of Science support research that drives technological advancements and addresses major societal challenges, including the development of sustainable materials. Overall, the involvement of these sponsors highlights a collaborative effort to advance the use of CS in construction. Their support is aligned with broader goals of sustainability, innovation, and practical application, reflecting a concerted effort to address environmental and infrastructure challenges through research on alternative materials.

3.10 Countries

Many countries are researching to find alternatives to conventional cement and concrete. Since CS concrete has the potential to act as cement alternative research is also conducted on it in many countries. These countries were analyzed using Scopus and VOSviewer. In VOSviewer, "bibliographic coupling" was chosen as the type of analysis, and "countries" were selected as the unit of analysis. The minimum document threshold was set to five, while the rest of the parameters were left at their default values. The results are displayed in Table 6. It can be observed that India tops the list in CS concrete research with 242 documents and 3,311 citations. It is followed by China with 39 documents and 1,264 citations. Several other countries are also present in the results. Similarly, Figure 21 represents the countries with the most published documents on CS concrete research. India and China are two top contributors according to Figure 21 as well. Network visualization is also presented in Figure 22. The size of nodes of India, China, Japan, and Iran renders these countries to be the top contributors in the CS concrete research. The close links between India, China, and Australia show the relation strength of their research. Their research is related to each other and co-cited. Density mapping is depicted in Figure 23. It can be observed from Figure 23 that the red color density represents India, which is the greatest contributor to CS concrete research. Then, China is represented by yellow color which represents the second highest contribution toward the CS concrete research. Then, green and blue colors show moderate to low research contributing countries, respectively.

4 Discussions

Extensive literature was selected to review different properties and aspects of CS and CS concrete. These parameters are discussed in the upcoming sections of this article.

4.1 Physical and chemical properties of CS

This article highlights both the physical and chemical properties of CS.

4.1.1 Physical properties of CS

This literature review examines the physical properties of CS, including specific gravity, water absorption, setting times, particle shape, appearance, and hardness, with a focus on its use as both a fine aggregate and a SCM in concrete. The specific gravity of CS, primarily influenced by its iron content, is around 3.5 $g\cdot cm^{-3}$, which is higher than that of typical natural aggregates [118,124,125]. This

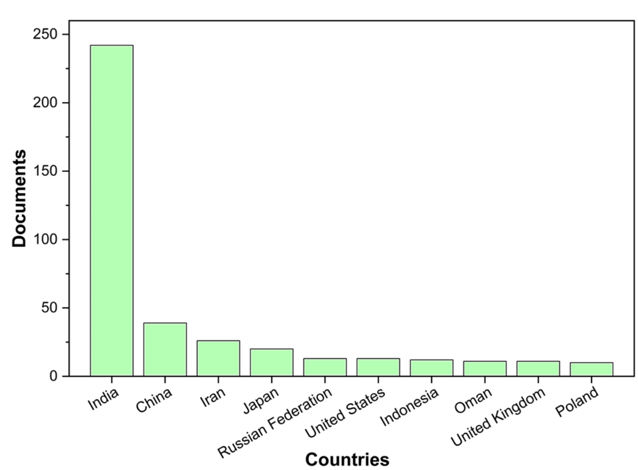

Figure 21: Contribution of some top countries linked with the research on CS concrete.

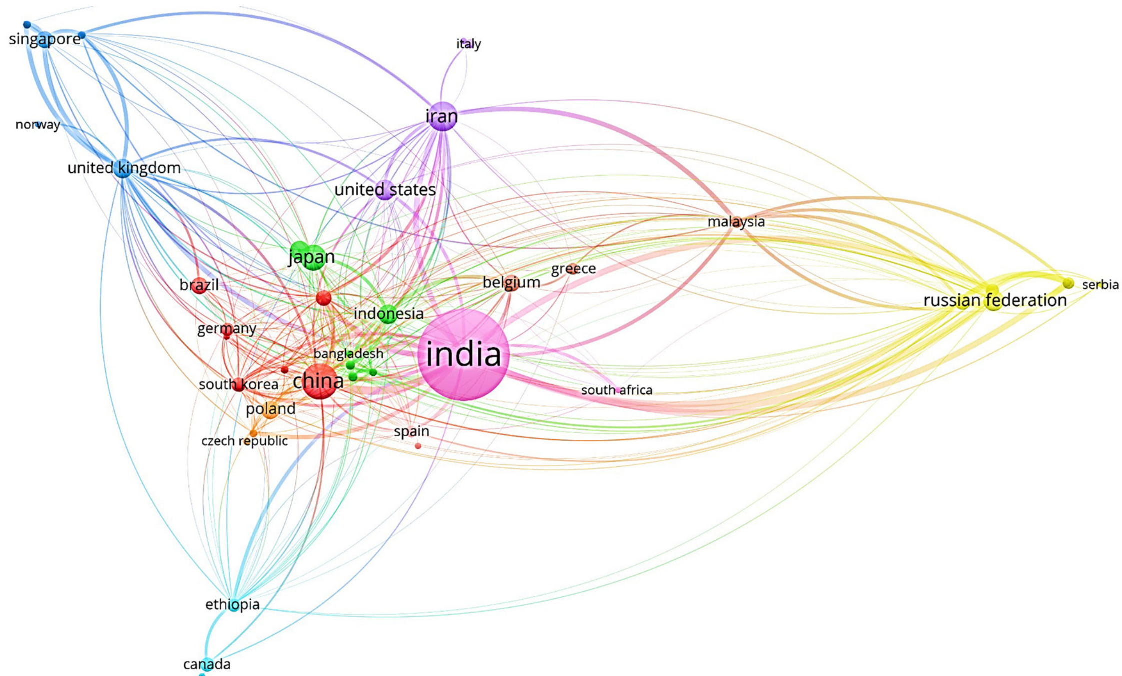

Figure 22: Network mapping of the countries linked with the research on CS concrete.

higher density, due to the approximately 45% iron content, suggests that CS could contribute to the increased weight and potentially higher compressive strength of concrete, but it may also affect the overall density of the structure, which requires careful consideration depending on the application [126]. The water absorption of CS is lower than that of conventional fine aggregates, which could enhance the workability of concrete when CS is used as an aggregate. However, this lower water absorption also implies that adjustments to the water-to-cement (W/C) ratio may be necessary to avoid excessive bleeding or segregation in the concrete mix. The average particle size of CS

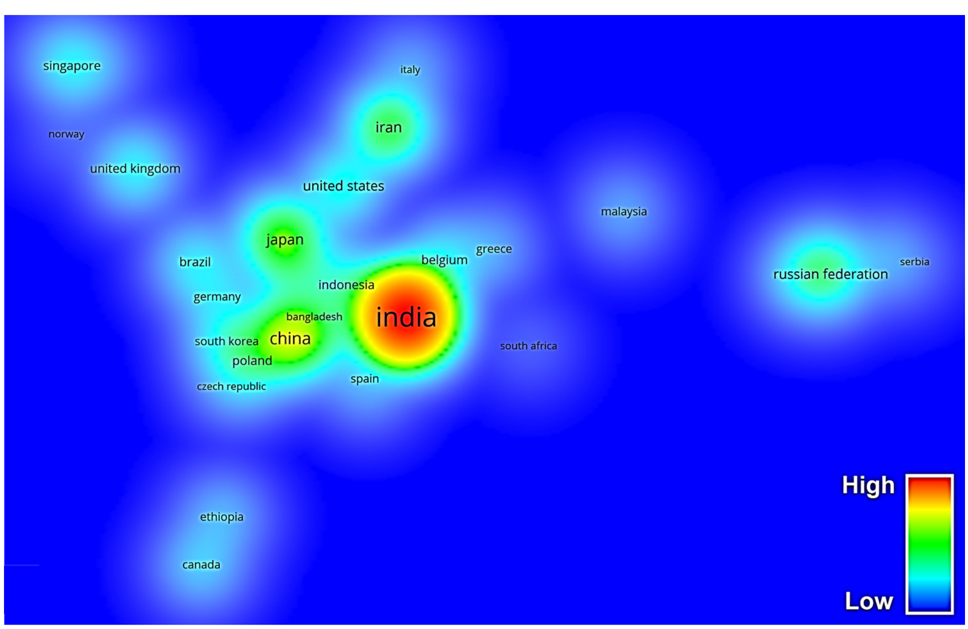

Figure 23: Density mapping of the countries linked with the research on CS concrete.

ranges from 4.75 to 0.075 mm, but its effectiveness in concrete is more pronounced when particles are less than 10 mm, as indicated by the literature. This suggests that while CS can be used as a fine aggregate, the specific particle size distribution must be carefully controlled to optimize concrete performance [127]. The irregular shape and dark, glossy appearance of CS particles after cooling indicate a rough texture despite the smoothness observed in scanning electron microscopy (SEM) images. This rough texture could improve the mechanical interlock between the CS particles and the cement paste, enhancing the strength of the concrete. However, the smooth surface could also reduce the friction between particles, potentially increasing workability when CS is used as an aggregate. This dual effect needs to be critically evaluated in the context of specific concrete applications, as the balance between workability and strength is crucial [128]. Some investigations on the physical properties of CS are listed in Table 7. The SEM of CS is presented in Figure 24. The SEM analysis reveals that CS particles have undulating shapes, which may affect the packing density and the overall porosity of the concrete. When used as an SCM, the microstructural characteristics of CS, such as these undulating shapes, could influence the pozzolanic activity and the long-term durability of the concrete. The increased workability of CS-based concrete is attributed to its smoothness when CS replaces fine aggregates [129]. Overall, while CS shows promise as both an aggregate and an SCM, its diverse physical properties necessitate a tailored approach depending on the intended use, with careful consideration of its impact on the concrete's mechanical and durability properties.

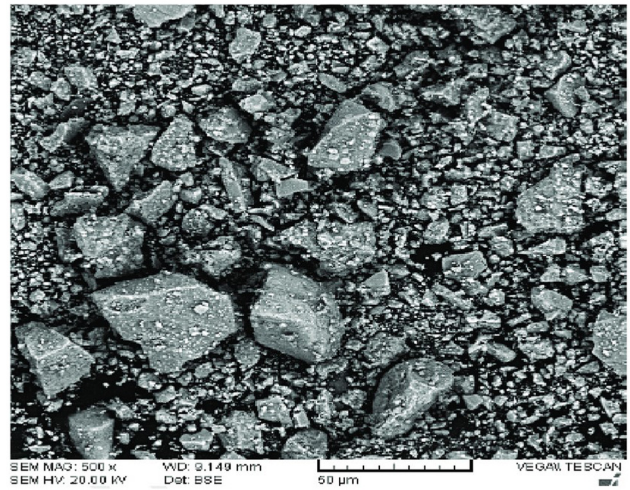

Figure 24: SEM of CS [74].

4.1.2 Chemical properties of CS

CS is composed of 30–34% silica (SiO_2), 4–5% alumina (Al_2O_3), 35–37% iron (Fe_2O_3), 4–6% calcium oxide (CaO), and nearly 1% copper, as detailed in Table 8, which presents the chemical composition of CS according to various studies [132]. The variation in the chemical composition across different studies suggests that the properties of CS can significantly differ depending on its source and production process. This variability must be considered when utilizing CS in concrete applications, whether as a fine aggregate or as a SCM. The wide range in the concentration of SiO_2 and Fe_2O_3 among the studies highlights the influence of raw materials and production processes on the final chemical makeup of CS. For instance, the high Fe_2O_3 content in some samples indicates that CS may impart greater density and strength to the concrete but could also lead to challenges in achieving workability and uniformity. Conversely, the presence of SiO_2, especially in its amorphous form, can contribute to early strength development in CS-based concrete, as SiO_2 participates in the hydration process, enhancing pozzolanic activity.

X-ray diffraction (XRD) analysis of CS shows the presence of mineral phases such as quartz, magnetite, pyroxene, fayalite, and anorthite [135]. The findings of the XRD analysis are illustrated in Figure 25. These minerals play a crucial role in determining the mechanical and chemical properties of CS when used in concrete. For example,

Table 7: Physical properties of CS based on previous studies

Physical properties/Ref.	Density ($kg·m^{-3}$)	Specific gravity	Specific surface area ($m^2·kg^{-1}$)	Initial setting time (min)	Fineness modulus
Raju *et al.* [130]	—	3.52	—	—	3.68
Liu *et al.* [75]	—	2.4	—	250	—
Maharishi *et al.* [125]	—	3.30	—	—	3.18
Chakrawarthi *et al.* [62]	1.75	3.56	—	—	3.00
Mavroulidou [131]	3.73	—	—	—	2.97

Table 8: Chemical composition of CS according to previous studies

References/chemical composition	SiO_2	Al_2O_3	Fe_2O_3	CaO
Chithra *et al.* [110]	25.84	0.22	68.29	0.15
Najimi and Pourkhorshidi [133]	9.57	4.43	57.42	22.5
Sivakrishna *et al.* [44]	27	3.0	0.60	63
Al-Jabri *et al.* [134]	33.05	2.79	53.45	6.06

magnetite and fayalite, due to their iron content, contribute to the overall density and potential magnetic properties of the slag, while quartz and anorthite are associated with the silicate phases that enhance the pozzolanic reactivity of CS [136]. According to ASTM standards [151], a material is considered pozzolanic if it contains more than 70% of a combined total of certain oxides, including SiO_2, CaO, Al_2O_3, MgO, Na_2O, and Fe_2O_3. The XRD results and chemical composition of CS, as presented in the studies, suggest that CS meets this criterion, making it a viable pozzolan. The pozzolanic properties of CS imply that it can enhance the long-term strength and durability of concrete, especially when used as an SCM [137]. However, the variability in its composition underscores the need for careful characterization of CS before its use in concrete to ensure consistent performance [138].

4.2 Reaction mechanism of CS

This section only addresses CS as a SCM. Reducing the particle size of CS through grinding can significantly enhance its reactivity, particularly when used as an SCM in concrete [141]. Full hydration of CS can be achieved at a certain level of particle fineness, as finer particles provide a greater surface area for the hydration reaction. Studies have indicated that CS particles larger than 60 μm contribute little to hydration, while those smaller than 30 μm play a crucial role in the hydration process. Particles as small as 10 μm can hydrate rapidly, contributing to early strength development in the concrete mix [142–144]. However, excessively fine CS particles can lead to premature hydration, forming a thick hydration layer that inhibits further hydration in the later stages, potentially compromising the long-term strength and durability of the concrete [145]. Grinding CS for around 60 min to achieve a specific surface area that optimizes hydration has been shown to be beneficial [77]. This balance between particle size and hydration rate is critical; while fine particles enhance early strength, they must be carefully controlled to avoid premature hydration and the associated negative effects on later-stage strength. To further enhance the pozzolanic activity of CS, the introduction of a chemical

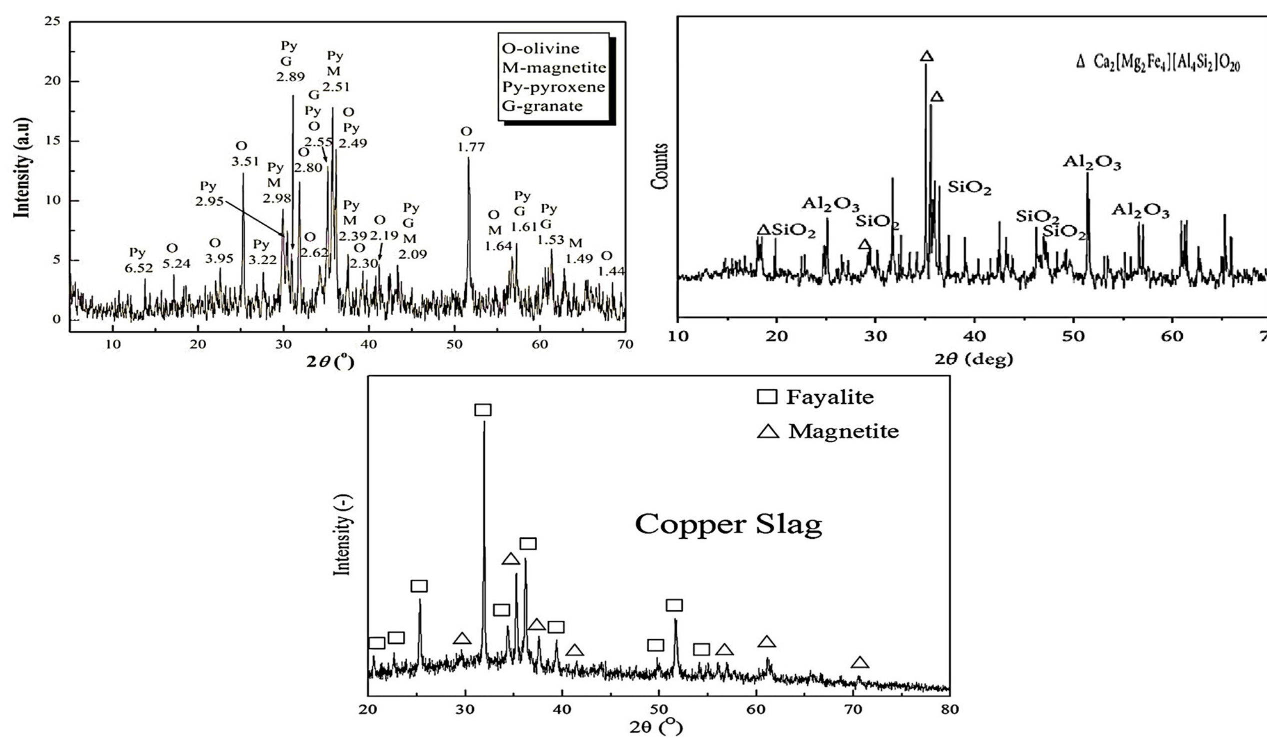

Figure 25: XRD analysis of CS [135,139,140].

activator has been proposed. When CS is used as a cementitious material, an acidic layer forms on the surface of the particles, which can inhibit the inner particles from reacting with water [146]. The mechanism involves the breaking of the O–Si–O–Al chain pattern, allowing charged ions of SiO_2, CaO, MgO, and Al_2O_3 to migrate outward, where they participate in pozzolanic reactions. This process results in the formation of calcium silicate hydrate (C–S–H) gel, which is crucial for binding the material and contributing to the overall strength of the concrete mix [147]. However, while the use of alkali activators can enhance the reactivity of CS, the potential impacts on the overall chemistry of the concrete mix, such as changes in pH and long-term durability, should be carefully considered. The reaction mechanism is illustrated in Figure 26, demonstrating how the use of alkali activators can effectively improve the pozzolanic activity and binding properties of CS in concrete.

4.3 Environmental impact

When utilizing CS as a construction material, it is imperative to assess its potential for heavy metal leaching, given the environmental and health risks associated with its improper disposal. CS, often discarded in open heaps, can lead to the leaching of heavy metals, such as zinc, arsenic, mercury, cobalt, iron, and copper when exposed to rainfall [132]. This leaching poses a significant risk of contaminating groundwater, which can lead to widespread environmental pollution, affecting soil, water bodies, animals, and human health. Despite these concerns, several studies have demonstrated the stability of heavy metals within CS when it is used in construction. For instance, a study where CS was submerged in distilled water for 15 days detected no leaching of heavy metals, including zinc, nickel, lead, and chromium [149]. Similarly, research has shown that concretes incorporating CS do not leach

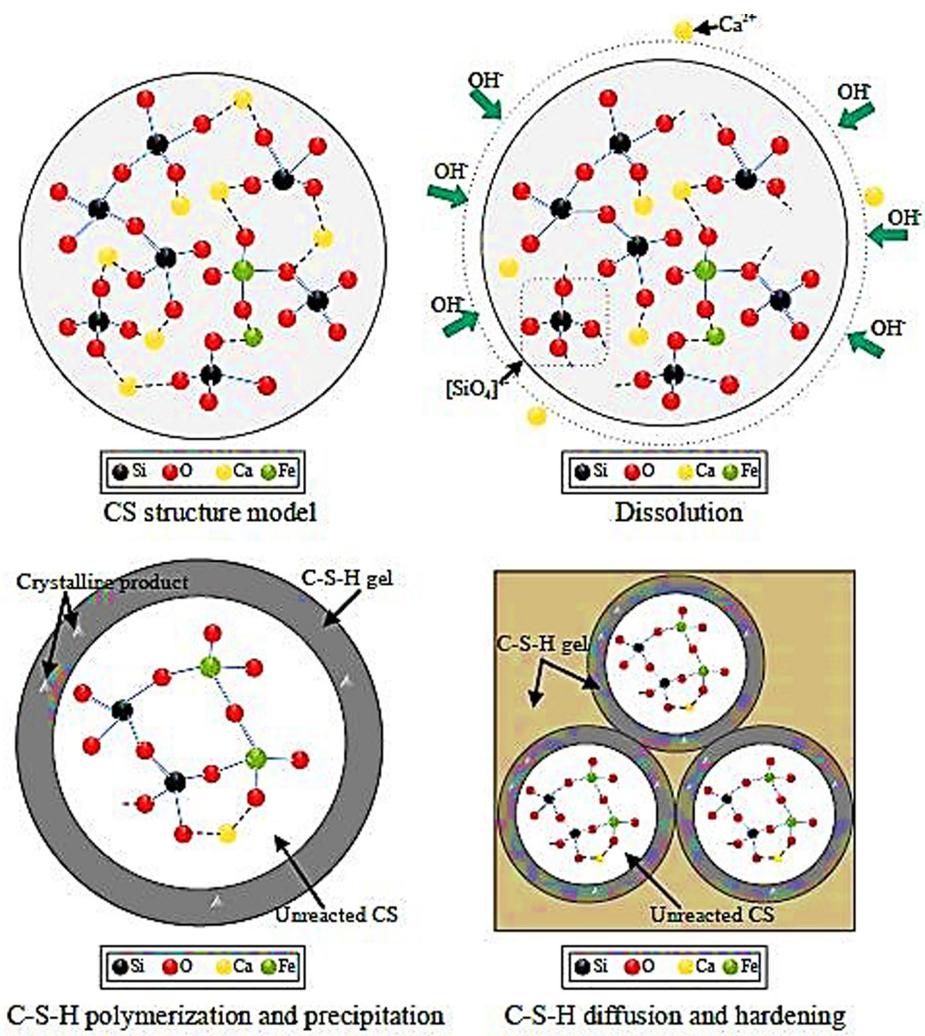

Figure 26: Reaction mechanism of CS in the presence of an alkali activator [148].

heavy metals, even when subjected to acid rain, indicating that the heavy metals in CS are highly stable [150]. The solidification of heavy metals in CS-based construction materials has been attributed to mechanisms such as ion exchange, encapsulation, and adsorption, which effectively immobilize the metals within the matrix of the material [150–152]. This quality of CS is owed to the fact that the CS hardening mechanism takes place due to ion exchange, encapsulation, and adsorption. In addition, Zain *et al.* [153] found that the heavy metal concentration in CS-based concrete was much lower than the allowable limits of American and Malaysian standards. This finding underscores the environmental suitability of CS, particularly when combined with OPC, making it a viable and eco-friendly option for construction.

However, it is crucial to recognize that the stability of heavy metals in CS may vary depending on the specific composition of the slag, the conditions of exposure, and the presence of other materials in the concrete mix. Therefore, while the existing studies provide strong evidence of the environmental safety of CS, ongoing monitoring and evaluation of its performance in different environmental conditions are essential. This approach will ensure that the use of CS in construction does not inadvertently contribute to environmental contamination over time.

4.4 Replacement ratios

Research by Chakrawarthi *et al.* [62] explored the effects of substituting various proportions of CS for cement in concrete mixes. The study found that the strength of CS-inclusive concrete increases with curing age, indicating that CS contributes positively to the long-term strength development of concrete. Specifically, concrete containing CS demonstrated higher strength compared to control samples without CS, supporting the idea that CS can enhance the mechanical properties of concrete [154]. Further investigations identified the optimal replacement ratio of CS for cement to be between 30 and 40%. Within this range, the compressive strength of the concrete was observed to increase by up to 60% compared to the control [134]. However, the study also found that the total replacement of cement with CS does not achieve the required strength, highlighting the limitations of using CS as a complete substitute. Moreover, adding fibers to the CS-inclusive concrete mix resulted in an additional 6% increase in strength, demonstrating that the combination of CS with reinforcing fibers can further enhance the material's performance. For example, replacing 20% of cement with CS led to a 35% improvement in compressive strength at 28 days [63]. However, the benefits of using CS diminish when the replacement ratio exceeds 40%. Beyond this threshold, the mix tends to aggregate, potentially compromising the concrete's workability and homogeneity. At 180 days, a mix with 40% CS replacement achieved a compressive strength of 53.8 $N\cdot mm^{-2}$, indicating that while high levels of CS can still produce strong concrete, careful mix design is necessary to avoid issues such as aggregation. Additionally, the increased free water availability in CS-inclusive concrete suggests that adjustments to the W/C ratio or the use of superplasticizers may be required to maintain the desired workability. For instance, the use of a 0.6% superplasticizer with 60% CS was found to produce high-flow able concrete, suggesting that admixtures can mitigate some of the challenges associated with high CS content [155–157].

Overall, while CS shows considerable potential as a partial replacement for cement, the proportion used must be carefully optimized to balance strength, workability, and long-term durability. The findings underscore the importance of fine-tuning the mix design, particularly when higher replacement ratios are considered, to achieve the best possible performance in concrete applications.

4.5 Fresh properties of CS concrete

A study investigated the effect of varying amounts of CS on the slump and workability of concrete, using two W/C ratios: 0.55 and 0.45. The results indicated that the workability of CS-based concrete initially increased with the addition of CS but decreased beyond a certain threshold. This behavior was observed for both W/C ratios, with higher w/c ratios generally yielding greater slump and workability [158]. Figure 27 presents the relationship between a concrete slump and the percentage of CS used, comparing two different W/C ratios: 0.55 (blue bars) and 0.45 (green bars). As observed, for both W/C ratios, the slump initially increases with the addition of CS, reaching a peak before gradually decreasing. At a W/C ratio of 0.55, the slump reaches its maximum value at around 20% CS, exceeding 200 mm, which suggests enhanced workability. Beyond this percentage, the slump decreases, with a significant drop as the CS content approaches 100%. Similarly, for the W/C ratio of 0.45, the slump also peaks at 20% CS but remains consistently lower than the slump values for the 0.55 W/C ratio across all CS percentages. The slump decreases sharply with further increases in CS content, indicating reduced workability, particularly beyond 40% CS. The overall trend suggests that while the introduction

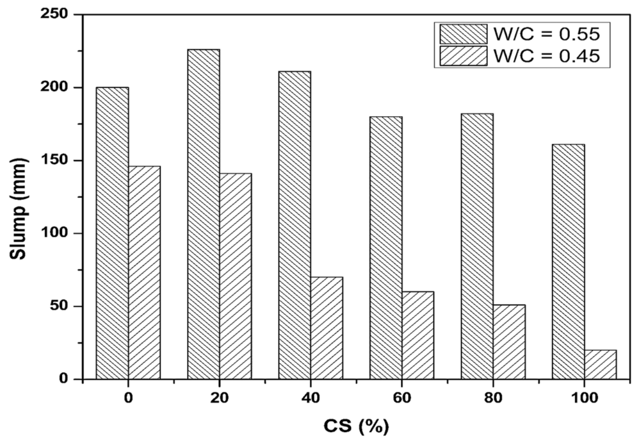

Figure 27: Workability test on CS concrete [158].

of CS initially improves the concrete's workability, excessive amounts of CS lead to a reduction in slump, likely due to the increased angularity and rough texture of CS particles, which increase internal friction and hinder the flow of the concrete mix. This effect is more pronounced at the lower W/C ratio of 0.45, where the mix's reduced water content exacerbates the decline in workability as CS content rises. Figure 27 illustrates these results, showing that CS-based concrete exhibited lower slump values compared to control samples. This finding contrasts with the expectation that CS would enhance workability, likely due to the angular shape of CS particles. The increased friction between these angular particles can reduce slump and workability, highlighting a potential challenge when using CS in concrete mixes. Further research corroborates these observations, noting that high CS content can lead to issues such as bleeding and segregation in concrete [159]. These problems are often associated with the high water absorption and the particle shape of CS, which can adversely affect the homogeneity and stability of the mix. Consequently, it is crucial to optimize the CS content in the mix design to avoid these negative effects and ensure consistent performance. Additionally, the inclusion of CS affects the initial setting time of concrete. Studies have shown that CS delays the initial setting time, which can be attributed to the presence of heavy metals that modestly interfere with the hydration process [160]. This delay can impact the construction schedule and workability, making it essential to consider this factor when using CS in concrete. Figure 28 illustrates the impact of varying CS dosages on the initial and final setting times of concrete. As observed, the control sample (0% CS) exhibits the longest initial and final setting times, approximately 4.5 and 6.5 h, respectively. When 10% CS is incorporated, both the initial and final setting times decrease slightly, indicating a faster setting process. At a 20% CS dosage, the setting times further reduce, suggesting that increased CS content continues to accelerate the setting time. However, at 30% CS, there is a noticeable decline in the setting time, with the initial setting time dropping to just above 3 h and the final setting time slightly above 5 h. This trend suggests that higher CS content accelerates the hydration process, likely due to the specific characteristics of CS, such as its angular particle shape and metallic content, which may influence the rate of reaction. The reduction in setting times with increasing CS dosage could be advantageous for applications requiring faster setting concrete, but it may also necessitate careful consideration to avoid premature setting, which could affect workability and long-term performance.

In summary, while CS can enhance certain aspects of concrete properties, its use requires careful management of the mix design to mitigate issues related to workability, bleeding, segregation, and setting time. Balancing these factors is critical for achieving optimal performance in concrete applications.

4.6 Mechanical properties

4.6.1 Compressive strength

The use of CS as a secondary cementitious material in concrete initially results in reduced early strength due to its lower reactivity compared to traditional cement. However, the strength of concrete incorporating CS tends to improve over time as the SCM's latent properties

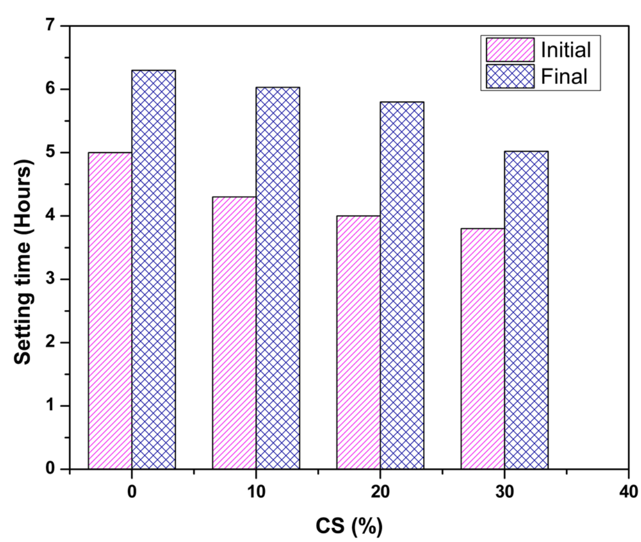

Figure 28: Initial and final setting times of CS concrete [74].

become active. This delayed strength gain can be mitigated by using activators, such as silicate and aluminate components released through grinding, which enhance the early strength development of the concrete. Research by Bharat demonstrated that incorporating CS up to 15% positively impacts concrete strength, but exceeding this amount can be detrimental [144]. Similarly, Tixier *et al.* found that substituting 15% CS and adding 1.5% slaked lime as an activator resulted in improved compressive strength [161]. Additionally, W/C ratio also impacts the compressive strength significantly. Furthermore, Moura *et al.* observed a 30.4% increase in compressive strength with a W/C ratio of 0.6 at 28 days [162]. This finding highlights the significant influence of the W/C ratio on concrete's compressive strength. The utilization of CS as a fine aggregate can also be used to enhance compressive strength. It owes to the fact that the structure of CS has sharp edges. These sharp edges aid in the cohesion of binders with aggregates [163]. Replacement of fine aggregates with CS can also result in a decrease in the compressive strength of concrete [164]. Patil [165] concluded that the addition of more than 80% of CS adversely affects the compressive strength of concrete. Kumar and Mahesh [166] found that the replacement of fine aggregate with 30% of CS resulted in strength gain of concrete. Chavan and Kulkarni [164] reported that 40% of CS is the most optimum proportion of replacement of fine aggregates in aggregate. After increasing the amount of CS from 40%, the hardening strength decreases. Chithra *et al.* [112] examined the technical feasibility of utilizing CS as a fine aggregate and reported the substitution of fine aggregates with CS and reported a compressive strength of 150 MPa in high-strength concrete. Various

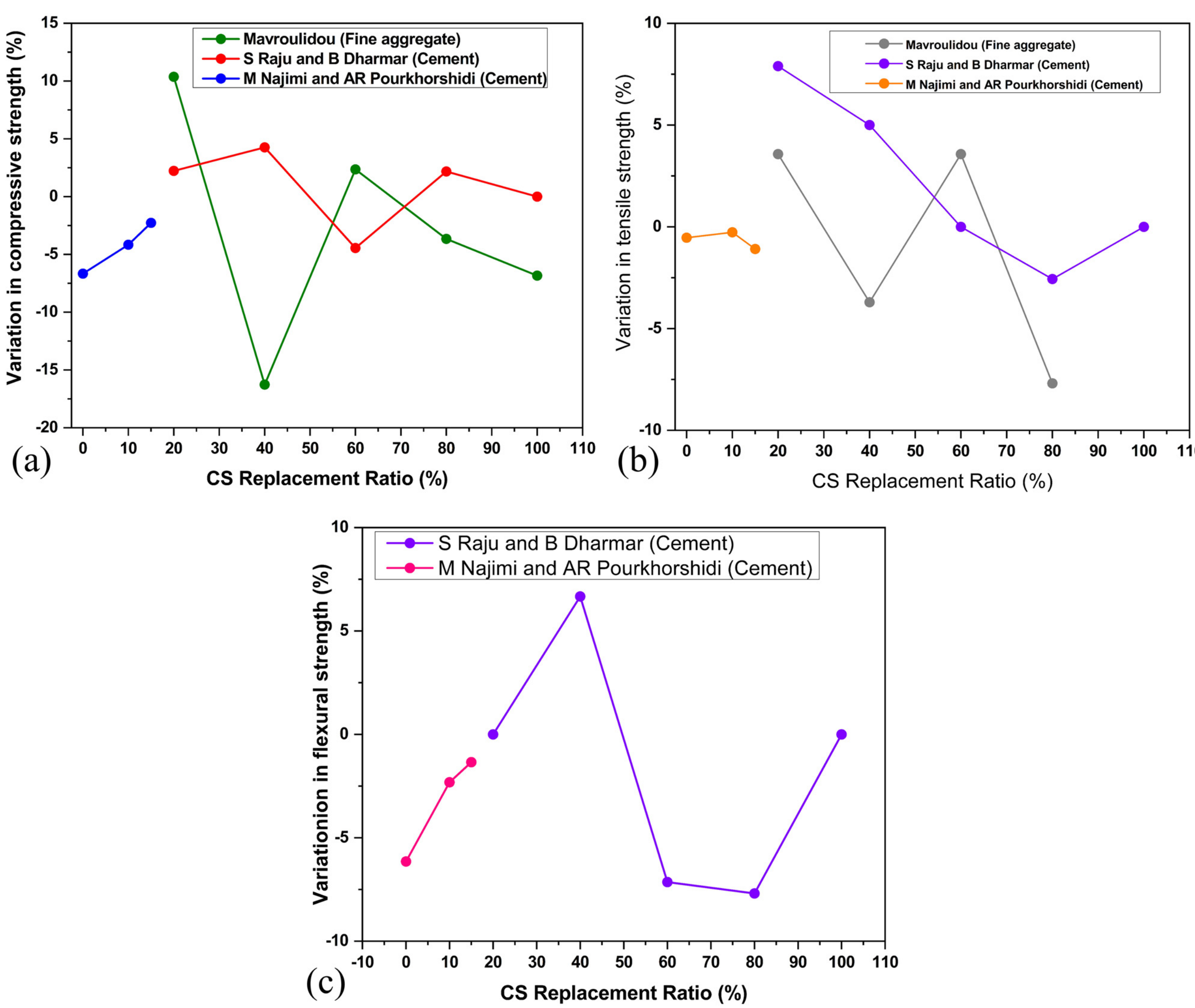

Figure 29: Variations in strengths by using different proportions of CS [123,131,167]: (a) compressive strength, (b) tensile strength, and (c) flexural strength.

other researchers concluded that the optimum compressive strength is achieved when CS is used within the range of 40%–50% [163]. Al-Jabri *et al.* [134] discovered that replacing 50% of the fine aggregate increased the compressive strength of mortar by 70%. Figure 29(a) illustrates the variation in compressive strength with different proportions of CS, emphasizing the importance of carefully balancing the CS content to optimize concrete performance. In summary, while CS can effectively enhance compressive strength, especially when used in moderate proportions, excessive use or improper mix design can lead to reduced strength. The incorporation of activators and careful adjustment of the W/C ratio are crucial for optimizing the performance of CS-based concrete.

4.6.2 Split tensile strength

Various studies are of the view that the split tensile strength of concrete is enhanced by using the CS in proportions [162]. Research indicates that the incorporation of CS can significantly enhance the split tensile strength of concrete. Studies have shown that substituting 15% of cement with CS, coupled with a W/C ratio of 0.5, improves the split tensile strength of the concrete [165]. This enhancement is attributed to the pozzolanic activity of CS, which contributes to the development of a more robust matrix within the concrete. Another study suggests that incorporating CS as a fine aggregate also enhances the split tensile strength of concrete [125]. Incorporating CS as a fine aggregate also positively impacts split tensile strength. A study revealed that using CS in fine aggregate form results in increased split tensile strength, with an optimal replacement proportion of 40% [79]. The effectiveness of CS as a fine aggregate is due to its angular particle shape, which enhances the bond between the binder and aggregates, leading to improved tensile properties. Moreover, CS has also been explored as a coarse aggregate in concrete. Research suggests that CS can serve effectively as a coarse aggregate due to its strong bond strength, which further contributes to the concrete's split tensile strength [115]. The ability of CS to enhance bond strength and tensile properties highlights its versatility as both a fine and coarse aggregate in concrete. It is due to the stronger bond strength due to the use of CS.

Figure 29(b) illustrates the variation in split tensile strength with different proportions of CS, underscoring the positive impact of CS on enhancing this property. Overall, the use of CS in concrete, whether as a cement substitute, fine aggregate, or coarse aggregate, can lead to improved split tensile strength, provided that the proportions are optimized to achieve the best performance.

4.6.3 Flexural strength

Flexural strength measures a material's ability to withstand bending forces without deforming or failing. The incorporation of CS into concrete, whether as a replacement for cement or fine aggregates, can influence flexural strength both positively and negatively. The specific effects of CS on flexural strength are contingent upon several factors, including the replacement ratio, particle size distribution, and the quality of the CS used. Research indicates that a CS replacement ratio of around 5% for cement is optimal for achieving maximum flexural strength [168]. This relatively low proportion allows for the beneficial properties of CS to enhance the flexural performance of concrete without adversely affecting the mix's overall characteristics. Conversely, replacing a significant portion of fine aggregates between 40 and 50% with CS has also been found to optimize flexural strength [79]. This range of replacement is effective in leveraging the angular shape and pozzolanic properties of CS to improve the concrete's resistance to bending forces.

Figure 29(c) illustrates the variation in flexural strength with different CS replacement proportions, highlighting the potential benefits of using CS in concrete mixes. Despite these positive findings, continuous research and testing are essential to fully comprehend the effects of CS on flexural strength and to refine the mix design guidelines. Adherence to established standards and guidelines will ensure the effective integration of CS into concrete mixes, optimizing performance and durability while addressing any potential challenges associated with its use.

4.7 Durability properties

4.7.1 Water absorption

Water absorption is a critical parameter in assessing the quality and durability of construction materials [169]. Lower water absorption in construction materials correlates with reduced susceptibility to carbonation and chloride attacks, enhancing the longevity of the structure [170]. In the context of CS-based concrete, several factors, including particle size and substitution proportions, significantly influence water absorption [134]. When CS is used as a secondary cementitious material, its fine particles contribute to a micro-filler effect within the concrete matrix. This effect, combined with the pozzolanic reactivity of CS, leads to the formation of a denser concrete structure with improved resistance to water absorption [154]. Despite this, studies have shown that replacing cement with CS can introduce additional porosity, though the pores are generally smaller than 10 μm in diameter. The permeability of water through these pores decreases as pore size diminishes [171]. CS-based concrete durability was assessed by Moura *et al.* [162] in a study in which capillary action of water was determined on the concrete. It was concluded that replacing 20% cement with CS resulted in 13.5% less water permeability through the concrete as compared to controlled samples. However, the capillary action of water in such concrete decreased by 24.1%. The reason behind this phenomenon is that CS utilization helped reduce the pore sizes in concrete and provided resistance to capillary action. Similarly, Boakye reported a reduction in the water absorption rate in concrete that utilized CS as SCM [172]. However, the effectiveness of CS in reducing water absorption has limitations. Studies indicate that the optimum proportion of CS to achieve reduced water absorption is around 40%. Beyond this threshold, water absorption begins to increase due to the larger pore sizes created by higher CS content [134]. Zhao *et al.* also reported a significant decrease in water absorption with 40% CS substitution but observed that increasing this proportion to 60% resulted in larger pore sizes and increased water absorption [149].

In summary, while CS can enhance the water resistance of concrete by reducing water absorption up to a certain proportion, its effectiveness diminishes with higher replacement levels. Optimal use of CS, particularly around the 40% mark, can help achieve a balance between improved durability and manageable water absorption.

4.7.2 Chloride attack

Chloride attack is harmful to concrete as it corrodes the steel bars in reinforced concrete and swells the concrete [173–175]. Therefore, it is crucial to enhance the durability of CS-based concrete to shield it from chloride penetration [176]. To mitigate this issue, it is essential to enhance the durability of concrete against chloride penetration. Incorporating CS into concrete has been shown to improve resistance to chloride attack by contributing to a denser and more impermeable concrete structure [177]. The effectiveness of CS in reducing chloride penetration depends on the quantity used. Studies indicate that an optimal replacement ratio of 20%–25% CS as a fine aggregate is effective in minimizing chloride attack while maintaining concrete durability [178]. At this proportion, CS helps in achieving a dense concrete matrix that impedes chloride ions from penetrating the structure. Additionally, the resistance to chloride penetration improves with increased curing age as the concrete continues to gain strength and density over time [179].

In summary, utilizing CS in concrete can enhance its resistance to chloride attack, provided that the amount used is carefully controlled. An optimal replacement ratio of 20%–25% CS is recommended to achieve a balance between durability and performance, with further improvements observed with prolonged curing.

4.7.3 Sulfate penetration

Sulfate attack is one of the worst hazards that affect the durability of concrete [180]. Sulfate ions penetrate concrete and react with the calcium hydroxide present in the concrete to form substances such as ettringite and gypsum [181–183]. These substances result in the cracking of concrete. Also, the reaction of sulfate with crucial compounds of hardened concrete increases the destruction of hardened concrete. It decomposes C–S–H. The sulfate penetration resistance depends greatly on the permeability quality of hardened concrete [184]. Hardened concrete with less permeability is less prone to sulfate attacks [185]. Studies concluded that using CS as an SCM in concrete improves the resistance against permeability in concrete. The pozzolanic properties of CS contribute to a denser microstructure, reducing the permeability of concrete and limiting the ingress of sulfate ions. Studies have shown that concrete containing CS exhibits a lower expansion rate when subjected to sulfate environments compared to traditional concrete mixes. This is attributed to the formation of more stable hydration products, such as C–S–H, which are less susceptible to sulfate attack [148,186,187]. Similarly, research reported that 20% replacement of cement by CS is the optimum amount to provide resistance against sulfate attack [125]. Another research found that sand replaced by 40% of CS provides the most optimum sulfate resistivity [143].

5 Limitations

This article's limitations primarily stem from the inherent challenges associated with scientometric analysis. The reliance on bibliometric databases like Web of Science and Scopus introduces potential biases due to incomplete coverage, especially concerning non-English or regional publications. Furthermore, citation metrics, while useful, may not fully capture the qualitative impact of research, as they often emphasize quantity over significance. The analysis is also subject to citation biases, including self-citations and variations in citation practices across different fields, which can affect the comparability of results. Additionally, the time lag in citation accumulation may lead to an underestimation of the impact of more recent studies, while older works might be undervalued due to the natural decline in citations over time.

6 Conclusion

This article provides a scientometric review of the literature regarding the utilization of CS as a substitute material in ordinary Portland cement concrete (OPCC). The review reveals that while research on CS concrete dates back to 1983, the most significant period of growth occurred between 2015 and 2022, during which the volume of literature on the topic saw an exponential increase. "Journal articles" were identified as the primary document types, while "engineering" and "material science" disciplines emerged as the major subject areas in published research on CS concrete. The journal "Construction and Building Materials" was revealed to be the major source, whereas "Dharmar, B." was found to be the leading author of the research on CS concrete. "India" was found to be the top country, "Thiagarajar College of Engineering" was found to be the top organization, whereas "National Natural Science Foundation of China" was found to be the top funding sponsor of the research on CS concrete. The article titled "Characteristics and utilization of CS – A review" was found to be the most cited document of the research on CS concrete. "Compressive strength" emerged as the most investigated mechanical property of CS concrete. CS is a pozzolana and can be utilized as a building material if used within a specific limit. It does not have greater early strength gain, but alkali activators can be used to break the acidic layer around its particles and its reactivity can be increased by many folds. It can also be achieved by grounding the CS particles and busting opening the active elements such as alumina and silica. CS has some quantities of heavy metals such as copper and zinc. These heavy metals can affect the setting time of the mixes containing CS as a binding material. The setting time of CS based concrete can be reduced by washing off the inert surface of CS particles or by grounding the CS particles. In addition, the inclusion of CS in concrete increases the workability of concrete but the addition of more than 80% concrete results in bleeding of concrete. For improving the workability, the optimum ratio of cement replacement by CS is 30%, while the optimum ratio to replace sand by CS is 40%–50%. CS is also beneficial for the enhancement of the mechanical properties of concrete. Although CS harms early strength gain, this problem can be mitigated by using Alkali activators. Most studies suggest that 5%–10% CS can be added to cement to attain the most beneficial mechanical properties. The addition of CS in concrete has been found to enhance the durability properties of concrete. Since CS imparts the micro filler effect to the structure of concrete and makes the concrete denser, concrete is hardly penetrated by any substance. The number of pores in concrete increases by adding CS, but their pore size is so minute that no substance can pass through them. The optimum amount of CS that can be used to improve durability properties is 20% if CS is used as SCM and 40% if CS is used as sand. The utilization of CS as cement has many ecological benefits as well. CS contains heavy metals that are incorporated and hardened in concrete. After the concrete hardens, these heavy metals do not leach under any circumstances. Hence, using CS as SCM or sand replacement in concrete successfully utilizes the heavy metals, saving the environment.

This scientometric review of CS utilization in OPCC offers several important implications and contributions to the field of construction materials. The significant increase in research on CS concrete from 2015 to 2022 underscores a heightened interest and recognition of CS as a viable alternative material. This trend highlights the need for continued exploration into its benefits and applications, suggesting that CS could play a substantial role in future concrete formulations. The identification of "compressive strength" as the most investigated mechanical property provides a clear direction for future studies. Researchers and practitioners can focus on optimizing CS content to achieve desired strength properties, addressing challenges related to early strength gain with alkali activators, and exploring the balance between CS content and concrete workability. The review offers practical insights into the optimal replacement ratios for CS as both a cement and sand substitute. These recommendations are crucial for engineers and construction professionals aiming to enhance concrete performance and workability while maintaining structural integrity. The review emphasizes the ecological benefits of using CS in concrete, particularly its role in stabilizing heavy metals and preventing leaching. This contributes to sustainable construction practices by providing a method for effectively utilizing industrial by-products and reducing environmental impact. By highlighting the need for further investigation into the long-term properties of CS concrete and its performance in various applications, the review opens avenues for future research. This includes exploring the durability of CS concrete over extended periods and its suitability for different environmental conditions. The review consolidates extensive research on CS concrete, offering a thorough examination of its properties, applications, and trends. This comprehensive overview aids in understanding the current state of knowledge and provides a valuable reference for future studies. By recognizing leading journals, authors, and funding organizations, the review identifies key contributors and sources of research. This information is valuable for researchers seeking collaboration opportunities and for understanding the primary drivers of research in this field. The review provides actionable guidelines for the effective use of CS in concrete mixes, including optimal replacement ratios and methods to enhance reactivity and workability. These guidelines can be directly applied in practice, facilitating the adoption of CS in construction projects. The review highlights the ecological benefits of using CS, emphasizing its role in environmental conservation by incorporating heavy metals into a stable concrete matrix. This contributes to promoting sustainable practices within the construction industry. In summary, this review not only advances the understanding of CS as a substitute material in concrete but also provides practical recommendations and identifies future research directions, contributing significantly to the field of sustainable construction materials.

7 Future recommendations

The investigation on the utilization of CS in concrete either as a SCM or as a fine aggregate has shown its potential as a sustainable material. However, the results reported in different studies can be ascribed to the alterations in types of CS, mix ratios, preparation methods, fineness of CS, and mix contents. The existing research advocates its viability; however, there is still a need for further research. Future studies are recommended to prioritize several key aspects. First, the environmental impact of the utilization of CS in concrete needs to be thoroughly investigated. Exploring the environmental aspects will help in evaluating the sustainability of such concrete mixtures and guaranteeing that their production and use align with ecofriendly procedures. Second, performing a lifecycle assessment of CS along with a cost–benefit analysis is crucial. This involves assessing the resource consumption and economic considerations in addition to the environmental impacts over the entire life of concrete structures. Such assessments are critical for making informed decisions regarding the feasibility and sustainability of the utilization of CS in concrete construction. Third, the tensile behavior of CS concrete should be examined in detail. Studying tensile behavior is important for designing structures that can endure different types of loading. Lastly, investigating the abrasion resistance of CS concrete is critical, especially in applications where wear and tear are substantial factors. Evaluating endurance to abrasion will help in determining the durability of CS concrete-based structures. In summary, addressing these research gaps will contribute to a comprehensive and detailed understanding of the potential and limitations of CS concrete.

Acknowledgments: The authors extend their appreciation to the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia for funding this research work through the project number (IF2/PSAU/2022/RV/10).

Funding information: The authors extend their appreciation to the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia for funding this research work through project number IF2/PSAU/2022/RV/10.

Author contributions: R.A.: conceptualization, resources, writing-original draft. M.F.J.: data acquisition, visualization, writing, and editing. R.A.: investigation, conceptualization, writing, reviewing, and editing. A.I.: resources, writing and editing. B.A.: software, supervision, formal analysis, writing-original draft. R.A.: data acquisition, visualization, and writing. M.A.K.: formal analysis, resources, writing, reviewing, and editing. All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

References

[1] Mohamad, N., K. Muthusamy, R. Embong, A. Kusbiantoro, and M. H. Hashim. Environmental impact of cement production and Solutions: A review. *Materials Today: Proceedings*, Vol. 48, 2022, pp. 741–746.

[2] Amjad, S. U., M. A. Budihardjo, I. B. Priyambada, and R. Asghar. Synthesis of geopolymer concrete using flyash. *IOP Conference Series: Earth and Environmental Science*, Vol. 1098, 2022, id. 012072.

[3] Li, X.-J. and Y. Zheng. Using LCA to research carbon footprint for precast concrete piles during the building construction stage:

A China study. *Journal of Cleaner Production*, Vol. 245, 2020, id. 118754.
[4] Sustainability | Free Full-Text | Issues, Impacts, and Mitigations of Carbon Dioxide Emissions in the Building Sector, (n.d.). https://www.mdpi.com/2071-1050/12/18/7427 (accessed March 5, 2023).
[5] Asghar, R., A. Shahzad, S. U. Amjad, and A. Akhtar. *Comparative study on the seismic performance of bare frame and infilled frame RC structures with brick masonry and low strength concrete block masonry infills*. Department of Civil Engineering, Capital University of Science and Technology, Islamabad, Pakistan, 2020, 8.
[6] Dong, J. F., Y. Xu, Z. W. Guan, and Q. Y. Wang. Freeze-thaw behaviour of basalt fibre reinforced recycled aggregate concrete filled CFRP tube specimens. *Engineering Structures*, Vol. 273, 2022, id. 115088.
[7] Li, W., Z. Xie, J. Zhao, P. K. Wong, and P. Li. Fuzzy finite-frequency output feedback control for nonlinear active suspension systems with time delay and output constraints. *Mechanical Systems and Signal Processing*, Vol. 132, 2019, pp. 315–334.
[8] Wei, J., H. Ying, Y. Yang, W. Zhang, H. Yuan, and J. Zhou. Seismic performance of concrete-filled steel tubular composite columns with ultra high performance concrete plates. *Engineering Structures*, Vol. 278, 2023, id. 115500.
[9] Huang, H., Y. Yuan, W. Zhang, and M. Li. Seismic behavior of a replaceable artificial controllable plastic hinge for precast concrete beam-column joint. *Engineering Structures*, Vol. 245, 2021, id. 112848.
[10] Sun, L., C. Wang, C. Zhang, Z. Yang, C. Li, and P. Qiao. Experimental investigation on the bond performance of sea sand coral concrete with FRP bar reinforcement for marine environments. *Advances in Structural Engineering*, Vol. 26, No. 3, 2023, pp. 533–546.
[11] Zhou, C., J. Wang, X. Shao, L. Li, J. Sun, and X. Wang. The feasibility of using ultra-high performance concrete (UHPC) to strengthen RC beams in torsion. *Journal of Materials Research and Technology*, Vol. 24, 2023, pp. 9961–9983.
[12] Huang, H., M. Li, Y. Yuan, and H. Bai. Experimental research on the seismic performance of precast concrete frame with replaceable artificial controllable plastic hinges. *Journal of Structural Engineering*, Vol. 149, 2023, id. 04022222.
[13] Chen, D., F. Kang, J. Li, S. Zhu, and X. Liang. Enhancement of underwater dam crack images using multi-feature fusion. *Automation in Construction*, Vol. 167, 2024, id. 105727.
[14] He, L., B. Chen, Q. Liu, H. Chen, H. Li, W. T. Chow, et al. A quasi-exponential distribution of interfacial voids and its effect on the interlayer strength of 3D printed concrete. *Additive Manufacturing*, Vol. 89, 2024, id. 104296.
[15] Dong, J. F., Q. Y. Wang, Z. W. Guan, and H. K. Chai. High-temperature behaviour of basalt fibre reinforced concrete made with recycled aggregates from earthquake waste. *Journal of Building Engineering*, Vol. 48, 2022, id. 103895.
[16] Liu, Y., J. Dong, S. Yuan, K. Li, X. Hu, and Q. Wang. Variable fatigue loading effects on corrugated steel box girders with recycled concrete. *Journal of Constructional Steel Research*, Vol. 215, 2024, id. 108526.
[17] Chen, D., F. Kang, J. Chen, S. Zhu, and H. Li. Effect of light source wavelength on surface defect imaging in deep-water concrete dams. *NDT & E International*, Vol. 147, 2024, id. 103198.
[18] Javed, M. F., R. Asghar, and S. K. U. Rehman. Automating the seismic design of reinforced concrete rectangular columns employing multi-expression programming: towards the automated design of reinforced concrete structures. *In Advanced Optimization Applications in Engineering*, IGI Global, 2024, pp. 197–236.
[19] Zhang, Y., W. Luo, J. Wang, Y. Wang, Y. Xu, and J. Xiao. A review of life cycle assessment of recycled aggregate concrete. *Construction and Building Materials*, Vol. 209, 2019, pp. 115–125.
[20] Vázquez-Rowe, I., K. Ziegler-Rodriguez, J. Laso, I. Quispe, R. Aldaco, and R. Kahhat. Production of cement in Peru: Understanding carbon-related environmental impacts and their policy implications. *Resources, Conservation and Recycling*, Vol. 142, 2019, pp. 283–292.
[21] A review on alternative binders, admixtures and water for the production of sustainable concrete - ScienceDirect, (n.d.). https://www.sciencedirect.com/science/article/abs/pii/S0959652621006284 (accessed January 5, 2023).
[22] Bai, B., J. Chen, F. Bai, Q. Nie, and X. Jia. Corrosion effect of acid/alkali on cementitious red mud-fly ash materials containing heavy metal residues. *Environmental Technology & Innovation*, Vol. 33, 2024, id. 103485.
[23] Kang, F., Y. Wu, J. Ma, and J. Li. Structural identification of super high arch dams using Gaussian process regression with improved salp swarm algorithm. *Engineering Structures*, Vol. 286, 2023, id. 116150.
[24] Liu, C., J. Cui, Z. Zhang, H. Liu, X. Huang, and C. Zhang. The role of TBM asymmetric tail-grouting on surface settlement in coarse-grained soils of urban area: Field tests and FEA modelling. *Tunnelling and Underground Space Technology*, Vol. 111, 2021, id. 103857.
[25] Shanmuganathan, R., B. Rath, H. S. Almoallim, T. A. Alahmadi, G. K. Jhanani, N. T. Lan Chi, et al. Utilisation of persistent chemical pollutant incorporating with nanoparticles to modify the properties of geopolymer and cement concrete. *Environmental Research*, Vol. 219, 2023, id. 114965.
[26] Rao, M. S. C., M. M. Vijayalakshmi, and T. R. Praveenkumar. Behaviour of green concrete (blended concrete) using agro-industrial waste as partial replacement of cement along with nanoparticles. *Applied Nanoscience*, Vol. 13, 2023, pp. 2285–2293.
[27] Tang, Y., Y. Wang, D. Wu, M. Chen, L. Pang, J. Sun, et al. Exploring temperature-resilient recycled aggregate concrete with waste rubber: An experimental and multi-objective optimization analysis. *Reviews on Advanced Materials Science*, Vol. 62, No. 1, 2023, id. 20230347.
[28] Zhang, W., S. Kang, B. Lin, and Y. Huang. Mixed-mode debonding in CFRP-to-steel fiber–reinforced concrete joints. *Journal of Composites for Construction*, Vol. 28, 2024, id. 04023069.
[29] Lai, L., M. Gan, J. Wang, L. Chen, X. Liang, J. Feng, et al. New class of high-entropy rare-earth niobates with high thermal expansion and oxygen insulation. *Journal of the American Ceramic Society*, Vol. 106, 2023, pp. 4343–4357.
[30] Zhou, F., W. Li, Y. Hu, L. Huang, Z. Xie, J. Yang, et al. Moisture diffusion coefficient of concrete under different conditions. *Buildings*, Vol. 13, 2023, id. 2421.
[31] Wang, Z., Q. Wang, C. Jia, and J. Bai. Thermal evolution of chemical structure and mechanism of oil sands bitumen. *Energy*, Vol. 244, 2022, id. 123190.
[32] AzariJafari, H., M. J. Taheri Amiri, A. Ashrafian, H. Rasekh, M. J. Barforooshi, and J. Berenjian. Ternary blended cement: An eco-friendly alternative to improve resistivity of high-performance self-consolidating concrete against elevated temperature. *Journal of Cleaner Production*, Vol. 223, 2019, pp. 575–586.

[33] Zhang, Y., Z. Gao, X. Wang, and Q. Liu. Predicting the pore-pressure and temperature of fire-loaded concrete by a hybrid neural network. *International Journal of Computational Methods*, Vol. 19, No. 8, 2022, id. 2142011.
[34] Deng, P., D.-S. Chang, X.-L. Chen, Z.-Y. Zhu, and R. Asghar. Analysis of the dynamic mechanism of square tubular t-joints with chord flanges subjected to impact loading. *Advanced Steel Construction*, Vol. 20, 2024, pp. 21–29.
[35] Shen, W., Y. Liu, M. Wu, D. Zhang, X. Du, D. Zhao, et al. Ecological carbonated steel slag pervious concrete prepared as a key material of sponge city. *Journal of Cleaner Production*, Vol. 256, 2020, id. 120244.
[36] Yao, X., X. Lyu, J. Sun, B. Wang, Y. Wang, M. Yang, et al. AI-based performance prediction for 3D-printed concrete considering anisotropy and steam curing condition. *Construction and Building Materials*, Vol. 375, 2023, id. 130898.
[37] Zhou, T., F. Yu, L. Li, Z. Dong, and E. H. Fini. Swelling-degradation dynamic evolution behaviors of bio-modified rubberized asphalt under thermal conditions. *Journal of Cleaner Production*, Vol. 426, 2023, id. 139061.
[38] He, H., S. Wang, W. Shen, and W. Zhang. The influence of pipe-jacking tunneling on deformation of existing tunnels in soft soils and the effectiveness of protection measures. *Transportation Geotechnics*, Vol. 42, 2023, id. 101061.
[39] Choudhary, J., B. Kumar, and A. Gupta. Utilization of solid waste materials as alternative fillers in asphalt mixes: A review. *Construction and Building Materials*, Vol. 234, 2020, id. 117271.
[40] Study on the interactive influence between economic growth and environmental pollution | SpringerLink, (n.d.). https://link.springer.com/article/10.1007/s11356-020-10017-6 (accessed January 5, 2023).
[41] Lo, F.-C., M.-G. Lee, and S.-L. Lo. Effect of coal ash and rice husk ash partial replacement in ordinary Portland cement on pervious concrete. *Construction and Building Materials*, Vol. 286, 2021, id. 122947.
[42] Liu, T., G. Zhao, B. Qu, and C. Gong. Characterization of a fly ash-based hybrid well cement under different temperature curing conditions for natural gas hydrate drilling. *Construction and Building Materials*, Vol. 445, 2024, id. 137874.
[43] Huang, H., Y. Yuan, W. Zhang, and L. Zhu. Property assessment of high-performance concrete containing three types of fibers. *International Journal of Concrete Structures and Materials*, Vol. 15, 2021, pp. 1–7.
[44] Sivakrishna, A., A. Adesina, P. O. Awoyera, and K. Rajesh Kumar. Green concrete: A review of recent developments. *Materials Today: Proceedings*, Vol. 27, 2020, pp. 54–58.
[45] Kishore, K. and N. Gupta. Application of domestic & industrial waste materials in concrete: A review. *Materials Today: Proceedings*, Vol. 26, 2020, pp. 2926–2931.
[46] Teh, S. H., T. Wiedmann, A. Castel, and J. de Burgh. Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia. *Journal of Cleaner Production*, Vol. 152, 2017, pp. 312–320.
[47] Salas, D. A., A. D. Ramirez, N. Ulloa, H. Baykara, and A. J. Boero. Life cycle assessment of geopolymer concrete. *Construction and Building Materials*, Vol. 190, 2018, pp. 170–177.
[48] He, J., S. Kawasaki, and V. Achal. The utilization of agricultural waste as agro-cement in concrete: a review. *Sustainability*, Vol. 12, 2020, id. 6971.
[49] Giergiczny, Z. Fly ash and slag. *Cement and Concrete Research*, Vol. 124, 2019, id. 105826.
[50] Thomas, B. S., J. Yang, A. Bahurudeen, J. A. Abdalla, R. A. Hawileh, H. M. Hamada, et al. Sugarcane bagasse ash as supplementary cementitious material in concrete – a review. *Materials Today Sustainability*, Vol. 15, 2021, id. 100086.
[51] Jittin, V., A. Bahurudeen, and S. D. Ajinkya. Utilisation of rice husk ash for cleaner production of different construction products. *Journal of Cleaner Production*, Vol. 263, 2020, id. 121578.
[52] Zhu, J., B. Ma, D. Li, Y. Zhang, and L. Xu. Role of bicarbonate in CO_2 corrosion of carbon steel. *Electrochimica Acta*, Vol. 478, 2024, id. 143818.
[53] Zhang, Y., M. Zeiml, C. Pichler, and R. Lackner. Model-based risk assessment of concrete spalling in tunnel linings under fire loading. *Engineering Structures*, Vol. 77, 2014, pp. 207–215.
[54] Fang, B., Z. Qian, Y. Song, X. Diao, T. Shi, X. Cai, et al. Evaluation of early crack resistance performance of concrete mixed with ternary minerals using temperature stress testing machine (TSTM). *Journal of Cleaner Production*, Vol. 465, 2024, id. 142780.
[55] Zhao, H., Y. Wang, X. Liu, X. Wang, Z. Chen, Z. Lei, et al. Review on solid wastes incorporated cementitious material using 3D concrete printing technology. *Case Studies in Construction Materials*, Vol. 21, 2024, id. e03676.
[56] Use of waste copper slag, a sustainable material | SpringerLink, (n.d.). https://link.springer.com/article/10.1007/s10163-014-0254-x (accessed January 5, 2023).
[57] Al-Jabri, K. S., M. Hisada, S. K. Al-Oraimi, and A. H. Al-Saidy. Copper slag as sand replacement for high performance concrete. *Cement and Concrete Composites*, Vol. 31, 2009, pp. 483–488.
[58] Tian, H., Z. Guo, J. Pan, D. Zhu, C. Yang, Y. Xue, et al. Comprehensive review on metallurgical recycling and cleaning of copper slag. *Resources, Conservation and Recycling*, Vol. 168, 2021, id. 105366.
[59] Gabasiane, T. S., G. Danha, T. A. Mamvura, T. Mashifana, and G. Dzinomwa. Environmental and socioeconomic impact of copper slag – a review. *Crystals*, Vol. 11, 2021, id. 1504.
[60] Sharma, P. M. G. Copper Slag: Converting waste into sustainable wealth, Times India (n.d.). https://timesofindia.indiatimes.com/blogs/voices/copper-slag-converting-waste-into-sustainable-wealth/ (accessed August 26, 2024).
[61] Zhang, Z., Q. Wang, and Z. Huang. Value-added utilization of copper slag to enhance the performance of magnesium potassium phosphate cement. *Resources, Conservation and Recycling*, Vol. 180, 2022, id. 106212.
[62] Chakrawarthi, V., B. Dharmar, S. Avudaiappan, M. Amran, E. S. Flores, M. A. Alam, et al. Destructive and non-destructive testing of the performance of copper slag fiber-reinforced concrete. *Materials*, Vol. 15, 2022, id. 4536.
[63] Siddique, R., M. Singh, and M. Jain. Recycling copper slag in steel fibre concrete for sustainable construction. *Journal of Cleaner Production*, Vol. 271, 2020, id. 122559.
[64] Sheikh, E., S. R. Mousavi, and I. Afshoon. Producing green Roller Compacted Concrete (RCC) using fine copper slag aggregates. *Journal of Cleaner Production*, Vol. 368, 2022, id. 133005.
[65] O. US EPA. TENORM: Copper Mining and Production Wastes, 2015. https://www.epa.gov/radiation/tenorm-copper-mining-and-production-wastes (accessed January 5, 2023).
[66] Phiri, T. C., P. Singh, and A. N. Nikoloski. The potential for copper slag waste as a resource for a circular economy: A review – Part I. *Minerals Engineering*, Vol. 180, 2022, id. 107474.

[67] The potential for copper slag waste as a resource for a circular economy: A review – Part II - ScienceDirect, (n.d.). https://www.sciencedirect.com/science/article/abs/pii/S0892687521003794 (accessed January 5, 2023).
[68] Afkhami, B., B. Akbarian, N. Beheshti, A. H. Kakaee, and B. Shabani. Energy consumption assessment in a cement production plant. *Sustainable Energy Technologies and Assessments*, Vol. 10, 2015, pp. 84–89.
[69] Green chemistry for sustainable cement production and use - Green Chemistry (RSC Publishing), (n.d.). https://pubs.rsc.org/en/content/articlelanding/2006/gc/b603997a/unauth (accessed March 15, 2023).
[70] Madlool, N. A., R. Saidur, M. S. Hossain, and N. A. Rahim. A critical review on energy use and savings in the cement industries. *Renewable and Sustainable Energy*, Vol. 15, 2011, pp. 2042–2060.
[71] Usha Kranti, J., A. Naga Sai, A. Rama Krishna, and K. Srinivasu. An experimental investigation on effect of durability on strength properties of M40 grade concrete with partial replacement of sand with copper slag. *Materials Today: Proceedings*, Vol. 43, 2021, pp. 1626–1633.
[72] Panda, S., P. Sarkar, and R. Davis. Abrasion resistance and slake durability of copper slag aggregate concrete. *Journal of Building Engineering*, Vol. 35, 2021, id. 101987.
[73] Rathee, M. and N. Singh. Durability properties of copper slag and coal bottom ash based I-shaped geopolymer paver blocks. *Construction and Building Materials*, Vol. 347, 2022, id. 128461.
[74] Ahmad, J., A. Majdi, A. F. Deifalla, H. F. Isleem, and C. Rahmawati. Concrete Made with partially substitutions of copper slag (CPS): State of the art review. *Materials*, Vol. 15, 2022, id. 5196.
[75] Liu, Y., B. Wang, Y. Fan, J. Yu, T. Shi, Y. Zhou, et al. Effects of reactive MgO on durability and microstructure of cement-based materials: Considering carbonation and pH value. *Construction and Building Materials*, Vol. 426, 2024, id. 136216.
[76] Sambhaji, Z. K. and P. B. Autade. Effect of copper slag as a fine aggregate on properties of concrete. *International Journal of Innovative Research in Advanced Engineering (IJIRAE)*, Vol. 3, 2016, pp. 410–414.
[77] Lan, W., A. Wu, and P. Yu. Development of a new controlled low strength filling material from the activation of copper slag: Influencing factors and mechanism analysis. *Journal of Cleaner Production*, Vol. 246, 2020, id. 119060.
[78] Chakrawarthi, V., S. Avudaiappan, M. Amran, B. Dharmar, L. Raj Jesuarulraj, R. Fediuk, et al. Impact resistance of polypropylene fibre-reinforced alkali–activated copper slag concrete. *Materials*, Vol. 14, 2021, id. 7735.
[79] Lori, A. R., A. Hassani, and R. Sedghi. Investigating the mechanical and hydraulic characteristics of pervious concrete containing copper slag as coarse aggregate. *Construction and Building Materials*, Vol. 197, 2019, pp. 130–142.
[80] Dong, J., Q. Wang, and Z. Guan. Structural behaviour of RC beams with external flexural and flexural-shear strengthening by FRP sheets. *Composites Part B: Engineering*, Vol. 44, 2013, pp. 604–612.
[81] Afgan, S. and C. Bing. Scientometric review of international research trends on thermal energy storage cement based composites via integration of phase change materials from 1993 to 2020. *Construction and Building Materials*, Vol. 278, 2021, id. 122344.
[82] Ahmad, W., A. Ahmad, K. A. Ostrowski, F. Aslam, and P. Joyklad. A scientometric review of waste material utilization in concrete for sustainable construction. *Case Studies in Construction Materials*, Vol. 15, 2021, id. e00683.
[83] Amin, M. N., W. Ahmad, K. Khan, and M. M. Sayed. Mapping research knowledge on rice husk ash application in concrete: a scientometric review. *Materials*, Vol. 15, 2022, id. 3431.
[84] Ghosh, A. and A. Hasan. Recent patterns and trends in sustainable concrete research in India: A five-year Scientometric review. *Materials Today: Proceedings*, Vol. 32, 2020, pp. 910–916.
[85] Gu, M., W. Ahmad, T. M. Alaboud, A. Zia, U. Akmal, Y. A. Awad, et al. Scientometric analysis and research mapping knowledge of coconut fibers in concrete. *Materials*, Vol. 15, 2022, id. 5639.
[86] He, C., S. Zhang, Y. Liang, W. Ahmad, F. Althoey, S. H. Alyami, et al. Review on mapping research knowledge for 3D printing concrete. *Materials*, Vol. 15, 2022, id. 4796.
[87] He, X., M. N. Amin, K. Khan, W. Ahmad, F. Althoey, and N. I. Vatin. Self-healing concrete: a scientometric analysis-based review of the research development and scientific mapping. *Case Studies in Construction Materials*, Vol. 17, 2022, id. e01521.
[88] Huang, S., H. Wang, W. Ahmad, A. Ahmad, N. Ivanovich Vatin, A. M. Mohamed, et al. Plastic waste management strategies and their environmental aspects: A scientometric analysis and comprehensive review. *International Journal of Environmental Research and Public Health*, Vol. 19, 2022, id. 4556.
[89] Khan, K., W. Ahmad, M. N. Amin, S. Nazar, and A. Scientometric-Analysis-Based. Review of the research development on geopolymers. *Polymers*, Vol. 14, 2022, id. 3676.
[90] Khan, K., W. Ahmad, M. N. Amin, and S. Nazar. Nano-silica-modified concrete: A bibliographic analysis and comprehensive review of material properties. *Nanomaterials*, Vol. 12, 2022, id. 1989.
[91] Krishna, U. S. R. and C. Tadi. Sustainable concrete pavements for low volume roads-Scientometric analysis of the literature. *IOP Conference Series: Earth and Environmental Science*, Vol. 982, 2022, id. 012005. IOP Publishing.
[92] Kuoribo, E. and H. Mahmoud. Utilisation of waste marble dust in concrete production: A scientometric review and future research directions. *Journal of Cleaner Production*, Vol. 374, 2022, id. 133872.
[93] Li, Z. and A. Radlińska. Artificial intelligence in concrete materials: A scientometric view. In: *Leveraging Artificial Intelligence in Engineering, Management, and Safety of Infrastructure*, CRC Press, 2022, pp. 161–183.
[94] Liu, W., H. Zhang, Q. Wang, T. Hua, and H. Xue. A review and scientometric analysis of global research on prefabricated buildings. *Advances in Civil Engineering*, Vol. 2021, 2021, pp. 1–18.
[95] Pan, Y., L. Deng, S. Li, J. Wang, and F. Zhang. A study using a combined method of scientometric and manual analysis to review the present research of plant fibres reinforced concrete. *Construction and Building Materials*, Vol. 341, 2022, id. 127551.
[96] Raza, A., M. Hechmi El Ouni, M. Azab, K. Ali, H. Haider, and A. Rashedi. A scientometric review on mechanical and durability performance of geopolymer Paste: Effect of various raw materials. *Construction and Building Materials*, Vol. 345, 2022, id. 128297.
[97] Zakka, W. P., N. H. A. S. Lim, and M. C. Khun. A scientometric review of geopolymer concrete. *Journal of Cleaner Production*, Vol. 280, 2021, id. 124353.
[98] Zhang, B., W. Ahmad, A. Ahmad, F. Aslam, and P. Joyklad. A scientometric analysis approach to analyze the present research on recycled aggregate concrete. *Journal of Building Engineering*, Vol. 46, 2022, id. 103679.
[99] Zhang, J., M. Wang, X. Zhou, W. Yu, Y. Gao, and Y. Zhang. Exploring the emerging evolution trends of probabilistic service

life prediction of reinforced concrete structures in the chloride environment by scientometric analysis. *Advances in Civil Engineering*, Vol. 2021, 2021, pp. 1–14.
[100] Zhao, X. A scientometric review of global BIM research: Analysis and visualization. *Automation in Construction*, Vol. 80, 2017, pp. 37–47.
[101] Qayyum, A., M. F. Javed, R. Asghar, A. Iqtidar, H. Alabduljabbar, M. A. Khan, et al. Promoting the sustainable construction: A scientometric review on the utilization of waste glass in concrete. *Reviews on Advanced Materials Science*, Vol. 63, No. 1, 2024, id. 20240036.
[102] Ahmad, W., A. Ahmad, K. A. Ostrowski, F. Aslam, P. Joyklad, and P. Zajdel. Sustainable approach of using sugarcane bagasse ash in cement-based composites: A systematic review. *Case Studies in Construction Materials*, Vol. 15, 2021, id. e00698.
[103] Lou, Y., K. Khan, M. N. Amin, W. Ahmad, A. F. Deifalla, and A. Ahmad. Performance characteristics of cementitious composites modified with silica fume: A systematic review. *Case Studies in Construction Materials*, Vol. 18, 2023, id. e01753.
[104] Prasad, K. V., V. Vasugi, and G. Senthil Kumaran. Application of 3D printing concepts in the Architecture Engineering and Construction (AEC) industry - A scientometric review. *Materials Today: Proceedings*, 2023.
[105] Al-Hashem, M. N., M. N. Amin, W. Ahmad, K. Khan, A. Ahmad, and H. A. Alkadhim. Research progress on shotcrete for construction applications: a scientometric review. *Science of Advanced Materials*, Vol. 14, 2022, pp. 1285–1297.
[106] Mei, J., G. Xu, W. Ahmad, K. Khan, M. N. Amin, F. Aslam, et al. Promoting sustainable materials using recycled rubber in concrete: A review. *Journal of Cleaner Production*, Vol. 373, 2022, id. 133927.
[107] Gorai, B. and R. K. Jana. Characteristics and utilisation of copper slag – a review. *Resources, Conservation and Recycling*, Vol. 39, 2003, pp. 299–313.
[108] Shi, C. and J. Qian. High performance cementing materials from industrial slags – a review. *Resources, Conservation and Recycling*, Vol. 29, 2000, pp. 195–207.
[109] Shi, C., C. Meyer, and A. Behnood. Utilization of copper slag in cement and concrete. *Resources, Conservation and Recycling*, Vol. 52, 2008, pp. 1115–1120.
[110] Chithra, S., S. R. R. Senthil Kumar, and K. Chinnaraju. The effect of Colloidal Nano-silica on workability, mechanical and durability properties of High Performance Concrete with Copper slag as partial fine aggregate. *Construction and Building Materials*, Vol. 113, 2016, pp. 794–804.
[111] Wu, W., W. Zhang, and G. Ma. Optimum content of copper slag as a fine aggregate in high strength concrete. *Materials & Design*, Vol. 31, 2010, pp. 2878–2883.
[112] Chithra, S., S. R. R. S. Kumar, K. Chinnaraju, F. A comparative study on the compressive strength prediction models for High Performance Concrete containing nano silica and copper slag using regression analysis and Artificial Neural Networks. *Construction and Building Materials*, Vol. 114, 2016, pp. 528–535.
[113] Mithun, B. M. and M. C. Narasimhan. Performance of alkali activated slag concrete mixes incorporating copper slag as fine aggregate. *Journal of Cleaner Production*, Vol. 112, 2016, pp. 837–844.
[114] Pasetto, M. and N. Baldo. Experimental evaluation of high performance base course and road base asphalt concrete with electric arc furnace steel slags. *Journal of Hazardous Materials*, Vol. 181, 2010, pp. 938–948.
[115] Khanzadi, M. and A. Behnood. Mechanical properties of high-strength concrete incorporating copper slag as coarse aggregate. *Construction and Building Materials*, Vol. 23, 2009, pp. 2183–2188.
[116] Giergiczny, Z. and A. Król. Immobilization of heavy metals (Pb, Cu, Cr, Zn, Cd, Mn) in the mineral additions containing concrete composites. *Journal of Hazardous Materials*, Vol. 160, 2008, pp. 247–255.
[117] Dash, M. K., S. K. Patro, and A. K. Rath. Sustainable use of industrial-waste as partial replacement of fine aggregate for preparation of concrete–A review. *International Journal of Sustainable Built Environment*, Vol. 5, 2016, pp. 484–516.
[118] Ambily, P. S., C. Umarani, K. Ravisankar, P. R. Prem, B. H. Bharatkumar, and N. R. Iyer. Studies on ultra high performance concrete incorporating copper slag as fine aggregate. *Construction and Building Materials*, Vol. 77, 2015, pp. 233–240.
[119] Huang, X., W. Ni, W. Cui, Z. Wang, and L. Zhu. Preparation of autoclaved aerated concrete using copper tailings and blast furnace slag. *Construction and Building Materials*, Vol. 27, 2012, pp. 1–5.
[120] Sharma, R. and R. A. Khan. Sustainable use of copper slag in self compacting concrete containing supplementary cementitious materials. *Journal of Cleaner Production*, Vol. 151, 2017, pp. 179–192.
[121] Al-Jabri, K. S., M. Hisada, A. H. Al-Saidy, and S. K. Al-Oraimi. Performance of high strength concrete made with copper slag as a fine aggregate. *Construction and Building Materials*, Vol. 23, 2009, pp. 2132–2140.
[122] Al-Jabri, K. S., R. A. Taha, A. Al-Hashmi, and A. S. Al-Harthy. Effect of copper slag and cement by-pass dust addition on mechanical properties of concrete. *Construction and Building Materials*, Vol. 20, 2006, pp. 322–331.
[123] Najimi, M., J. Sobhani, and A. R. Pourkhorshidi. Durability of copper slag contained concrete exposed to sulfate attack. *Construction and Building Materials*, Vol. 25, 2011, pp. 1895–1905.
[124] Use of waste copper slag, a sustainable material | SpringerLink, (n.d.). https://link.springer.com/article/10.1007/s10163-014-0254-x (accessed January 5, 2023).
[125] Maharishi, A., S. P. Singh, and L. K. Gupta. Strength and durability studies on slag cement concrete made with copper slag as fine aggregates. *Materials Today: Proceedings*, Vol. 38, 2021, pp. 2639–2648.
[126] Dong, J., Y. Liu, S. Yuan, K. Li, F. Zhang, Z. Guan, et al. Mechanical behavior and impact resistance of rubberized concrete enhanced by basalt fiber-epoxy resin composite. *Construction and Building Materials*, Vol. 435, 2024, id. 136836.
[127] Wang, R., Q. Shi, Y. Li, Z. Cao, and Z. Si. A critical review on the use of copper slag (CS) as a substitute constituent in concrete. *Construction and Building Materials*, Vol. 292, 2021, id. 123371.
[128] Rasoul Abdar Esfahani, S. M., S. A. Zareei, M. Madhkhan, F. Ameri, J. Rashidiani, and R. A. Taheri. Mechanical and gamma-ray shielding properties and environmental benefits of concrete incorporating GGBFS and copper slag. *Journal of Building Engineering*, Vol. 33, 2021, id. 101615.
[129] Yang, Z., Y. Liu, M. Chen, X. Wang, C. Ye, X. Li, et al. Influence of coupling effects between gravel soil porosity and cement grout weight on diffusion laws and morphologies of penetration grouting. *Applied Sciences*, Vol. 12, No. 15, 2022, id. 7601.
[130] Raju, S., J. Rathinam, B. Dharmar, S. Rekha, S. Avudaiappan, M. Amran, et al. Cyclically loaded copper slag admixed reinforced concrete beams with cement partially replaced with fly ash. *Materials*, Vol. 15, No. 9, 2022, id. 3101.

[131] Mavroulidou, M. Mechanical properties and durability of concrete with water cooled copper slag aggregate. *Waste and Biomass Valorization*, Vol. 8, 2017, pp. 1841–1854.
[132] Sun, L., Y. Feng, D. Wang, C. Qi, and X. Zeng. Influence of CaO on physical and environmental properties of granulated copper slag: Melting behavior, grindability and leaching behavior. *International Journal of Environmental Research and Public Health*, Vol. 19, 2022, id. 13543.
[133] Najimi, M. and A. R. Pourkhorshidi. Properties of concrete containing copper slag waste. *Magazine of Concrete Research*, Vol. 63, No. 8, 2011, pp. 605–615.
[134] Al-Jabri, K. S., A. H. Al-Saidy, and R. Taha. Effect of copper slag as a fine aggregate on the properties of cement mortars and concrete. *Construction and Building Materials*, Vol. 25, No. 2, 2011, pp. 933–938.
[135] Mantry, S., B. B. Jha, and A. Satapathy. Evaluation and characterization of plasma sprayed Cu Slag-Al composite coatings on metal substrates. *Journal of Coatings*, Vol. 2013, 2013, pp. 1–7.
[136] Buildings | Free Full-Text | Holistic Analysis of Waste Copper Slag Based Concrete by Means of EIPI Method, (n.d.). https://www.mdpi.com/2075-5309/10/1/1 (accessed January 5, 2023).
[137] Yang, Z., D. Zhang, C. Li, Z. Zhang, Y. Zhu, Y. Yang, et al. Column penetration and diffusion mechanism of Bingham fluid considering displacement effect. *Applied Sciences*, Vol. 12, No. 11, 2022, id. 5362.
[138] Katare, V. D. and M. V. Madurwar. Design and investigation of sustainable pozzolanic material. *Journal of Cleaner Production*, Vol. 242, 2020, id. 118431.
[139] (PDF) An Innovated Application of Reutilize Copper Smelter Slag for Cement-based Electromagnetic Interference Composites, ResearchGate (n.d.).
[140] Dimitrijevic, M., D. Urosevic, S. Milić, M. Sokić, and R. Markovic. Dissolution of copper from smelting slag by leaching in chloride media. *Journal of Mining and Metallurgy, Section B: Metallurgy*, Vol. 53, 2017, id. 407.
[141] Concrete with copper slag fine aggregate – Okayama University, (n.d.). https://okayama.pure.elsevier.com/en/publications/concrete-with-copper-slag-fine-aggregate (accessed January 5, 2023).
[142] Feng, Y., J. Kero, Q. Yang, Q. Chen, F. Engström, C. Samuelsson, et al. Mechanical activation of granulated copper slag and its influence on hydration heat and compressive strength of blended cement. *Materials*, Vol. 12, 2019, id. 772.
[143] Zhu, J., Q. Li, X. Li, Y. Zhou, F. Liu, and J. Song. Effect of coupled mechanical-chemical activation on hydration activity of copper slag powder. *Applied Sciences*, Vol. 12, 2022, id. 6018.
[144] Sheida, K., M. Seyedi, M. A. Afridi, F. Ferdowsi, M. J. Khattak, V. K. Gopu, et al. Resilient reinforcement learning for voltage control in an islanded dc microgrid integrating data-driven piezoelectric. *Machines*, Vol. 12, No. 10, 2024, id. 694.
[145] Feng, Y., Q. Yang, Q. Chen, J. Kero, A. Andersson, H. Ahmed, et al. Characterization and evaluation of the pozzolanic activity of granulated copper slag modified with CaO. *Journal of Cleaner Production*, Vol. 232, 2019, pp. 1112–1120.
[146] Use of Copper Slag and Cement By-Pass Dust as Cementitious Materials, (n.d.). https://www.astm.org/cca10485j.html (accessed January 5, 2023).
[147] Mechanical performance and reaction mechanism of copper slag activated with sodium silicate or sodium hydroxide - ScienceDirect, (n.d.). https://www.sciencedirect.com/science/article/abs/pii/S0950061820329056 (accessed January 5, 2023).
[148] Jin, Q. and L. Chen. A review of the influence of copper slag on the properties of cement-based materials. *Materials*, Vol. 15, 2022, id. 8594.
[149] Zhao, Y., J. Wang, G. Cao, Y. Yuan, X. Yao, and L. Qi. Intelligent control of multilegged robot smooth motion: a review. *IEEE Access*, Vol. 11, 2023, pp. 86645–86685.
[150] Toxicity characterization and long-term stability studies on copper slag from the ISASMELT process - ScienceDirect, (n.d.). https://www.sciencedirect.com/science/article/abs/pii/S0921344907001619 (accessed January 5, 2023).
[151] Arif, M., F. Jan, A. Rezzoug, M. A. Afridi, M. Luqman, W. A. Khan, et al. Data-driven models for predicting compressive strength of 3D-printed fiber-reinforced concrete using interpretable machine learning algorithms. *Case Studies in Construction Materials*, Vol. 21, 2024, id. e03935.
[152] Afridi, H. F., D. Khan, W. A. Khan, H. Jamal, A. A. Durrani, M. A. Afridi, et al. Utilizing waste engine oil and Sasobit to improve the rheological and physiochemical properties of RAP. *Discover Civil Engineering*, Vol. 1, No. 1, 2024, id. 131.
[153] Zain, M. F. M., M. N. Islam, S. S. Radin, and S. G. Yap. Cement-based solidification for the safe disposal of blasted copper slag. *Cement and Concrete Composites*, Vol. 26, 2004, pp. 845–851.
[154] Wang, D., Q. Zhang, Y. Feng, Q. Chen, C. Xiao, H. Li, et al. Hydration and Mechanical Properties of Blended Cement with Copper Slag Pretreated by Thermochemical Modification. *Materials*, Vol. 15, 2022, id. 3477.
[155] Materials | Free Full-Text | Evaluation of Mode II Fracture Toughness of Hybrid Fibrous Geopolymer Composites, (n.d.). https://www.mdpi.com/1996-1944/14/2/349 (accessed January 5, 2023).
[156] Hsie, M., C. Tu, and P. S. Song. Mechanical properties of polypropylene hybrid fiber-reinforced concrete. *Materials Science & Engineering, A: Structural Materials: Properties, Microstructure and Processing*, Vol. 494, 2008, pp. 153–157.
[157] Mubarak, M., R. S. Muhammad Rashid, M. Amran, R. Fediuk, N. Vatin, and S. Klyuev. Mechanical properties of high-performance hybrid fibre-reinforced concrete at elevated temperatures. *Sustainability*, Vol. 13, 2021, id. 13392.
[158] Mechanical Properties and Durability of Concrete with Water Cooled Copper Slag Aggregate | SpringerLink, (n.d.). https://link.springer.com/article/10.1007/s12649-016-9819-3 (accessed January 5, 2023).
[159] De Schepper, M., P. Verlé, I. Van Driessche, and N. De Belie. Use of secondary slags in completely recyclable concrete. *Journal of Materials in Civil Engineering*, Vol. 27, No. 5, 2015, id. 04014177.
[160] Ting, L., W. Qiang, and Z. Shiyu. Effects of ultra-fine ground granulated blast-furnace slag on initial setting time, fluidity and rheological properties of cement pastes. *Powder Technology*, Vol. 345, 2019, pp. 54–63.
[161] Tixier, R., R. Devaguptapu, and B. Mobasher. The effect of copper slag on the hydration and mechanical properties of cementitious mixtures. *Cement and Concrete Research*, Vol. 27, 1997, pp. 1569–1580.
[162] Moura, W. A., J. P. Gonçalves, and M. B. Lima. Copper slag waste as a supplementary cementing material to concrete. *Journal of Materials Science*, Vol. 42, No. 7, 2007, pp. 2226–2230.
[163] Wu, W., W. Zhang, and G. Ma. Mechanical properties of copper slag reinforced concrete under dynamic compression. *Construction and Building Materials*, Vol. 24, 2010, pp. 910–917.

[164] Chavan, R. R. and D. B.Kulkarni. Performance of copper slag on strength properties as partial replace of fine aggregate in concrete mix design. *International Journal of Advanced Engineering Research and Studies*, Vol. 2, No. 4, 2013, pp. 95–98.

[165] Patil. Performance of copper slag as sand replacement. - Google Scholar, (n.d.). https://scholar.google.com/scholar_lookup?title=Performance+of+copper+slag+as+sand+replacement+in+concrete&author=Patil, +M.&author=Patil, +Y.&author=Veshmawala, +G.R.&publication_year=2016&journal=Int.+J.+Appl.+Eng.+Res.&volume=11&pages=4349%E2%80%934353 (accessed January 5, 2023).

[166] Kumar, M. P. and Y. Mahesh. The behaviour of concrete by partial replacement of fine aggregate with copper slag and cement with GGBS - an experimental study. *Journal of Mechanical and Civil Engineering*, Vol. 12, No. 3, 2015 May, pp. 51–56.

[167] Raju, S. and B. Dharmar. Mechanical properties of concrete with copper slag and fly ash by DT and NDT. *Periodica Polytechnica Civil Engineering*, Vol. 60, 2016, pp. 313–322.

[168] Microstructural, mechanical, and electrical properties of copper slag admixtured cement mortar - ScienceDirect, (n.d.). https://www.sciencedirect.com/science/article/abs/pii/S2352710219301391 (accessed January 5, 2023).

[169] Zhang, S. P. and L. Zong. Evaluation of relationship between water absorption and durability of concrete materials. *Advances in Materials Science and Engineering*, Vol. 2014, 2014, id. e650373.

[170] Smyl, D., F. Ghasemzadeh, and M. Pour-Ghaz. Modeling water absorption in concrete and mortar with distributed damage. *Construction and Building Materials*, Vol. 125, 2016, pp. 438–449.

[171] Wu: An approach to the recent trends of concrete. - Google Scholar, (n.d.). https://scholar.google.com/scholar_lookup?title=An+approach+to+the+recent+trends+of+Concretescience+and+Technology&author=Wu, +Z.W.&publication_year=1979&journal=J.+Chin.+Ceram.+Soc.&volume=7&pages=262%E2%80%93270 (accessed January, 5 2023).

[172] Boakye: Durability and strength assessment of copper. - Google Scholar, (n.d.). https://scholar.google.com/scholar_lookup?title=Durability+and+Strength+Assessment+of+Copper+Slag+Concrete&author=Boakye, +D.M.&author=Uzoegbo, +H.&publication_year=2014 (accessed January 5, 2023).

[173] Berrocal, C. G., K. Lundgren, and I. Löfgren. Corrosion of steel bars embedded in fibre reinforced concrete under chloride attack: State of the art. *Cement and Concrete Research*, Vol. 80, 2016, pp. 69–85.

[174] Wang, D., X. Zhou, B. Fu, and L. Zhang. Chloride ion penetration resistance of concrete containing fly ash and silica fume against combined freezing-thawing and chloride attack. *Construction and Building Materials*, Vol. 169, 2018, pp. 740–747.

[175] A Review of the Engineering Properties of Metakaolin Based Concrete: Towards Combatting Chloride Attack in Coastal/Marine Structures, (n.d.). https://www.hindawi.com/journals/ace/2020/8880974/(accessed March 15, 2023).

[176] Fractal Fract | Free Full-Text | Mechanical Properties and Chloride Penetration Resistance of Copper Slag Aggregate Concrete, (n.d.). https://www.mdpi.com/2504-3110/6/8/427 (accessed January 5, 2023).

[177] Boakye: Assessment of concrete with pulverized copper. - Google Scholar, (n.d.). https://scholar.google.com/scholar_lookup? title = Assessment + of + concrete + with + pulverized + copper + slag + as + partial + replacement + of + cement&author = Boakye, + D.& author = Uzoegbo, + H.&publication_year = 2014&journal = Concr. + Beton&volume = 139&pages = 14%E2%80%9317 (accessed January 5, 2023).

[178] Zhou, Y. and W. Liu. Application of granulated copper slag in massive concrete under saline soil environment. *Construction and Building Materials*, Vol. 266, 2021, id. 121165.

[179] Properties of Cement Based Materials Containing Copper Tailings, (n.d.). http://i-rep.emu.edu.tr:8080/xmlui/handle/11129/333 (accessed January 5, 2023).

[180] Durability of Concrete in Marine Environment–A Review, (n.d.). https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/6343 (accessed January 5, 2023).

[181] Mohr, B. J., M. S. Islam, and J. France-Mensah. Leachate testing for delayed ettringite formation potential in cementitious systems. *Cement*, Vol. 12, 2023, id. 100060.

[182] Karahüseyin, S. and Ş. Erdoğdu. Evaluation of ground rhyolite and metakaolin in view of preventing delayed ettringite formation in the long term. *International Journal of Civil Engineering*, Vol. 21, 2023, pp. 251–264.

[183] Miyamoto, S., D. Naruse, K. Hayashi, H. Minagawa, and M. Hisada. Evaluating the strength development of mortar using clinker fine aggregate with a combination of fly ash and its inhibitory effects on alkali–silica reaction and delayed ettringite formation. *Journal of Material Cycles and Waste Management*, Vol. 25, 2023, pp. 816–825.

[184] Handayani, L., S. Aprilia, Abdullah, C. Rahmawati, T. B. Aulia, P. Ludvig, et al. Sodium silicate from rice husk ash and their effects as geopolymer cement. *Polymers*, Vol. 14, 2022, id. 2920.

[185] Maes, M. and N. De Belie. Resistance of concrete and mortar against combined attack of chloride and sodium sulphate. *Cement and Concrete Composites*, Vol. 53, 2014, pp. 59–72.

[186] Schmidt, T., B. Lothenbach, M. Romer, J. Neuenschwander, and K. Scrivener. Physical and microstructural aspects of sulfate attack on ordinary and limestone blended Portland cements. *Cement and Concrete Research*, Vol. 39, 2009, pp. 1111–1121.

[187] Gu, Y., P. Dangla, R. P. Martin, O. Omikrine Metalssi, T. Fen-Chong. Modeling the sulfate attack induced expansion of cementitious materials based on interface-controlled crystal growth mechanisms. *Cement and Concrete Research*, Vol. 152, 2022, id. 106676.