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Review

Mapping and synthesizing the viability of cement replacement materials via a systematic review and *meta*-analysis

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ABSTRACT

Supplementary cementitious materials (SCM) are alternative to the conventional cement and have been studied by so many authors owing to the high carbon content of cement. The use of SCM is significant in addressing challenges of carbon emission and its impact on the 2050 carbon reduction RoadMap. Available studies shows that SCM obtained from both industrial and agricultural wastes presents significant variability in performance as cement dosage in concrete increases. The first aim of this study is to map and synthesize the available evidence from literatures to support this variability. The second objective is to provide statistical evidence from available literatures of certain SCM that enhance the structural performance of low carbon concrete in terms of compressive strength. From the results, trend of findings from literatures on the use of SCM shows a surge in research for cement replacement occurring over the last decade with optimal performance for industrial waste SCM shown to be limiting at 40% cement replacement while that from agricultural waste occurs at 10% cement replacement. Data were sourced from Scopus database and selected from peer review journals of both primary and secondary studies on cement replacement materials. 728 published articles were obtained from the search using four strings namely,’Recent cement* replacement and cementitious materials’’, ‘’Recent supplementary cementitious materials’, ‘’Eco-friendly and cementitious materials’’ and ‘’Low carbon intensive cement replacement materials’. Meta-analysis is carried out on the selected articles having quantitative data to synthesise some of the result of the published articles to examine the impact of Ground granular base slag and Pulverized Fuel Ash cement on concrete strength development as cement replacement. It is shown that Ground granular base slag, Pulverized Fuel Ash and Metakaolin improve and enhance the eco friendliness of the concrete. From the results, optimal percentage of cement replacement is a gap which remains unresolved due to mineralogy and reactivity of the SCMs and would provide the solution for the desired green concrete optimization. It is shown with statistical evidence from *meta*-analysis that ground granular base slag and Pulverised fuel ash decreases the effect of low compressive strength by at least 2% to about 75% which is considered in our opinion as effective to enhance the sustainability of concrete.

1. Introduction

The negative impact of cement in concrete on the environment has aroused the need for an alternative solution by using SCM to produce low carbon concrete. Result from literatures indicates that the performance of low carbon concrete is influenced by the type of SCM materials used as well as the percent cement replacement. Guidelines and procedures on the dosage of SCM for effectiveness in low carbon concrete requires that careful selection of materials be carried out with the use of systematic reviews and *meta*-analysis. The efficacy of research interventions with the use of systematic reviews and *meta*-analysis to establish guidelines in clinical practice has been demonstrated in the health care [1]. The 2050 Roadmap developed by the international Energy Agency and World Business Council for Sustainable Development considered reduction in rise of global warming to 2 degrees through the reduction of carbon emissions. This implies that emissions from cement manufacture should be reduced by 2050 compared to its current level in view of global energy demand between 12 and 23%. To attain the 2050 target, the use of waste materials as SCM is emphasized

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Nomenclature

abbreviations

SCM	Supplementary cementitious materials
GGBS	Ground granular base slag.
PFA	Pulverised fuel ash
DOI	Digital object identifier
CaO	Calcium oxide
SiO_2	Silicon dioxide
SBA	Sugarcane bargasse
GGCS	Ground granular corex slag
CDW	Construction and demolition waste
CC	Calcined clay
TFT-LCD	Thin film transistor liquid crystal displayMHA
LS	Limestone
MSWIFA	Municipal solid waste incinerator fly ash
OPC	Ordinary portland cement
PL	Perlite
ZL	Zeolite
AWS	Agricultural waste SCMs
GP	Glass powder
FBC	Fluidized bed combustion fly ash
RHA	Rice husk ash
VFAS	Vitrified MSWIFA
EFCA	Expanded fly ash aggregate.
ASR	Alkali silica reaction
POFA	Palm oil fuel ash
CCA	Corn cob ash
RSA	Rice straw ash
Fe_2O_3	Iron oxide.
Al_2O_3	Aluminium Oxide
MnO	Manganese oxide
MHA	Millet husk ash
CO_2	Carbon dioxide
LCA	Life cycle analysis
ACR	Alkali carbonate reaction
PM	Pumice
IWS	Industrial waste SCMs
NOS	Naturally occurring SCMS.
VA	Volcanic ash
UEO	Used engine oil.

for low carbon concrete production [2,3]. In view of the role of concrete for the implementation of United Nation sustainable Development Goals (SDGs) for sustainable housing, there has been a surge in the interest of researchers for sustainable concrete which made it necessary for a thorough and careful application of evidence-based materials selection for cost effectiveness and sustainability [4,5]. These myriads of research are conducted across locations with different methods, materials and at some point, occurring at the same time which could induce repetition, bias, and lack of updated information on the status of an intervention. For this reason, other field of study encourages collaboration and synergy in the form of protocol registration. This is evident in the field of medicine with the Cochrane Collaboration and in social welfare, education, crime, and justice with the Campbell reviews [6,7]. Such collaboration is not seen in the areas of concrete research considering that concrete is the second most used materials after water [8] and its place in addressing vision 2050 target for zero carbon emissions [9], hence the need for systematic review and *meta*-analysis of cement replacement materials. Unfolding of a research gap in any field of research is based on the extent to which the previous boundaries of research can be expanded with a view to answer research question. This requires building a solid foundation on the discovered body of knowledge through literatures reviews of existing findings in comparison with similar contextual reviews. The reports often are influenced by bias and lack of empirical evidence. Most traditional literature reviews do not meet clear aims due to lack of evidence to support decisions validity, evidence-based knowledge, and reliability [10,11]. The Preferred Reporting Items for Systematic reviews and Meta Analyses (PRISMA) statement published in 2009 (hereafter referred to as PRISMA 2009 offers a guideline to mitigating inadequate reports from systematic reviews. Building on the success of PRISMA 2009 statement, new development using machine learning to acquire evidence and emerging sources of bias has necessitated an update to the PRISMA 2020 statement [12]. With the PRISMA protocol on systematic research, evidence-based reviews are conducted with inclusion and exclusion criteria and data (literatures) for reviews which include specific questions aims at focusing on the study while eliminating bias [13,14]. The description of careful steps to offer protectivity is expressed using systematic research with a research protocol to separate the researcher from influencing the outcome of the study. The success of PRISMA has recorded earlier application primarily in the field of medicine and other studies, therefore its extension to the *meta*-analyses of literatures on concrete cannot be over-emphasized. From the PRISMA 2020 statement, there is a strong suggestion for a structured background of studies and objective to be contained in the abstract. The inclusion of eligibility criteria, data extraction and sources are also provided in the methods while limitations and implication of key findings are confined to results and conclusions. A review protocol was developed based on PRISMA 2020 statement as a guide using information from the Search terms, databases, and screening criteria considering the aim of this review. Concrete is a widely used construction material after water, as a result it has attracted a plethora of research over the year [15]. Owing to the concern for low carbon concrete and with the awareness on anthropogenic carbon emission from construction materials and its devastating effect on the environment, using SCM in multiple combinations has increased the interest of many researchers. There is significant effort from literatures reporting on the progress made so far for the use of alternative materials to replace cement and aggregates but the extent of empirical evidence relative to efforts to address content and target objective are limited and scarce [16]. The potential of sustainable low concrete materials is seen in most recycled industrial waste and very recently the advent of the use of alkali-activated material described as geopolymer. The combinations and selection of mix proportion that abound in many literatures has posed certain questions of durability, structural performance, and sulphate resistance [17]. The future of low carbon concrete lies the chances of environmental safety and economy which is inherent in the choice and the ability of research to closing the research gaps that comes with these opportunities. Studies on low carbon concrete materials has attested to the veracity of certain materials amongst which are GGBS, silica fume, alkaline solution and lightweight aggregate [18–20].

1.1. Research gap

The use of cement replacement materials in concrete due to it high carbon footprint on the environment have been widely researched from previous studies. While previous studies did show the potentials of these materials regarding compressive strength enhancement, reduction of embodied carbon, economic as well as sustainable impact on the environment, the relationships and development of most recent new cement replacement materials and their sustainable effect on the environment remains unclear. Reports from previous studies demonstrated strong knowledge in this regard however a wholistic view of the trend in mechanical behaviour is still lacking. With the need to lower carbon emission from concrete, attentions of stakeholders and end users from the built environment has shifted to the views of the research community in making decisions. The replacement of cement in concrete with industrial and agricultural waste is faced with the challenges of the new materials exhibiting cementitious and pozzolanic properties based on their calcium oxide and silicon oxide composition. Studies has provided solutions in the form of geo-polymerization with the replacement of calcium oxide predominant in cement with aluminium oxide, but this is not without the challenges of non-availability of bulk deposit of waste aluminosilicates materials to meet the market demand [21], poor durability and alkali silica reaction [22]. For instance, review of SCMs using agricultural waste derived from Banana leaf, elephant grass, bamboo, wheat etc. was lacking in the systematic approach hence the results presented does not impact on their potential for use in concrete durability [23,24]. Owing to the chemical composition of ground granular base slag and pulverized fuel ash as cementitious materials and pozzolanic materials, there is significant reduction in embodied carbon when used as SCMs in concrete [25]. The combination of GGBS and PFA investigated by different authors at different location presents conclusions to suggest that optimal cement dosage occurs at 30% [26,27]. Other studies have shown increased performance at 40% [28] and 60% cement replacement [29]. This variability requires statistical evidence on their contribution to maximum compressive strength in low carbon concrete. Based on these finding from literatures, it is necessary to determine ***the contribution of GGBS and PFA to maximum compressive strength of low carbon concrete.***

1.2. Significance of the study

Over the years the use of industrial and agricultural waste has shown potency for cement replacement in concrete while available literatures do not provide sufficient data on the dosage of SCM in concrete that improves structural performance and sustainability demand. Owing to the need for reduction of carbon emissions, there is impending challenges on the supply chain of PFA because of shutting down of about 40% of coal factories in the US and that of the UK and Netherlands by 2030 culminating in the demand on other suitable SCMs [30]. The dependence on a particular SCMs also posed the challenges of deficiency in the needed cementitious composition which is supplemented with the combination of SCMs. For instance, GGBS having the needed chemistry of calcium silicate hydrate is latent with hydraulic and slow reactivity, PFA is subjected to high carbon content, Biomass having composition of silica is prone to high water demand and copper slag with the calcium silica showing low reactivity and metals leaching [31]. This suggests the need to updating the status of SCMs library from available literatures in terms of their performance when used in combination to aid characterization and test method. A viable library of SCMs showing product composites and their performance will reduce materials waste from trials mixes which will enhance cost effectiveness and sustainability in the construction industry through the reduction of embodied carbon in reduction, reusing and recycling of waste materials. This study therefore aims to equip concrete designers with a complete and transparent repository of knowledge in the selection of sustainable SCMs for the construction industry.

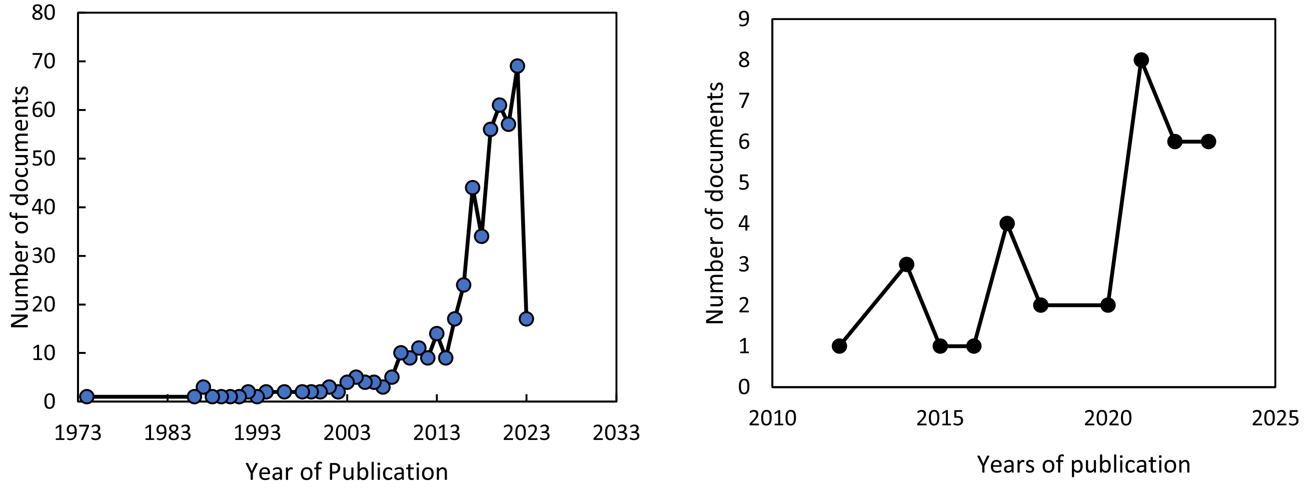
2. Methods

This study uses the method of systematic analysis of literature of 728 articles on recent replacement materials in concrete. The review protocol is based on the reporting checklist of PRISMA 2020 statement [12]. Research articles were extracted based on the Search terms, databases, and screening criteria. The key word used for the search is ‘’ Recent cement replacement materials in concrete’’. The repetition and occurrence of cement replacement materials across the study period and the authors affiliation were also considered. The articles extracted were considered for publications from 1974 to date on cement replacement materials in concrete and searched on Scopus. The choice of Scopus were based on the fact they are comprehensive and offer a higher abstracting and indexing in terms of materials science citation index, engineering index, research alert, science citation index expanded. The analysis method in this review and the inclusion criteria was developed based on the PRISMA protocol and applied on data obtained from Scopus search engine. The eligibility criteria are presented in Table 1. Four search queries were initiated in Scopus to widen the scope of search. The trend of the articles in Scopus for the search queries is as shown in Fig. 1. The target's location for the article from Scopus were abstract and keywords. The search for the literatures used in this study was last conducted on March 23rd, 2023, for queries 1 and 2. Additional search queries were conducted on March 25th, 2023, for search query 3 and 4 on Scopus and the types of published articles for searches 2, 3 and 4 are shown in Fig. 2, Fig. 3 and Fig. 4. The search strings and the number of articles selected are shown in Table 2. Key information obtained from the search on the published articles include title, year of publications, source title, affiliations, abstract, authors keyword, publisher, document type; and were exported to Microsoft Excel spreadsheet. Empirical and descriptive papers on cement replacement materials were considered for inclusion while others were discarded. The eligibility criteria for assessment were developed in excel using the IF Function in MS excel with a code 1 for inclusion and code 0 for exclusion for search of cement replacement materials in the abstract and keyword. Selection was based on concurrent appearance of cement replacement and concrete in either the abstract or the keyword. The study covered all published articles on cement replacement materials to some extent without prejudice to the methods, materials, results, conclusion, and locations the research work was carried out. The selected papers were found to report on either supplementary cementitious material in concrete or cement replacement materials in concrete. It was considered in our view that the validity of the findings from this study will be enhanced as a systematic review that is devoid of bias as two reviewers conducted the selections.

The data management of the selected samples for inclusion in the study was imputed in MS Excel spreadsheet based on the requirement of the PRISMA Protocol as shown in Table 3 and selected process as presented in Fig. 5 and Fig. 6. The PRISMA 2020 statement checklist which contained 27 items but was also adjusted to suit the requirement of the present study.

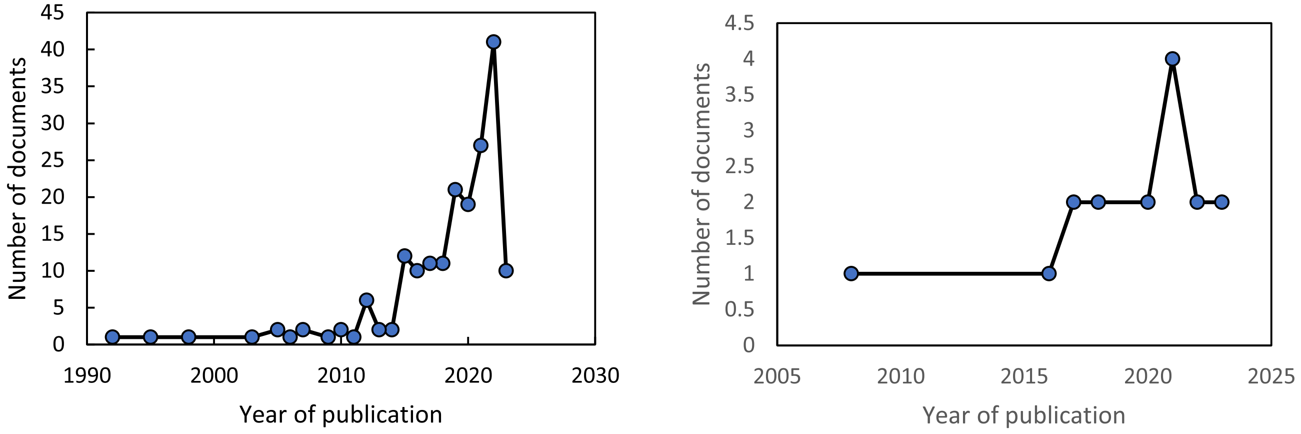
Table 1
Eligibility criteria for selection.

Criteria	Inclusion	Exclusion	Reasons
Materials	All SCM inclusion	Aggregate replacements are excluded	it is not included in the research question
Methods	All	No exclusion	All methods are need for the sample to be wholistic
DOI	All publications with DOI and ISBN were included	Papers without DOI were excluded	Papers with digital identifier has wider, coverage and acceptability
Impact of SCM on concrete	Mechanical properties on concrete included	Mechanical properties on soil excluded	The research question is limited to concrete
Paper quality	Empirical and descriptive papers were included	Qualitative papers were excluded	The research question requires quantitative measurement of the result obtained
Article type	All	No exclusion	All literatures are need for the sample to be wholistic



a: 1st search query between 1974-2023

b: 4th search query between 2008-2023



c: 2nd search query published between 1990-2023

d: 3rd search query between 2008-2023

Fig. 1. (a-d):Documents published (March 23rd, 2023, date of search on Scopus).

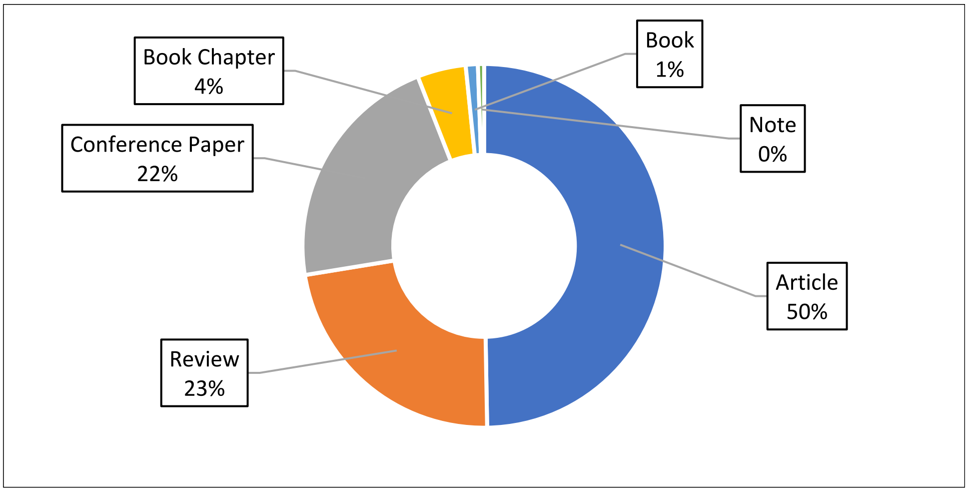


Fig. 2. Types of published documents for search query 2.

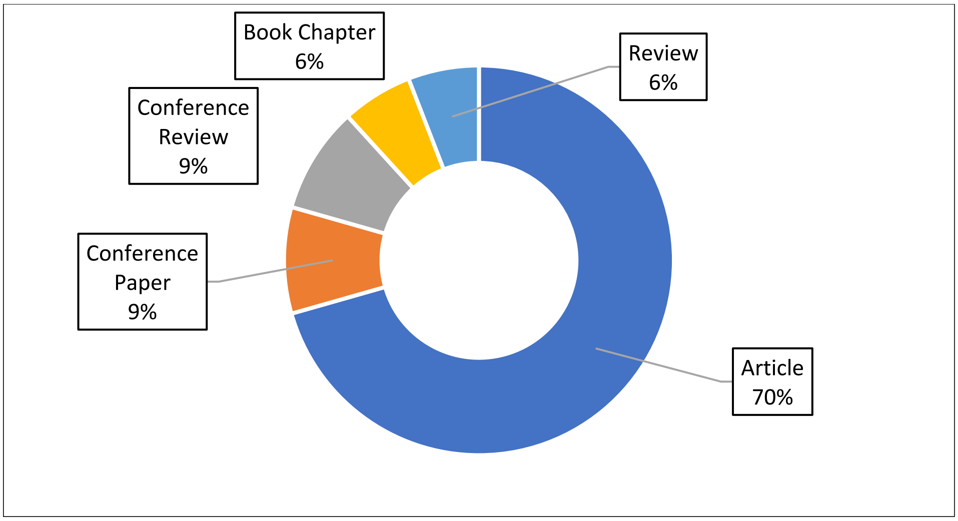


Fig. 3. Types of published documents for search query3.

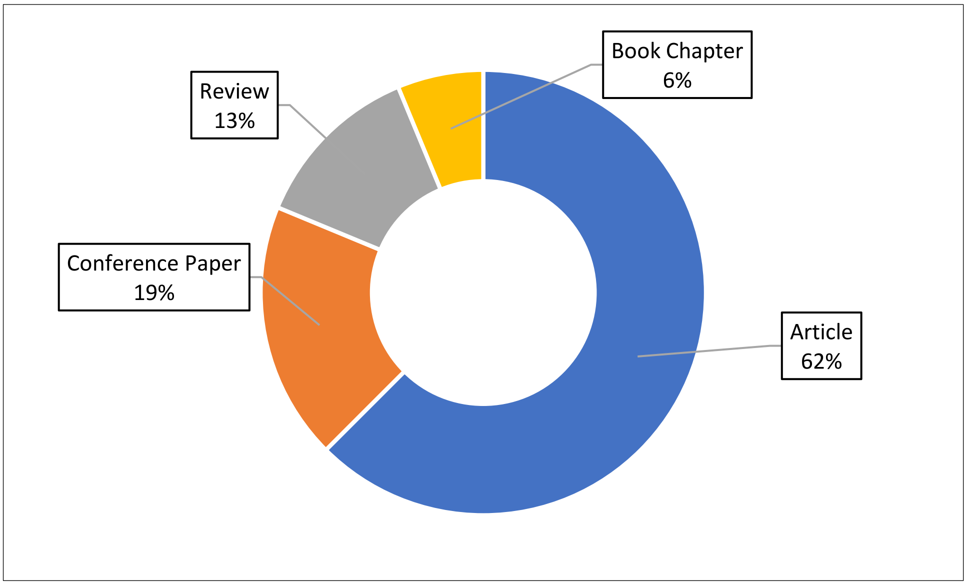


Fig. 4. Types of published documents for search query 4.

Table 2
Searches by keyword and document selection.

Searches by keyword	Scopus All fields	(Title-Abs-key)
''Recent cement* replacement and cementitious materials''	493	145
''Recent supplementary cementitious materials''	185	140
''Eco-friendly and cementitious materials''	34	23
''Low carbon intensive cement replacement materials''	16	11
Total		
Total without redundancies in the same database	242	
Total after title, abstract and keywords assessment	208	
Total after entire manuscript assessment	140	

3. Results

The initial search for this study was carried out on 728 published articles from the search engines and databases with 493 articles from the first search query, 185 articles from the second search query, 34 articles from the 3rd search query, and 16 articles from the 4th search query, all on Scopus. During the screening process of the first search query, Non-inclusion of the word cement, concrete, or replacement in the article authors keyword results to exclusion from which 388 articles were selected. The occurrence of SCM in the selected articles were carefully

Table 3
The Prisma 2020 Checlist.

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	Page 1
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	Page 1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	Page 3–5
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	Page 5
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	Table 1, page 7
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	Page 10
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Table 2, Page 13
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	Page 13
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	Page 7
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	Page 7
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	NA
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	Page 10
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	Page 11,13,38–45
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	Page 42
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	Page 38–39
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	Page 39
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If *meta*-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	Page 38
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, *meta*-regression).	Page 41–42
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	Page 39–40
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	Page 41
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	Page 41
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	Page 9, 11,
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	Page 5
Study characteristics	17	Cite each included study and present its characteristics.	Page 5, 20–26
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	Page 26
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimates and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	Page 28
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	Page 26
	20b	Present results of all statistical syntheses conducted. If *meta*-analysis was done, present for each the summary estimate and its precision (e.g., confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	Page 28
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	Page 26
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	Page 9, 11,
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	Page 5
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	Page 22–37
	23b	Discuss any limitations of the evidence included in the review.	
	23c	Discuss any limitations of the review processes used.	
	23d	Discuss implications of the results for practice, policy, and future research.	
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	NA
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	Page 4,6,7
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	NA

(*continued on next page*)

Table 3 (*continued*)

Section and Topic	Item #	Checklist item	Location where item is reported
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	NA
Declaration of Competing Interests	26	Declare any competing interests of review authors.	NA
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	

sorted and a selection of 145 articles was made with the weight of the SCM as presented in Table 2. Similarly, for the search query 2, Non-inclusion of the word cement, concrete, or supplementary materials in the article authors keyword result to articles exclusion from which 140 articles were selected. The occurrence of SCM in the selected articles were carefully sorted and a final selection of 92 articles was made with the weight of the SCM as shown in Table 2. The selected articles reported on 13 supplementary cementitious materials and the distribution of the articles is shown in Fig. 7 and the total articles for inclusion after screening for searches 3 and 4 were 34 articles and the distribution of articles types and categories is as presented in Fig. 8 while the trend of publication for the selected articles between 2005 and 2023 as presented in Fig. 9. Search 3 was examined on the content of articles abstract for the keyword 'cementitious and eco-friendly materials' as a condition for inclusion. 11 articles were removed that do not meet the criteria for inclusion and 23 was included. Article search 4 were subjected to careful examination and articles reporting on low carbon and supplementary cementitious were included for this review from which 5 articles were excluded and 11 included.

The repetition of articles on the selected articles from the results of search queries 1 and 2 were further examined and 29 articles were further excluded as it was found to appear on both selected articles of query 1 and 2, hence the final selected were 140 articles. The distribution of the articles between year of article publication and publishers after search through title, abstract and keywords are presented in Table 4. The distribution of SCMs that appears in the search and the percentage distribution of the selected articles is presented in Fig. 10. The selected articles were mapped into six domains for ease of reviews depending on the subject matter and shown in Fig. 11. From the mapping, there is high volume of research doing experimental testing on cement replacement materials while the least is low carbon green concrete which shows that the term green concrete is beginning to evolve in the search for cement replacement materials.

4. Co-Occurrence of Keywords, SCMs, and countries

The growing interest on the cement replacement materials has increase the volume of literatures available on the subject and the weight of their relevance in terms of structural performance and sustainability still very demanding. Mapping and visualization of keywords used in the search from Scopus database are illustrated using network for Co-Occurrence of SCMs to evidence the frequency of research using Vos viewer. The weight occurrence of each study is scored based on average yearly study and is shown in the bubble of Fig. 12. It is demonstrated that more studies have been carried out with the use of PFA and MK compared to that of GGBS. Not much studies have been done in the use of alcofine as SCM. The use of IWS like SBA, MHA RHA, Biomass and Date palm ashes is still attracting little attention from research even as the potency of replacing cement has been demonstrated. The blend of PFA and MK have been studied more frequently than that of PFA and GGBS. Also limited studies have investigated the use of gypsum and CDW with PFA.

The countries within which this research was undertaken cut across United Kingdom, United States of America, Turkey, India, Australia, Pakistan, Malaysia with significance dominance in the India, United States and Malaysia as shown in Fig. 13. Earlier studies initiated from the United Kingdom in 2016 as shown on the scale but was dominated from that from India from 2018 to 2020. Emerging of research for SCMs appears in Pakistan and Saudi Arabia within 2022.

5. Findings

Supplementary eco-friendly sustainable cementitious materials started appearing in literatures around 1998 from earlier studies works [32,33]. With the need for a better solution to mitigate the problems of high carbon concrete, there has been a transition for a better nomenclature from sustainable, supplementary, low carbon and now eco-friendly cement replacement materials. This is however bound to change as the solution to the concrete carbon discuss keep evolving. This review keeps to the view that all such transition in nomenclature implies same description of any materials that can replace cement in concrete at optimal performance without compromising sustainability and the environment. There is significant evidence from research findings over the past decades to support the viability of SCMs as a sustainable replacement material for cement in concrete, however other factors that can significantly affect the selection of effective cement replacement materials have not been widely explored.

From available research to our knowledge, we can conclude that this study is the first systematic review to consider and review literatures on cement replacement materials from the 1974 to date with consideration for factors that would impact positively on the choice of cement replacement materials for other researchers.

5.1. % cement replacement

There is deficiency in cementitious and pozzolanic properties of most SCMs hence to achieve the desired properties requires combinations of two or more materials for optimal results. Cementitious properties are activated with the availability of CaO while the pozzolans are mainly due to aluminium and SiO_2 composition. The potential of SCM combinations was tested with the blend of gypsum and PFA to 50% cement replacement in the work of Hansen and Sadeghian [34] with optimal result obtained for 5% gypsum without PFA (33.3 MPa) and 25% PFA without gypsum(34.6 MPa). The mineralogy of PFA shows a composition of CaO (24.5%), SiO_2 (35.2%) while that of gypsum is CaO (37.7%) and SiO_2 (4%) [35]. The exhibition of cementitious properties is activated with the composition of CaO while that of the pozzolanic properties is influenced by SiO_2[36]. With the cementitious and pozzolanic properties of SCMs predominantly depending on the chemical composition of CaO and SiO_2, the ratio of CaO/SiO_2 approaching 1 is noted in GGBS, PFA and Alco fine as shown in Table 5 which suggests their potentials of effective SCMs. Reduction in voids of geopolymer concrete was shown with increase in densification leading to improvement in mechanical properties when alcofine is blended with MK and GGBS [37]. Other SCMs materials due to the unbalanced pozzolanic and cementitious chemical composition, a blended of either as binary or ternary SCMs is necessary to supplement the needed deficiency of CaO and SiO_2.

It can be deduced from the result that CaO /SiO_2 ratio of less 1 enhances the mechanical properties of blended binary SCMs. From the chemical composition PFA shows a CaO /SiO_2 ratio of 0.69 while that of gypsum is 9.425. An improvement in the hydration of PFA was noted even as it was reported that the additions of gypsum to cement concrete is detrimental to early strength development. The mix exhibited a tendency of segregation but was mitigated with an increase in superplasticizer. A composition of EFCA in a blended aggregate also subjected to incineration at 900^0c as an aggregate replacement for a combined binder with PFA and 5% bottom ash binder yielded a high performance in comparison with the control [48]. The two binders are sourced from waste product of same industries but at different collecting points due to their density and mineralogy, however a decrease in strength was shown with more than 5% replacement. Concrete hydration contributes immensely to the development of strength as it defines the activities in the aggregate matrix zone which enhance water absorption capacity of the aggregate. As hydration contributes to strength, the tendency for aggregate with high water absorption is likely to demand for more water needed for formation of calcium silicate or aluminium silicate. Assessment of the physical properties of EFCA shows water absorption of 0.62% with the performance not exceeding 5% SCM replacement. Beyond the binder composition ratio, some SCM materials exists in different class with increase in performance induce by the water to cement ratio and the dosage of the superplasticiser. When cement was replaced with PFA between 60 and 80%, even when workability was improved with a low dosage, the improvement in flexural strength requires the additions of fiber [38]. Beyond the replacement of cement, there are recycled aggregate that possess cementitious properties and when used in concrete even as aggregate replacement, resulted to good performance. It brings to bear the impact of dual advantage in reducing the self-weight on the structure with positive effect on the embodied carbon through the reduction of reinforcement and positive reactivity of the aggregate thereby enhancing the cohesion of the aggregate matrix bond interface. From the study of Md Yunus [45], the combined effect of 20% metakaolin and glass powder blended with rubberized aggregate at 5 to 20% aggregate replacement improved concrete properties with optimal performance at 5% rubberized aggregate. This demonstrated the potential for the use of recycled waste as both aggregate and binder in concrete for a potential impact on sustainability as well as cost. Industrial waste from the high technology industries has not been left out in the search for a sustainable solution. The growing high-tech industries all over the world, comes with the challenges of waste especially TFT-LCD. The chemical analysis of the TFT-LCD indicates SiO_2 (62.3%), Al_2O_3 (17.2%), and CaO(7.5%) with more potential as pozzolans than cementitious materials as a cement replacement in concrete. In the work by Jang et al.,[44], Two types of TFT-LCD at (88 μm sieve pass) for A and (150 μm sieve pass) were used at 3, 5 and 10% cement replacement. The mechanical performance of the concrete was optimal with the type A at optimal replacement of 5% cement. The effect of ASR is significant owing to high content of SiO_2. ASR is a phenomenon responsible for the deleterious reaction of certain normal weight aggregate due to their mineralogy that affect concrete durability. The consideration of agricultural waste as potential SCM was examined in a review carried out by Pandey and Kumar [49]. Among the potential SCM identified are SBA, RHA, POFA and CCA. From the mineralogy analysis in comparison with that from industrial waste, the silica content of CCA was higher than that of GGBS. Chemical composition of POFA as presented in the review of literatures [50] indicates high silicon dioxide content and very low calcium oxide. This shows that POFA is more pozzolanic than cementitious hence its effectiveness for use as SCMs depend on a blend with high calcium oxide binder. Concrete tests show a reduced workability with the RHA and RSA sample while increase in compressive is noted with the blend of POFA and SBA samples. Certain SCM declined in performance when used alone due to lack complementary properties either as pozzolans or cementitious. The use of calcined kaolinite-based waste shows a poor performance when used as SCM to 10% replacement but was optimised with the addition of limestone powder and was shown to exhibit good performance between 30 and 50% cement replacement [51]. The study for up to 30% replacement with coal gangue and alkaline red mud was reported by Yi et al., [52] to aid thermal resistance and improvement in pozzolanic activities on the concrete. Regarding other use of industrial waste GGBS and PFA as SCM, the replacement of cement to 10% was optimal with good compressive strength while flexural strength was optimal at 12.5% replacement [53]. The use of CDW grinded in fine particles exhibited an increase in carbonation depth, Sorptivity, and chloride diffusion with an increase in percentage replacement with CDW, however a decrease in resistivity is shown with increase in CDW dosage [42,54]. The poor performance of the CDW is evident on its low chemical composition which neither qualities it as a pozzolans nor cementitious. However, the chemical composition of metakaolin at SiO_2(52.81%) higher than that of CEM11(19.77%) and GGBS (31.32%) presents the characteristic and potency for use as pozzolans. From previous studies, the use of metakaolin at 10 to 50% cement replacement was achieved where the influence of water was significant [42,55]. While the use of metakaolin shows optimal performance at 20% cement replacement at water to cement ratio (w/cm) of 0.4 using high superplasticizer compared to 20% cement replacement at w/cm of 0.6 at low superplasticizer.

5.2. % concrete geo polymerization

With the intention to achieve carbon emission reduction by 2050, the demands for Cements in concrete has not abated mainly due to the uncertainties surrounding available SCMs and the likely consequences of cement dependencies is eminent [56]. As the percentage of replacement increases, the negative impact on the mechanical performance become obvious owing to the depletion in calcium oxide. The use of geopolymer concrete offers the advantage of introducing aluminium silica, a compound whose good mechanical performance can be activated in an alkaline solution often made of sodium hydroxide and sodium silicate mixture optimal at different molarity. Due to poor strength development of PFA in a geopolymer concrete, the use of silica fume is found to improve compressive strength [57]. From the review of literatures for geopolymer concrete in the work of Albidah [58], the addition of silica fume to geopolymer concrete using PFA was detrimental to mechanical performance of the concrete but the addition of GGBS shows improved performance. Other limiting factors affecting the performance of geopolymer concrete include alkaline binder ratio(A/Bi) while the use of GGBS in geopolymer concrete was effective compared to the use of metakaolin at 0 to 50% cement replacement. This is evident from the X-Ray fluorescence test on both materials which indicate that in a geopolymer concrete, the percent composition of MnO, CaO Fe_2O_3 outweighs that of SiO_2, and Al_2O_3 in determining the performance [59,60] while higher concentration of alkaline solution has been suggested by Wongpa et al.,[61] to improve the performance of geopolymer concrete. The effect of sand binder ratio on a combination of agricultural waste and industrial waste have been studied by Alnahhal et al., [62] using PFA, GGBS, POFA, and bottom ash (BA). An increase in flexural strength was seen in the sample with GGBS while optimal compressive strength is associated with PFA sample. Understanding of the reactivity of the different element of the chemical composition of the SCMs is necessary for the microstructural characteristic of the geopolymer composites. A more reactive element may result to ions polarization as seen in the blend of RHA and PFA geopolymer concrete. High amount of silica and alumina were dissolved, and poor mechanical performance observed [63].

5.3. Experimental work

The experimental search for a sustainable binder material to replace cement has been stretched to a reasonable extent and the potentials in many materials are being unveiled. Durability is the simplest of test to assess concrete performance in fulfilment of the relevant exposure class. Experimental test for mechanical performance is often in the evaluation

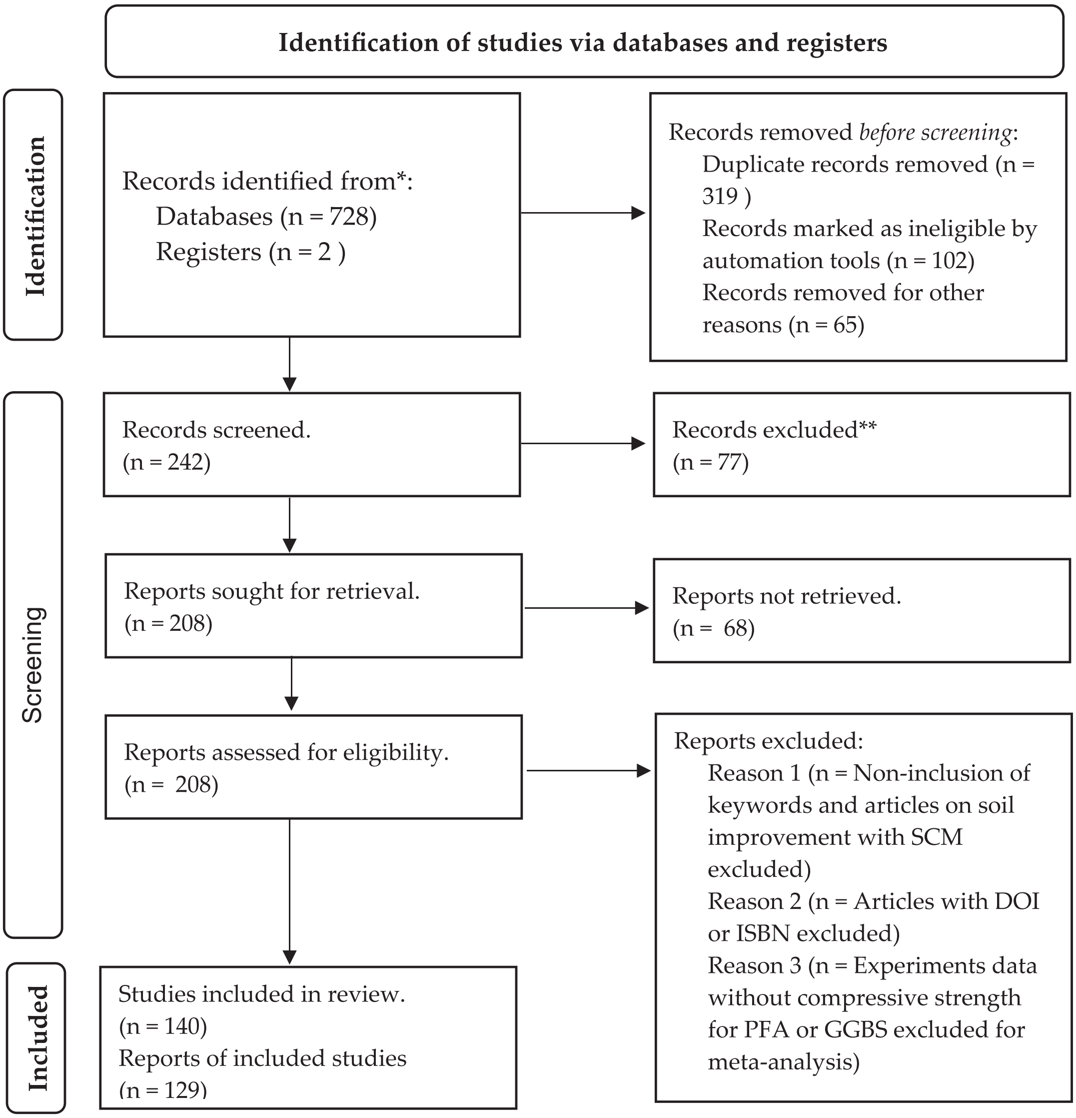


Fig. 5. The Prisma 2020 flow chart.

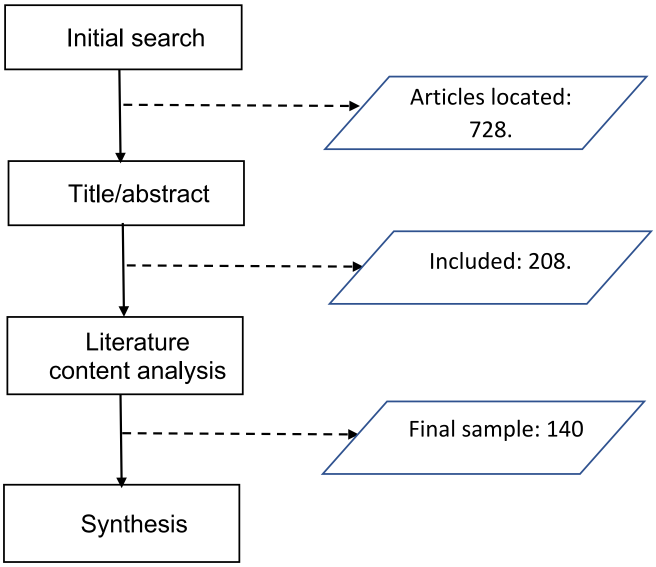


Fig. 6. Study selection process.

of compressive strength, flexural strength, split tensile strength while durability measures concrete deterioration in form of chemical attack, weathering actions, water resistance, chloride penetration [64]. Available SCM for use for the low carbon concrete faces the test of durability as a first pass. The effectiveness of GGBS to improve concrete durability is undoubted owing to its cementitious composition [65]. Other natural materials existing materials like the VA having high composition in SiO_2 (68.85%) and Al_2O_3 (11.43%) has been tested for the potency of cement replacement. High weight loss was evident on the decomposition of calcium hydroxide during water absorption test. The addition of water indicates limited reduction in compressive strength with potential for high strength at high temperature [66]. The study on agricultural waste using MHA blended with SBA and MK shows a reduction in workability and concrete density. Further test on the compressive strength result to optimal performance at 10% replacement [67]. With compressive strength enhanced by 17% replacement, further optimization could be indicative of an improved performance. When 10% dolomite powder (DP) combines with 20% GGBS, improvement in compressive strength was noted however loss in weight occurs. It can be deduced that most natural occurring SCMs like DP and VA neutralises calcium hydroxide on hydration with an activation of its reactive ability under alkaline environment due its high Iron oxide content. The existence of pores is found around the inter transition zone between the paste and the aggregate

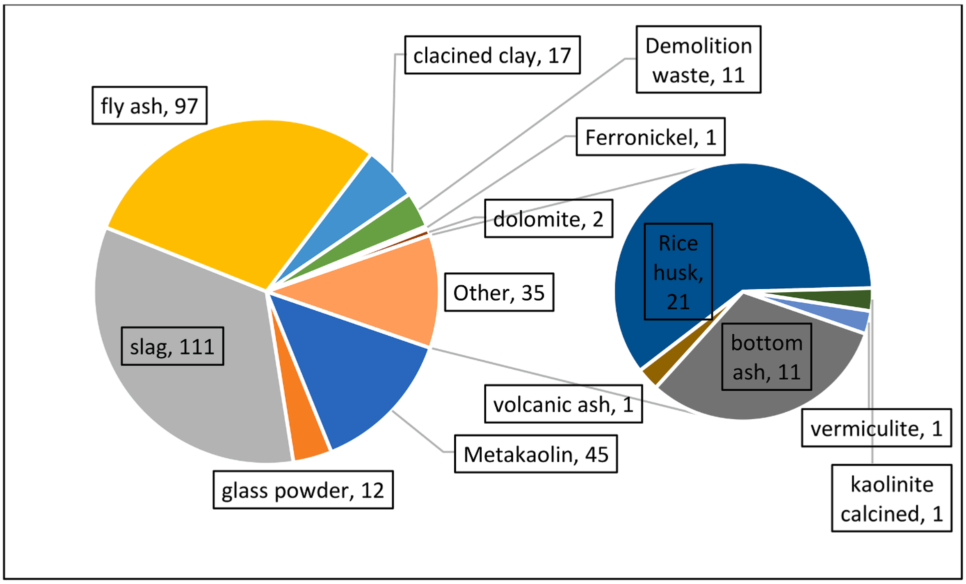


Fig. 7. Distribution of articles in the selected publication reporting on SCM from search 1 and 2.

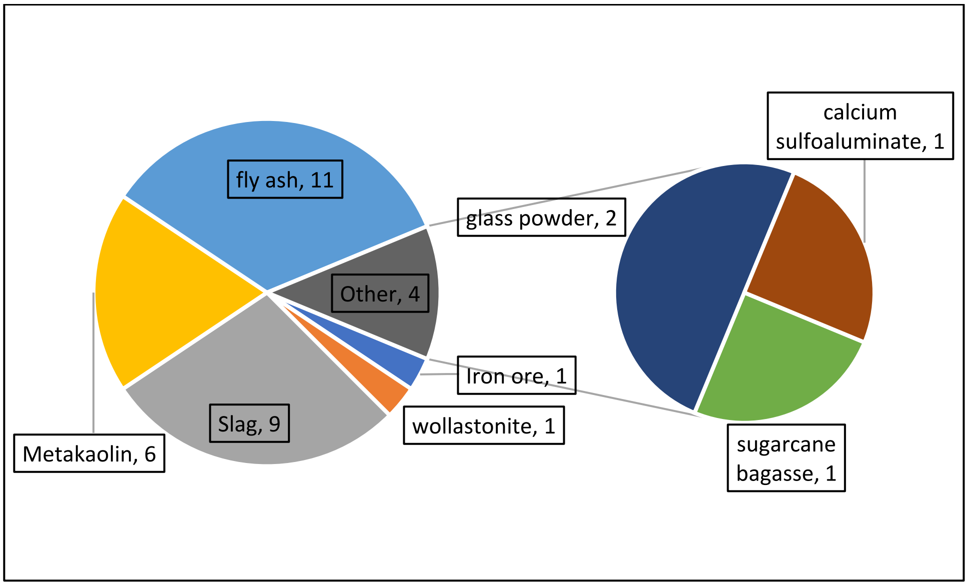


Fig. 8. Distribution of articles in the selected publication reporting on SCM from search 3 and 4.

creating the space for water to percolate into the aggregate hereby enhancing the need for more water, but very recently the use of alccofine as a cement replacement filled the pores and reduces concrete permeability [68] even as some specimen with low porosity yield high compressive strength [69].

5.4. Low carbon green concrete

The depletion of most raw materials has taken place from their natural deposit either in the form of aggregate sourcing or limestones in the production of cement. Reports available indicates the cements itself is responsible for about 900 kg of embodied carbon for every 1000 kg of cement produced which amount to 5% of global anthropogenic carbon dioxide emissions [70]. This brings to bear the non-sustainability of the construction industry if the target of replacing cement as a concrete binder is not met. A sustainable low carbon green concrete is one whose binder is not completely cement and the coarse aggregate replaced with lightweight from recycled waste. The issue of concrete cracking, sulphate attack, alkali silica reaction (ASR), reinforcement corrosion, thermal and drying shrinkage are all effects of poor durability which can be mitigated with the use of low carbon concrete. The use of glass for industrial and domestic use is predominant which has added to the huge generation of waste and has been exacerbated with impending threats for lack of effective recycling [71]. The depleting sources of natural aggregate (NA) promotes challenges to the environment through River sand and Quarries mining and is responsible for the environment degradation with unbalance biodiversity [72]. In a bid to enhance eco diversity and prevent further depletion, the use of recycled glass as a replacement for fine aggregate promotes the drives for a sustainable low carbon green concrete [73]. However, the works of Mansour et al., [74] presents the viability of glass aggregate to reducing ASR when used in combination with PFA, GGBS and silica fume. The potential of SCMs differ on the sustainability scale to offer low carbon concrete which is informed by their chemical composition. A study of most SCMs revealed

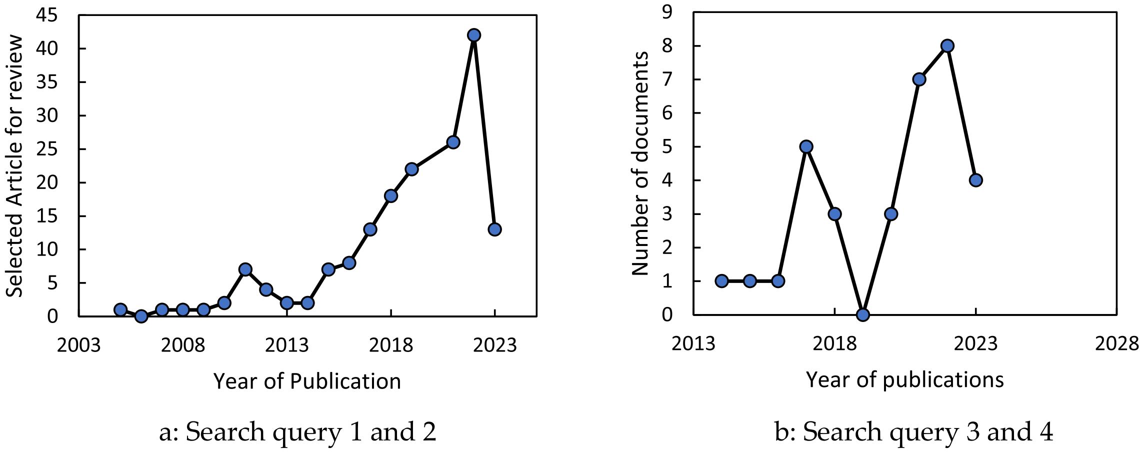


Fig. 9. (a-b): Trend of selected publication for review.

Table 4
Number of articles and publishers after Title, abstract and keywords assessment.

Publisher	2019–2023	2014–2018	2009–2013	2005–2009	Total
Elsevier Ltd	54	13	0	0	67
MDPI	9	0	0	0	9
SAGE Publications Inc.	1	1	0	0	2
Springer Science and BusinessMedia Deutschland GmbH	11	0	0	0	11
Springer Science and Business Media Deutschland GmbH	0	0	0	0	0
Penerbit UTHM	1				1
American Concrete Institute	4	0	0	0	4
International Conference on Durability of Concrete Structure	1	0	0	0	1
IOP Publishing Ltd	4	0	0	0	4
Cailiao Daobaoshe/ Materials Review	1	0	0	0	1
Horizon Research Publishing	1	0	0	0	1
Electrochemical Science Group	3	0	0	0	3
Horizon Research Publishing	1	0	0	0	1
King Saud University	1	0	0	0	1
MDPI AG	2	0	0	0	2
Techno-Press	1	0	0	0	1
Transstellar Journal Publications and Research Consultancy Private Limited (TJPRC)	1	0	0	0	1
SAGE Publications Ltd	1	0	0	0	1
ASTM International	0	1	1	0	2
IAEME Publication	0	4	2	0	6
Wiley-Blackwell	0	0	1	0	1
Thomas Telford Services Ltd	0	0	0	1	1
Institute for Research and Community Services, Institute Teknologi Bandung	0	0	1	1	2
Materials Research Society	0	0	1	0	1
Taylor and Francis Ltd.	1	0	0	0	1
Indian Society for Education and Environment	0	0	1	0	1
National Institute of Science Communication and Policy Research	1	0	0	0	1
fib. The International Federation for Structural Concrete	3	0	0	0	3
IOP Publishing Ltd	4	0	0	0	4
Springer	15	8	5	0	28
Trans Tech Publications Ltd	5	3			8
Associated Cement Companies Ltd.	1	2	0	0	3
EDP Sciences	1	1	0		2
Trans Tech Publications Ltd	5	3	0		8
Fundatia Serban Solacolu	1	0	0		1
Materials Research Society	0	0	1		1
American Society of Civil Engineers (ASCE)	2	2	1		5
Hindawi Limited	1	0	0		1
American Institute of Physics	4	4	0		8
Asian Regional Conference on Soil Mechanics and Geotechnical Engineering	1				1
Others	3				3
	145	42	14	2	203

that using life cycle analysis (LCA) adopts the performance of GGBS in achieving low carbon green concrete to 48% CO_2 reductions which is equivalent to cost saving of 16.28% [75]. This is owing to its chemical composition for SiO_2 and Al_2O_3 and presenting the potential for optimality at 60% cement replacement. Experimental studies as presented by Wang [76] using a blend of PFA and GGBS indicates that while PFA alone improves concrete chloride diffusion with enhancement of hydration phase leading to the reduction of unfavourable crystal phase, the addition of GGBS increases compressive strength. The compressive strength of PFA could only exceeds that of GGBS on additions of MK. When compared with PFA, GGBS exhibited low heat of hydration which is seen in low early strength development with high resistance to

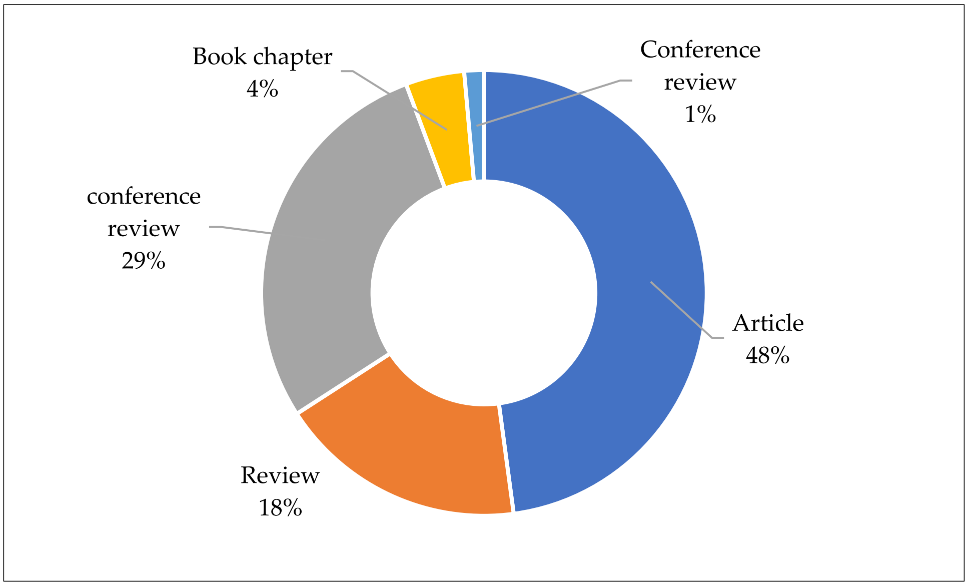


Fig. 10. Selected article types for review.

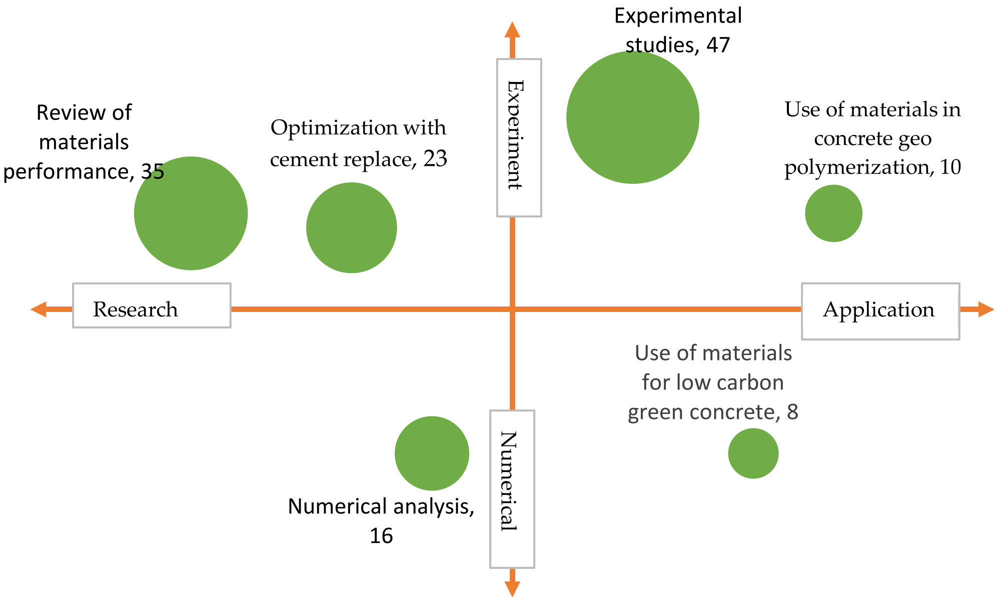


Fig. 11. Selected article domain mapping.

chemical corrosion. Regarding the issue of concrete deterioration, RHA shows high sulphate resistance at low water to cement ratio of 0.4–0.57 which is indicative of low deterioration, compared to the control specimen with silica fume [77]. Optimizing green concrete with other SCMs improves the deficiency inherent with an overriding performance on the concrete. This could be achieved by physical and chemical examination of their properties. Examining the effect of iron tailings from industrial mining waste, the results indicate a more finer iron tailing presents the possibility for use to produce low carbon concrete [78]. Grinding of the iron tailings reduces concrete porosity with good hydration activity.

5.5. Numerical results

Numerical models were used in simulating the characteristic of SCMs and the impact to influence the formation of low carbon concrete examined. Creating these models is necessary considering the power of artificial intelligence and machine learning that has been deployed in virtually all fields of human endeavour which further eliminates bias inherent in human decision. Chloride diffusivity of concrete at different levels of GGBS replacement using the probabilistic assessment model was carried out by Attari, McNally and Richardson [79]. Results indicates there is reduction in the effect of chemical corrosion with GGBS at low cement replacement, however disparity becomes significant at high percent GGBS replacement. This underscores the credibility of GGBS to addressing the durability questions in low carbon concrete. Notwithstanding the mix proportions of concrete, the workability conditions and environment also influences its desired outcome and can impede and distort the chemical compositions without effective numerical simulations. Another method used in model predictions is the Taguchi approach. This model uses a systematic analysis with flow charts on concrete data sets of concrete samples and analyse results with statistical tools of ANOVA. In consideration of statistical parameters on dataset containing basaltic PM, barite, GGBS and colemanite. Results indicates that GGBS and Colemanite were the most effective SCMs with

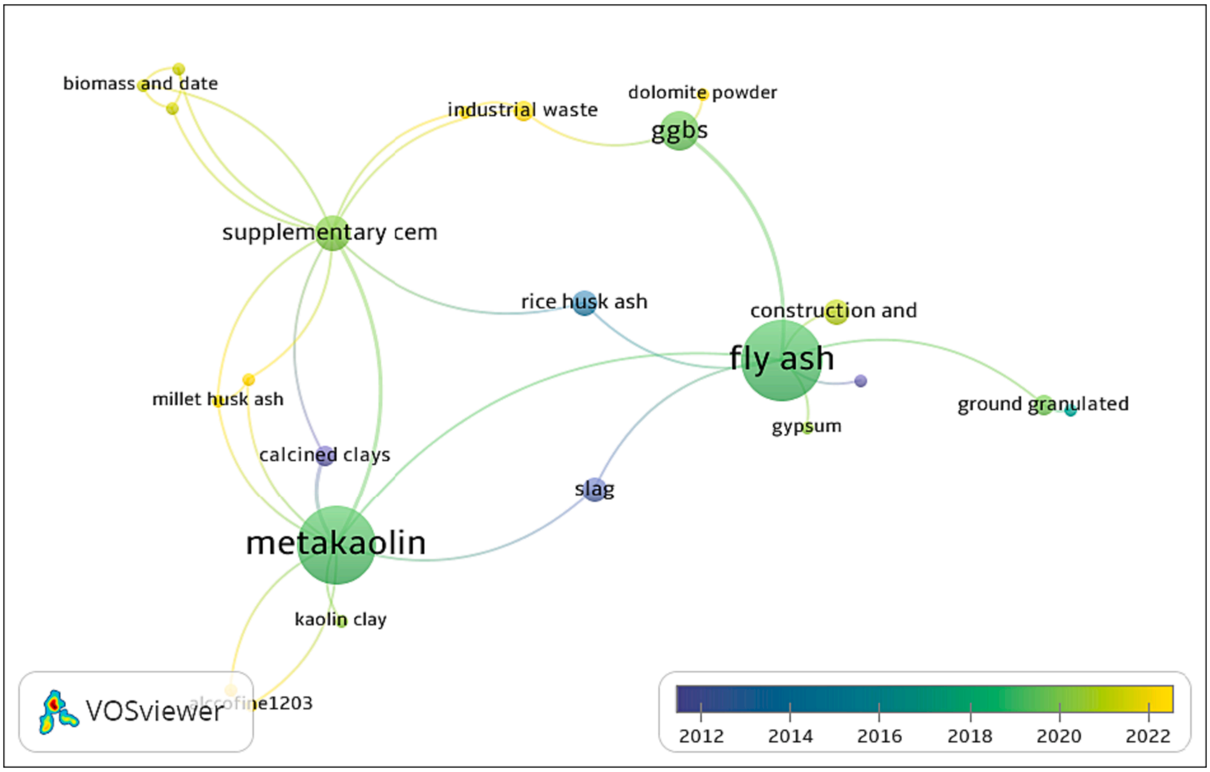


Fig. 12. Co-occurrence network of keywords and SCM presented in selected articles (from 2012 to 2022).

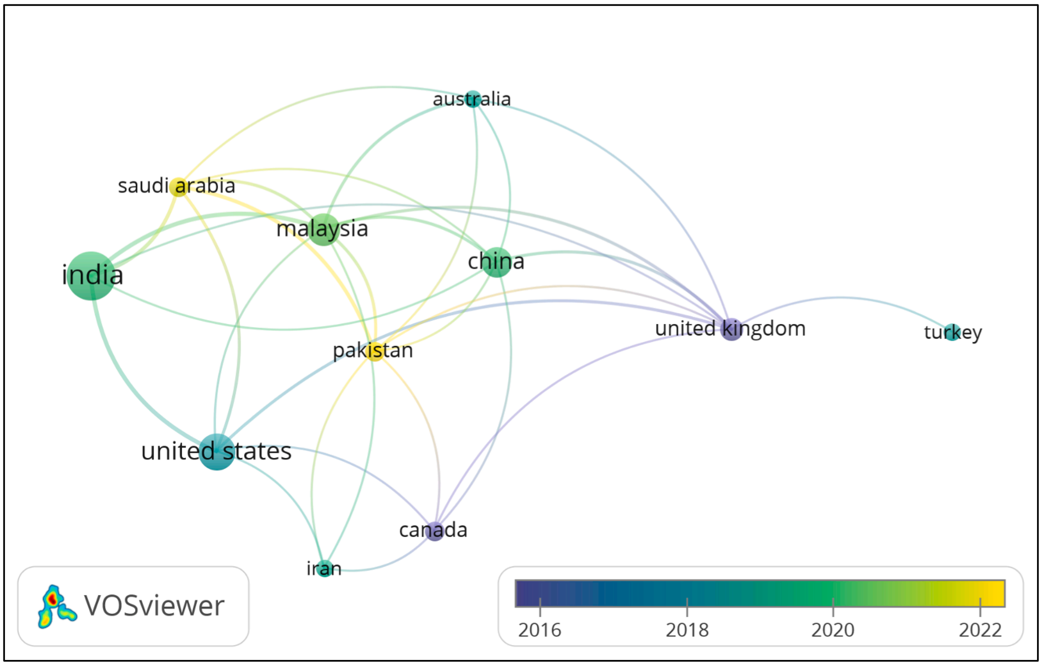


Fig. 13. Co-occurrence network of Countries presented in selected articles (from 2016 to 2022).

capillary water absorption. Hence the contributions of the two SCMs could significantly affect the mechanical performance of a low carbon concrete. Considering the impact of agricultural waste on low carbon concrete, Life cycle analysis (LCA) conducted on the viability RHA and PFA, shows the potential of cement replacement up to 30% enhance significant benefits on carbon emission, durability, and mechanical performance [80].

The advent of geopolymer concrete on low carbon concrete has shown wide acceptance from the literatures due to its ability to enhance low carbon concrete ang good structural matrix. On analysing the effectiveness of PFA and GGBS blended using statistical model on a geopolymer concrete, variables such as alkaline binder ratio were significant factor that influence the geopolymer concrete performance. Statistical prediction shows that optimal binder ratio for Na_2SiO_3-to-NaOH in alkaline solution ranges between 1.5 and 2.5 [81]. Concrete structures accommodate facilities from other engineering services such

Table 5
Chemical compositions of cementitious and pozzolanic properties of SCMs.

Mix	SCMs blend	CaO	SiO_2	CaO/SiO_2 ratio	% cement replacement	Compressive strength, Mpa	Reference
FG-FA-C	Gypsum	32.05	3.80	8.43	10	28.5	[34]
	PFA	1.44	59.39	0.024	15	28.4	
	Cement	39.88	19.54	2.041	20	25	
TM1	PFA	3.08	61.18	0.050	50	50.19	[38]
TM5	PFA	3.08	61.18	0.050	60	38.17	
VFAS-GGBS-PFA	MSWIFA	42.10	3.33	12.642			
	GGBS	33.76	44.84	0.75	30	58	
	VFAS	32.4	52.8	0.61	10	55	[39]
	Cement	62.51	19.57	3.194	0	58	
	PFA	11.88	43.16	0.275	30	73	
	CC	0.03	54.74	0.000548	10	70	
PCL	LS	53.47	0.55	97.218	20	87	[40]
	Cement	63.53	19.98	3.179	0	82	
GGBS-PFA -Silica fume-Zeolite	PFA	11.12	58.58	0.189	35	30	
	Silica fume	0.66	91.64	0.00720	7	42.5	
	GGBS	36	37.22	0.96	45	30	
	Cement	62.95	20.74	3.035	0	30	[41]
	ZL	3.61	69.78	0.051	15	33	
Mek-GGCS	MK	0.02	52.81	0.000378	15	81.2	[42]
	GGCS	35.15	31.32	1.122	50	61	
CDW		9.62	69.75	0.13	10	45	[43]
	CDW	9.62	69.75	0.13	5	52	
TFT-LCD	TFT-LCD	7.50	62.30	0.120	10	30	[44]
MEK-glass powder	MK	0	52	0	20	34.27	[45]
	GP	10.45	72.08	0.14	5	38.51	
MEK-GGBS-Alcofine	Alcofine	32.10	35.31	0.90	15	35	
	GGBS	33.70	31.24	1.078	50	35	[37]
	MK	0.27	50.10	0.00538	35	32	
SBA-UPHC		2.52	62.44	0.040	20	119.7	
		2.52	62.44	0.040	40	114.8	
	SBA	2.52	62.44	0.040	60	101.9	[46]
Expanded PL	Perlite	0.5	76.2	0.0065	20	52	[47]
	POFA						

as mechanical and electrical engineering. This service includes component connections, conduiting, instrumentation and others. It becomes necessary that electrical conductivity of the concrete become resistant to avoid impending danger of shock and possible harm on users. Using the technique of electrical resistivity (ER), an appraisal on the binder replacement was conducted on GGBS and PFA, at varying percentage of cement replacement for binder ratio for which the optimal result was significant at 70% GGBS and 50% PFA [82]. In the study by Hafez *et al.*, [83], reliable sustainability measure was determined for functional performance based on economic and environment properties of blended SCMs for low carbon concrete mix using inventory for PFA, GGBS, Silica fume, CC, Ordinary Portland cement (OPC). It was found that while the cost of the materials can be reduced to 70%, there is the likelihood for a 30% reduced impact on the environment. The developed algorithms optimize the mix proportions regardless of the SCMs and the percent cement replacement. A similar interest in concrete 3D printing for the construction industry has presented the potential results through simulation of rheological properties for low carbon concrete mix proportioning [84]. Investigation into the time dependent yield stress calcined clay and limestone at 62.5% cement replacement using 3D printing was demonstrated. Mechanical properties of the sample shows a high compressive strength for the CC sample compared to that of LS [85]. Testing indicates no blocking nozzle, a phenomenon that is attributed to 3D printing poor performance of concrete.

5.6. Reviews

SCMs have evolved over the decades such that the choice of potential materials as cement replacement is based on chloride penetration, sulfate resistance, carbonation, drying shrinkage, corrosion resistance, pozzolanic and morphological effects [86]. The need for standard test for most emerging new materials is necessary at this point. Emerging materials are evolving and showing contingent behaviour on response to reactivity, microstructural development, and durability due to lack of available standard to characterise their design [31,87]. Literature reviews conducted on SCMS revealed reactivity of these materials informs the choice of mix proportion. Reviews has shown that the choice of PFA for instance is based low heat of hydration, improved resistance to reinforcement corrosion [88], better resistance to ASR [89] and reduced carbon footprint [90]. Research on the performance of PFA shows that reactivity can be admixed to improve its potentials especially with the use of nanotechnology. This is in view of the low heat of hydration which enhance the properties of nano-PFA and culminating to sustainable construction [91]. The explorations and mitigations of some limitations on SCMs are necessary to benchmark their potential for mix proportioning. Using PFA has shown reduced water demand which enhances workability, however due to low heat of hydration, development of compressive strength at early is poor [92,93]. The blending of SCMs shows comparative advantage because the deficiency in one can be complemented in the other. While GGBS shows decrease in slump value, PFA exhibited improvement for concrete chloride penetration [87]. PFA and GGBS has been described and classified as eco-friendly [94,95] because of low carbon emission. Although blending both poses some negative effect. The use of nano silica due to its fineness have been shown to filled pores created in the emerging low carbon green concrete for which combination with Metakaolin is found to have yield good performance due to its pozzolanic characteristic [96,97]. Owing to low heat of hydration associated with most SCMs, it has been suggested that activation of their latent pozzolanic characteristics with the use of geopolymer is needed for optimal performance [98].

CC is often used as MK due to their pozzolanic activities and has shown good improvement in altering the pore structure of concrete when used as partial replacement through the diffusions of harmful ions [33]. With the optimization of SCMs from literatures as shown in Table 6, a decline in mechanical performance is accompanied with increase in the dosage of cement replacement. The optimal performance of

AWS is limited to 10–20% while that of IWS is 60–80% cement dosage. From Table 6, there are potentials in both industrial and agricultural waste materials for use as cement replacement. Some of available AWS include SBA, ground raw vermiculite, RHA, MHA, POFA, CCA, while that of IWS include GGBS, PFA, MK, GO, Microsilica, Silicomanganese slag, CCA, Low calcium bentonite, GP, Copper slag, Trass, Methylcellulose. Other natural existing materials include PM, PL, ZL, limestone filter, and CC. For most AWS materials, the percent cement replacement is limited to 10% while that of the IWS have extended to 60% with concerns for durability for some cases. When fibres are added to AWS, replacement can be extended to 20% with remarkable improvement in strength. It is also shown that the low heat of hydration for both GGBS and PFA can be mitigated if activated in alkaline environment. Most SCMs that impact positively on rebar corrosion are CC, while ASR are reduced with use of metakaolin, PFA, glass powder, and GGBS with a blend of SCMs after careful examination of their chemical and physical properties results in performance improvement. AWS shows a good improvement in improving concrete durability while IWS enhances the concrete performance in terms of compressive strength and flexural strength.

Available SCMs from literatures are characterized into IWS, AWS and NOS depending on their source and are presented in Fig. 14 as pozzolanic, cementitious and effective SCM. The characteries of effective SCM is based on a balance composition of CaO and SiO_2 for which the CaO/SiO_2 ratio approaches 1. Nearly all AWS can be described as pozzolanic while GGBS, PFA and Alco fine appears to be effective in terms of its CaO/SiO_2 ratio. Mapping of SCMs shows that most of the SCM are pozzolanic while the NOS are cementitious. A sustainable SCM therefore is suggested to present a balance chemical composition in terms of CaO and SiO_2.

5.7. Meta analysis

Several studies on the impact of PFA and GGBS to enhancing the compressive strength of low carbon concrete has shown optimal cement dosage at 30, 40 and 60%% [26–28] with a suggestion to be describe as sustainable SCMs from their chemical composition. Improving the compressive strength remain a concern due to the issue of low heat of hydration which has significantly impacted on early strength development. It is necessary therefore to determine using *meta*-regression if the addition of GGBS and PFA to produce low carbon concrete is making positive impact on the maximum compressive strength. The magnitude of the treatment is expressed in effect size which provides an outcome on how statistical result can be interpreted and combined. The effect size considered in this study is the risk ratio (RR). The precision of the effect size is reported with 95% confidence interval for a range of upper and lower bounds. With a combination of the results of sample, a more accurate result to determine the treatment effect is possible. Based on the research question, the size effect is calculated for each study by considering maximum compressive strength of sample and total compressive strength for each study when GGBS and PFA is used in concrete as a cement replacement. This is referred to as the treatment effect. Another consideration was when OPC was used, and this was referred to as the control effect.

For instance, considering the study by Hansen and Sadeghian [34], the maximum compressive strength for the treatment effect is 34.6 MPa. The total compressive strength for all samples in the treatment effect is 234 MPa. The maximum compressive strength for the control effect is 43.2 MPa. the total compressive strength for all samples in the control effect is 158.4 MPa.

$$RR = \frac{A_1}{B_1}, \tag{1}$$

$$RR = \frac{0.1478}{0.2727} = 0.5422$$

The confidence interval (CI) was calculated using the relation from Hespanhol et al [125] as

$$CI = log_e(RR) \pm \sqrt[z]{\frac{(n_l - x_1)/x_1}{n_1}} + \sqrt[z]{\frac{(n_2 - x_2)/x_2}{n_2}} \tag{2}$$

Where n_l is the total compressive strength for the treatment effect (234 MPa), x_1 is the maximum compressive strength of the treatment effect (34.6 MPa), n_2 is the total compressive strength of the control effect (158.4 MPa) and x_2 is the maximum compressive strength of the control effect (43.2 MPa). z is the normal distribution value at 95% confidence which is 1.96.

The upper confidence interval,

$$CI_{upper} = EXP(log_e(RR) + \sqrt[z]{\frac{(n_l - x_1)/x_1}{n_1}} + \sqrt[z]{\frac{(n_2 - x_2)/x_2}{n_2}}) \tag{3}$$

while.

The lower confidence interval,

$$CI_{lower} = EXP(log_e(RR) - \sqrt[z]{\frac{(n_l - x_1)/x_1}{n_1}} + \sqrt[z]{\frac{(n_2 - x_2)/x_2}{n_2}}) \tag{4}$$

In putting the values, CI_{upper}= 0.808, CI_{lower} = 0.363.

The variance in the risk ratio, Var RR is calculated.

$$VAR_{RR} = \frac{1}{A_1} + \frac{1}{B_1} + \frac{1}{C_1} + \frac{1}{D_1} \tag{5}$$

$$VAR_{RR} = \frac{1}{A_1} + \frac{1}{B_1} + \frac{1}{C_1} + \frac{1}{D_1} = \frac{1}{34.6} + \frac{1}{234} + \frac{1}{43.2} + \frac{1}{158.4} = 0.0626$$

Using same approach, the size effect and confidence interval for all the study are presented in Table 7.

5.7.1. Meta regression coefficient

The desire synthesis level of a mega regression is to fit a confidence interval around the slope based how effective the absolute latitude predicts effect sizes. The study of the efficacy of ground granular base slag and pulverized Fly Ash on maximum compressive strength of low carbon was conducted using data set from 13 literatures. Regression coefficient for bivariate covariant as derived from previous studies [137,138] is presented in Equation 6–10 and used for this study. It has been shown that the vector regression coefficient matrix can be expressed as an inverse of the variance–covariance weighted [139–141].

$$\beta = \left[X^T w^{-1} X\right]^{-1} X^T w^{-1} Y \tag{6}$$

$$V = \left[X^T w^{-1} x\right]^{-1} \tag{7}$$

$$P = w^{-1} - w^{-1} X V X^T w^{-1} \tag{8}$$

$$Qt = Y^T P Y \tag{9}$$

$$\tau^2 = max\left[0, \frac{Qt - k - m}{trace(P)}\right] \tag{10}$$

Beta β is the meta regression coefficient. X is the design matrix, P is the Probability of the control effect, V is the variance covariance of the regression coefficient used to estimate the confidence interval of the regression coefficient, W is the variance covariant matrix which is also a weighting matrix, k is the degree of freedom of the effect size number and Y is the effect size matrix.

5.7.2. Forest plot

The result and summary of the findings from *meta*-analysis are visually presented using the forest plot using a combination of the effect sizes and confidence intervals for the studies. This enhances the understanding of the variability measure using the test of heterogeneity.

Table 6
Summary of cement replacement dosage and their impact.

Focus	SCM used	Result	Mechanical properties optimized	Key papers	Gap
Development of eco-friendly SCM	SBA	20% cement replacement was optimal, 20–60% replacement decreased concrete properties by increased porosity	Flexural (19/19.3) and compressive strength (119.7/114.6 MPa)).	[46]	% Replacement for optimality not significant
	ground raw vermiculite	5–10% cement replacement was optimal	Flexural strength range b/w 8.52–7.28 compared to fly ash of 8.48–7.91 MPa	[99]	Impact on carbon not measured
Carbon fibre reinforced concrete tested for concrete mix of silica fume and methyl-cellulose	methylcellulose and silica fume	Decrease in compressive strength with no impact in the flexural strength		[100]	
Water glass cement used in combination with nano clay	Hybrid combination of Nano clay with water glass powder	Cement replacement was feasible at 20% nano clay and 5–50% water glass powder	No significant effect of alkali silica reaction (ASR).	[101]	The compressive strength development between 7 and 28 days is less the 10%.
Concrete specimen was mix in combination with superplasticizer while thermal conductivity test and SEM was performed	off-white RHA	Cement replacement to 15% is feasible	Reduction in the concrete porosity and increase in compressive and split tensile strength noted.	[102]	
Chemical analysis of GGBS	GGBS	Blaine test shows the surface area of GGBS to be 870 m^2/kg compared to cement 360 m^2/kg while chloride migration coefficient was determined	Chloride penetration was reduced	[103]	
GGBS, MK, and PFA mixed at different combination as self-compacting concrete	GGBS, MK PFA	GGBS demand more water without affecting concrete mechanical properties.	Modulus of elasticity enhanced with MK and GGBS combined	[104]	SCC of PFA were lower at all combination
Trass and fly ash combined at different to determine the effect of Alkali carbonate reaction (ACR)	Trass, PFA	Chemical analysis shows Trass higher SiO_2(60.5%) compare to PFA (57.65%), however, CaO were (6.75%) for Trass and (2.32%) for PFA	Hybrid of combination of trass and PFA were optimal at 20% cement replacement	[105]	Trass did not reduce ACR compared to PFA.
Vacuum mixing of concrete to remove air content	Copper slag	Reduction of embodied carbon was significant	Coper slag effective at 20% cement replacement	[106]	
Use of agro- based waste materials as a SCM	RHA	Analysis shows an increased in the poison ratio of the concrete to 0.4 with inverse correlation with concrete	10% Cement replacement was feasible at compressive of 22.8 compared to control of 36.1mpa	[107]	Strength development to 10% replacement not significant
Mechanical properties investigate as a cement replacement	Low calcium bentonite	Split tensile test was marginally low sample tested	Compressive strength optimal at 15% replacement bentonite	[108]	Use of recycle aggregate was found to reduce the density of concrete
Optimization of RHA	RHA	Addition of steel fibre improves the properties of the concrete.	Compressive strength optimal at 20% replacement	[109]	
SBA, MK, and MHA as a blend for SCM	SCBA, MK, MHA	There was reduction in concrete density and permeability	Compressive strength optimal at 7% of SCBA, 7% of MK, and 7% of MHA	[67]	The percentage replacement is not significant
60% replacement of cement on different combination with Limestone filter, RHA, MK	RHA, MK, LF	Additional hydrated lime did not improve mechanical properties	MK, RHA increased the viscosity of SCC	[110,111]	15–60% reduction in compressive strength was noted
Optimization of coal bottom ash (CBA).	CBA	Pozzolanic index achieved with a blend of CBA	The workability of 25% blended CBA was equivalent to 50% that of GGBS	[112]	Impact on compressive strength not significant
Potential of silicomanganese slag as SCM	silicomanganese slag	Hydraulic index of 1.2 was obtained	Compressive strength is 10% lower than the control	[113]	Mechanical loss occurs at 20–30% replacement
Strength of Mgo-activated GGBS	GGBS	Mgo GBBS paste induces high me	Mgo indicates a good activator of GGBS at 10% optimum	[114]	
Compatibility between natural SCM and new SCM	PL, PM, and ZL.	Air entrant agent impact positively of SCM	Same rheological properties with air entrant concrete were noted	[115]	
Optimization of UEO with superplasticizer as SCM	UEO	% Cement replacement limited to 0.5%	Consumption of consumption of portlandite was enhanced which support eco-friendly solution	[116]	The impact of mechanical properties was limited
Industrial waste as alkaline activator of concrete	GGBS	Low carbon concrete was achieved at 25 MPa	Compressive strength lower that NaOH activated concrete	[117]	
Advantage of MK over micro silica	MK, Microsilica	10% replacement with micro silica optimal	Flexural of MK is greater than Micro silica	[118]	Compressive strength not reported

(*continued on next page*)

Table 6 (*continued*)

Focus	SCM used	Result	Mechanical properties optimized	Key papers	Gap
20% PFA for all mixes combine with copper slag	Cupper, PFA	Compressive strength improves by 40% with decrease in water demand	Cupper slag replacement improves density and elastic modulus	[119]	
20% PFA for all mixes combine with graphene	PFA, silica fume and graphene oxide		lower resistivity and chloride penetrability was noted	[120]	Graphene and fly ash resulted to lower compressive strength at 28 days
Combining recycled gysum, PFA	Recycled gypsum, PFA	Gypsum expands in concrete		[34]	About 5% gypsum decreases workability and dehydrated concrete
80% flysh in concrete	bottom ash, fly ash	50% fly ash resulted to good strength and poor slump and v-funnel	Good compressive strength noted	[38]	Poor flexural strength
5% bottom ash, fly ash		Compressive strength improved		[48]	
60% GGBS	GGBS	Studies conducted on pavement structure	60% replacement with GGBS, results was optimal	[75]	
30% optimal	MSWIFA	MSWIFA at 30% replacement combines with PFA produce good compressive strength		[39]	
5% glass powder	MK, GP	5% glass powder at 90 curing optimal	Combing MK and glass powder improve concrete strength	[45]	
CC with LS	CC, LS	High compressive strength	Low corrosion value on reinforcement	[40]	
20% replacement with PFA with 0.5% basalt fibre	PFA		Basalt fibre increased tensile strength by 37%	[121]	
45% GGBS, 35% Fly ash, 15% zeolite	GGBS, PFA	High durability and compressive strength	Concrete water absorption and chloride penetration reduced by 37 and 74%	[41]	
20% replacement with FBC	Fluidized PFA	High compressive strength	Chloride penetration resistance and reduction in Ph of concrete pore solution	[122]	High water demand and low workability
20% metakaolin replacement and GGBS replacement to 50%	MK		61% ASR was reduced by 10% MK	[42]	Carbonation for GGBS sample increased with low workability
10% Korean MK replacement	Korean MK, silica fume	40% liquified plasticizer used	Good compressive strength	[123]	Low workability with MK sample
10% construction and CDW	CDW		High carbonation depth	[42]	Loss in compressive strength
12.5% GGBS replacement	GGBS	10% GGBS replacement was optimal	Good compressive strength	[53]	
20% calcined clay CC, replacement	CC	20% CC was optimal		[51]	
Overview of agricultural waste as SCM	RHA, RSA, CCA, POFA, and SBA		GGBS was found to be cementitious with high CaO	[49]	RHA and RSA reduce slump and workability
		High compressive strength	Water glass reduce ASR	[44]	Workability reduced
GGBS activated with Alcofine		High compressive strength	40% increase in compress strength, 14% flexural strength, 84% split tensile	[36]	
SCM on geopolymer	GGBS, PFA,MK		GGBS improve mechanical properties of geopolymer concrete	[58]	
Combination of GGBS with MK in geopolymer concrete	GGBS, MK	50% Replacement optimal	Compressive strength increases with high molarity solution	[59]	
Overview of GGBS and fly in geopolymer	GGBS, PFA		Tensile and compressive strength increases	[60]	Workability decreases as Molarity increases
Potassium activated geopolymer	PFA,	Tensile and compressive strength increases	Higher casing to cement bond	[124]	

The numerical value of the treatment effect is included with an assumption for either a fixed, random effect model, a line of no effect, and an overall treatment effect. The overall treatment effect is calculated as a summation of the product of the risk ratio of each study and the upper and lower bound of the standard deviation obtained from the random effect coefficient calculation. The upper and lower bound of the standard deviation are presented in Table 12 and the overall size effect in Table 8 for the fixed effect model and the forest plot in Fig. 9.

5.7.3. *Absolute latitude*

Bubble plot is used as a visualization of the weight of study as function of the location represented by the absolute latitude for which study was carried out in determining the efficacy of the treatment. The absolute latitude is obtained from the location for which the experiment was carried out as presented in Table 9. The farther the location from the equator, the more efficacious is the treatment effect.

The bubble plot is plotted using data presented in Table 10.Table 11..

Bubble is the visualization of the weight of the study expressed as a function of the variance of the risk ratio.

$$Bubble = \frac{1}{sqrt(VarRR)}$$

The data computed for the bubble plot is presented in Table 7 and the bubble plot is as shown in Fig. 15.

From the result of the fixed effect model considering the impact of individual studies, the combined effect size shows a RR of 0.254. This is an indication that GGBS and PFA can reduce the risk of low compressive strength when used as SCM by 74.6%. However, using a meta regression random effect model, the risk ratio is 0.495 occurring with a confidence interval of 0.25 to 0.98. This shows that there is a mean effect by using

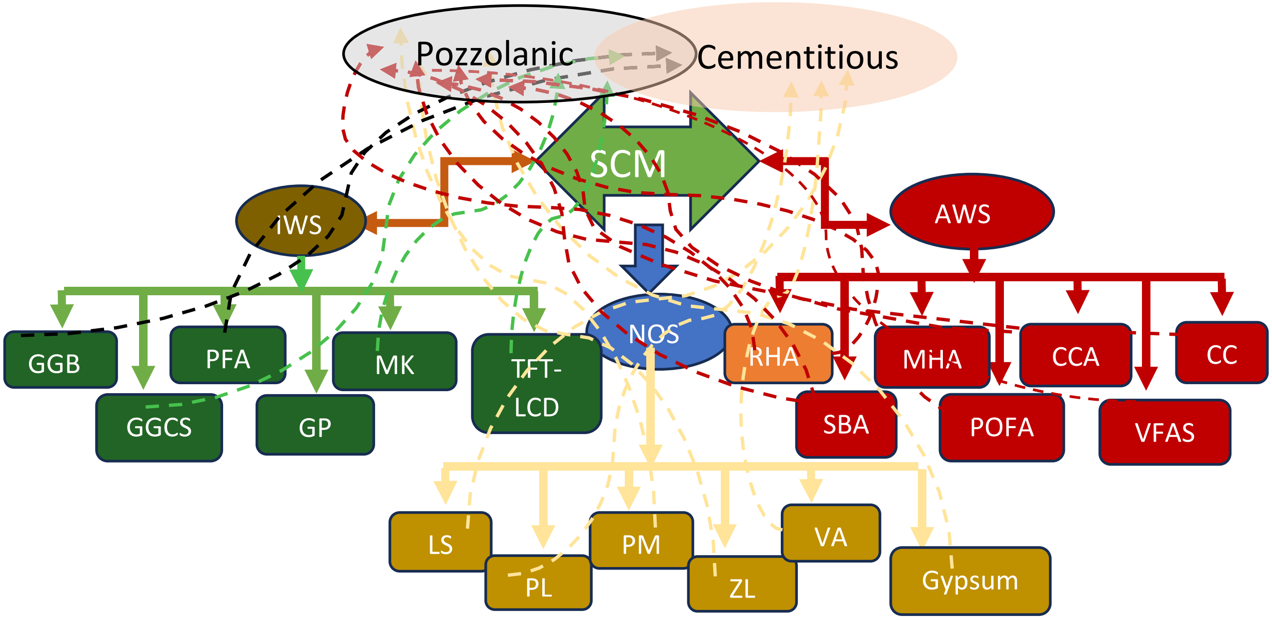


Fig. 14. Mapping of SCMs based on pozzolanic and cementitious characteristics.

Table 7
Data from study intervention.

Study	Treatment		Control							
	Max. compressive strength, MPa (A)	Total (B)	Max. Compressive strength, MPA (C)	Total (D)	A/B = E	C/D = F	Risk ratio, RR (G)	Loge (RR) H	CI $_{Lower}$ (K)	EXP (CI $_{Upper)}$ (L)
[34]	34.6	234	43.2	158.4	0.147	0.272	0.542	−0.612	−1.011	0.363
[126]	58	293	54	152	0.197	0.355	0.557	−0.584	−0.899	0.406
[40]	35	121	45	105	0.289	0.428	0.674	−0.393	−0.749	0.472
[127]	48.4	826.4	40.4	207.6	0.058	0.194	0.300	−1.2008	−1.589	0.203
[128]	81	1436	98	751	0.056	0.130	0.432	−0.838	−1.119	0.32644
[129]	79.6	466.3	32.9	60.6	0.170	0.542	0.314	−1.156	−1.462	0.231
[130]	47.75	103.8	32.15	59.51	0.460	0.540	0.851	−0.160	−0.474	0.622
[131]	31.7	222.1	25.8	56.8	0.142	0.454	0.314	−1.157	−1.587	0.204
[132]	21.76	181.57	23.04	65.01	0.119	0.354	0.338	−1.084	−1.597	0.202
[133]	76.2	545.4	72.2	200.7	0.139	0.359	0.388	−0.945	−1.224	0.294
[134]	46.2	414.1	43.2	86.4	0.111	0.5	0.223	−1.499	−1.843	0.158
[135]	28.9	71.5	31.3	48.4	0.404	0.646	0.625	−0.469	−0.820	0.440
[136]	68	148	43	80	0.459	0.537	0.854	−0.156	−0.424	0.653

PFA and GGBS in decreasing the effect of low compressive strength by at least 2% to about 75% as presented in the forest plot of Fig. 16. The meta regression yields a z-value of -2.0011 ($P > 0.001$) as shown in Table 13 with a RR of -0.704 in the log unit which suggest that the Null hypothesis of GGBS and PFA contributing to maximum compressive strength of concrete when used as SCM be accepted. The location co-ordinate of each study represents the bubble in Fig. 15 with the magnitude equivalent of the study weight. The equator is represented with the line of null effect exhibiting a risk ratio of 1 (ie exp(0)) which suggest that any study carried out near the equator will not have any significant impact on compressive strength using GGBS and PFA. From the bubble plot of Fig. 15 study conducted in Turkey [127] on Latitude 41.11^0 with a RR of 0.3 and that of [134] in Australia on Latitude 39.920 with a RR of 0.22 are far from the equator and will have a significant effect on the maximum compressive strength of concrete when GGBS and PFA are used as SCM. However, that of Wang et al [130] which is carried out in China on Latitude 23.0330 with a risk ratio of 0.85 and Xie et al [136] conducted in Abu Dhabi on latitude 24.523 with a RR of 0.854 is likely not to have a significant impact as their latitude is close to the equator. The proportion of variance can be expressed by 95% confidence interval using the relation.

Table 8
Overall size effect treatment.

Study	Risk ratio, RR	SD(0.0067) *RR
[34]	0.542	0.003
[126]	0.557	0.003
[40]	0.674	0.004
[127]	0.30	0.002
[128]	0.432	0.002
[129]	0.314	0.002
[130]	0.851	0.005
[131]	0.314	0.002
[132]	0.338	0.002
[133]	0.388	0.002
[134]	0.223	0.001
[135]	0.625	0.004
[136]	0.854	0.005
Total		**0.254**

SD = Standard deviation of the latitude for fixed effect model.

$$CI_L = L_a + 1{\cdot}96s_E$$

$$CI_u = L_a - 1{\cdot}96s_E$$

Where CI_L = lower confidence interval,

Table 9
Absolute latitude for study.

Study	Absolute Latitude	Location/affiliation
[34]	44.637	Dalhousie University, Halifax, Canada
[126]	22.306	The Hong Kong Polytechnic University, Kung Hom, Kowloon, Hong Kong
[40]	35.722	Iran University of Technology, Tehran
[127]	41.11	Istanbul Technical University, Maslak, Turkey
[128]	24.365	Abu Dhabi University, United Arab Emirates
[129]	23.033	Guangdong University of technology, China
[130]	23.033	Guangdong University of technology, China
[131]	12.82	Institute of Science and Technology, Kattankulathur, Tamil Nadu, India
[132]	10.903	Amrita School of Engineering, Amrita University, India
[133]	40	Tsinghua University, China
[134]	39.92	University of Adelaide, SA, Australia
[135]	35.693	University of Tehran, Tehran, Iran
[136]	24.523	New York University, Abu Dhabi

CI_u = Upper confidence interval,
L_a = point estimate of the latitude.
s_E = standard error of the latitude.
The time variance is estimated to be between −0.025 to 0.019.

6. Conclusion

The widespread use of agricultural and industrial waste as cement replacement materials has affirmed the viability of emerging alternative cement materials for which potentials can be sustainable and durable. The desire for low carbon concrete evident due to its impact on the environment requires a compressive search owing to the fact the performance of cement in concrete has stand the test of time meeting all set criteria of performance except that of sustainability. Due to the huge demand on sustainable low carbon concrete, the mere performance of concrete in terms of compressive strength is no longer a sufficient metrics to measure its performance hence it has been supplemented using recycle industrial and agricultural waste to account for eco friendliness, economy, and sustainability.

- Mechanical properties of SCMs from industrial waste from same source as shown in the combination of gypsum and PFA exhibit poor performance due to variability in density and mineralogy. The chemical composition of PFA at CaO (24.5%) compared to gypsum at CaO (37.7%) and SiO2(35.2%) for PFA while that of gypsum (4%) presents more of a cementitious material than the latter from which its mechanical strength is based. As the cementitious properties of SCMs is dependent on high CaO composition and pozzolanic nature exhibited with more of SiO_2. The ratio of CaO/SiO for PFA is 0.69 and that of gypsum is 9.425. The performance of the concrete with a blend of PFA and gypsum resulted to performance owing to high CaO/SiO_2 ratio which culminated to its poor cementitious composition.
- SCMs sourced from industrial waste shows optimal mechanical performance to 40% cement replacement while that sourced from agricultural waste is limited to 10% cement replacement.
- Analysis of the chemical composition of SCMs indicates that alcofine, GGBS and PFA possess cementitious and pozzolanic properties with their CaO/SiO_2 ratio approaching 1 while other SCMs will need to be supplemented with either a binary or ternary blend to attain effective use.
- Chemical compositions of most agricultural waste like POFA indicates that they are more pozzolanic than cementitious with a high composition of silicon dioxide, hence the effectiveness of their use as SCMs depend on a suitable blend with SCMs having high composition of calcium or aluminium oxide.
- The existence of pores is found around the inter transition zone between the paste and the aggregate of concrete with alternative cementitious materials creating the space for water to percolate into the aggregate hereby enhancing the need for more water.

Table 11
Study Size effect.

Sample study	Risk ratio, RR	Loge (RR)	Var RR	Absolute latitude	Bubble	Null
[34]	0.542	−0.612	0.062	44.637	3.995	0
[126]	0.557	−0.584	0.045	22.306	4.675	0
[40]	0.674	−0.393	0.068	35.722	3.818	0
[127]	0.300	−1.200	0.051	41.11	4.409	0
[128]	0.432	−0.838	0.024	24.365	6.378	0
[129]	0.314	−1.156	0.061	23.033	4.028	0
[130]	0.851	−0.160	0.078	23.033	3.569	0
[131]	0.314	−1.157	0.09	12.82	3.289	0
[132]	0.338	−1.084	0.110	10.903	3.011	0
[133]	0.388	−0.945	0.033	40	5.440	0
[134]	0.223	−1.499	0.058	39.92	4.124	0
[135]	0.542	−0.612	0.101	35.693	3.143	0
[136]	0.557	−0.584	0.057	24.523	4.180	0

Table 12
Bubble plot Parameter.

Design Matrix		Null line	Bubble size	Predictor	, SD	LCI	UCI
1	10	0	5	−0.733	0.061	−1.219	−0.247
1	20	0	5	−0.764	0.024	−1.073	−0.454
1	30	0	5	−0.794	0.013	−1.022	−0.567
1	40	0	5	−0.825	0.027	−1.148	−0.503
1	50	0	5	−0.856	0.065	−1.359	−0.353
1	10	0	5	−0.733	0.061	−1.2196	−0.247

Table 10
Data Set for Meta analysis.

	Measured PFA/GGBS	Total	Control Without	Total	RR	Ln RR	v_{LnRR}	Latitude
[34]	34.6	234	43.2	158.4	0.542	−0.612	0.062	44.637
[126]	58	293	54	152	0.557	−0.584	0.045	22.306
[40]	35	121	45	105	0.674	−0.393	0.068	35.722
[127]	48.4	826.4	40.4	207.6	0.300	−1.200	0.051	41.11
[128]	81	1436	98	751	0.432	−0.838	0.024	24.365
[129]	79.6	466.3	32.9	60.6	0.314	−1.156	0.061	23.033
[130]	47.75	103.8	32.15	59.51	0.851	−0.160	0.078	23.033
[131]	31.7	222.1	25.8	56.8	0.314	−1.157	0.092	12.82
[132]	21.76	181.57	23.04	65.01	0.338	−1.084	0.110	10.903
[133]	76.2	545.4	72.2	200.7	0.388	−0.945	0.033	40
[134]	46.2	414.1	43.2	86.4	0.223	−1.499	0.058	39.92
[135]	28.9	71.5	31.3	48.4	0.625	−0.469	0.101	35.693
[136]	68	148	43	80	0.854	−0.156	0.057	24.523

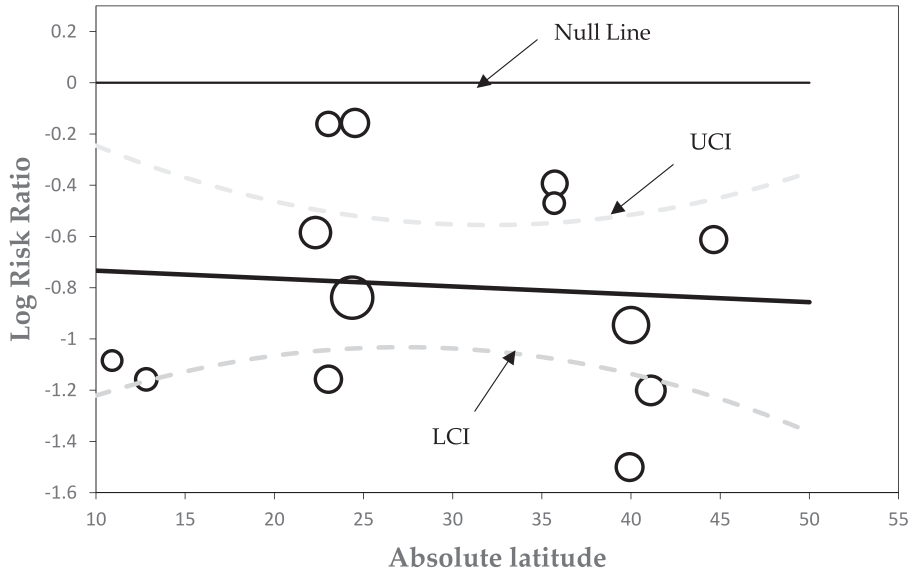


Fig. 15. Bubble plot.

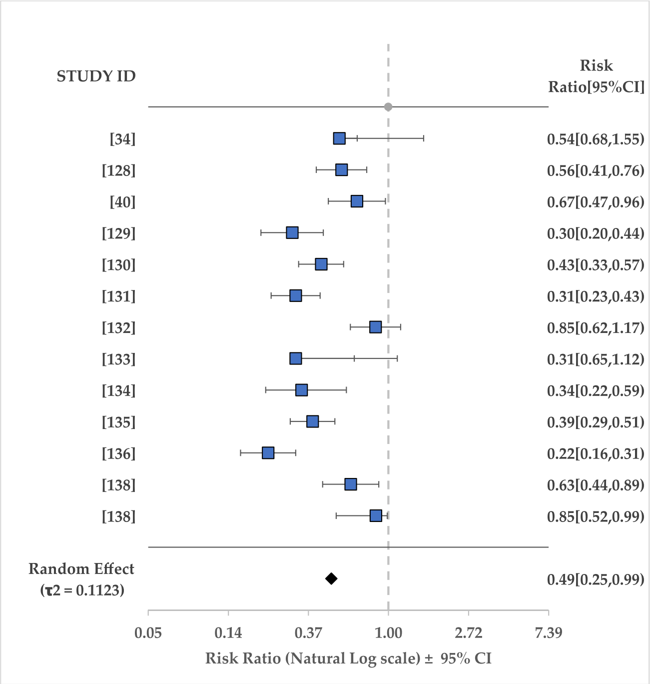


Fig. 16. Meta-analysis of available studies the impact of % cement replacement on compressive strength. Relative risk estimates (effect size [ES], 95% confidence interval [CI], (P value for publication bias = 0.045).

Table 13
Random-effect model – Regression result.

Random effect, Z-Distribution	Point estimate	Standard error	95% Lower	95% Upper	Z value	P value
Intercept	**−0.703**	0.351	−1.390	−0.014	−2.001	0.045
Latitude	**−0.003**	0.011	−0.025	0.018	−0.274	0.783

- The use of Alcofine shows to be effective in the reduction of concrete voids when used in geopolymer concrete which presents increase densification leading to improvement in mechanical properties when blended with metakaolin and GGBS.
- It was shown that ground granular base slag and Pulverised fuel ash can reduce the risk of poor compressive strength by at least 2% to 75%.
- There is a high risk with a RR of 0.85 for poor performance from experimental work carried out within latitude 23–24^0 using GGBS and PFA to improve the compressive strength of concrete compared to the probability of good performance with a RR of 0.23 when similar studies is carried out within latitude 39–41^0.
- Chemical compositions of SCM sourced from agricultural waste indicates that they are more pozzolanic than cementitious hence their blends with SCMs sourced from industrial waste provides a sustainable use.
- Pozzolanic activities of SCMs provide viable solutions to durability in terms of ASR and chloride sulphate action while cementitious activities exhibit structural performance.

Recommendations and future directions.

- From the results of the review, the following areas are recommended for future directions.

1. The mechanical properties of low carbon concrete with SCMs materials should be investigated with the injection of a solution of aluminium silicates in the curing tank.
2. The use of lightweight aggregate from industrial waste is also recommended having inert chemicals element that is not prone to ASR as a replacement to granite, following that the ASR tendency of granite [142] is traceable to the composition of deleterious minerals of biotite and pyrite [143] which leads to the formation of secondary ettringite in microcracks [144].
3. Optimization of mechanical properties of blended SCMs of agricultural and industrial waste considering that the combination of POFA and PFA resulting to dissolution of SiO_2 from polarization of hydroxyl ions.

CRediT authorship contribution statement

Promise D. Nukah: Conceptualization, Methodology, Software. **Samuel J. Abbey:** Data curation, Writing – original draft. **Colin A. Booth:** Software, Resources, Project administration. **Ghassan Nounu:** .

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.conbuildmat.2023.133290.

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